TESIS DOCTORAL

A soil vulnerability and quality approach for a functional evaluation of agricultural land use of the territory in Navarre

RODRIGO ANTÓN SOBEJANO

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RODRIGO ANTÓN SOBEJANO

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A soil vulnerability and quality approach for a functional evaluation of agricultural land use of the territory in Navarre

Director:

Dr. Iñigo Virto Quecedo
Departamento de Ciencias
Universidad Pública de Navarra

Universidad Pública de Navarra
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European Commission-Joint Research Centre
(Ispra, Italia)

D. IÑIGO VIRTO QUECEDO, Profesor Titular de Universidad del Área de Edafología y Química Agrícola del Departamento de Ciencias de la Universidad Pública de Navarra

INFORMA:

que la presente memoria de Tesis Doctoral titulada **"*A soil vulnerability and quality approach for a functional evaluation of agricultural land use of the territory in Navarre*"** elaborada por D. Rodrigo Antón Sobejano, ha sido realizada bajo mi dirección, y que cumple las condiciones exigidas por la legislación vigente **para optar al grado de Doctor**.

Y para que así conste, firma la presente en Pamplona a 3 de mayo de 2021.

Dr. Iñigo Virto Quecedo

El autor de esta tesis disfrutó desde mayo de 2016 hasta junio de 2020, de una ayuda predoctoral de la Universidad Pública de Navarra (UPNA). Además, la financiación y apoyo recibido de dicha institución a través de ayudas de movilidad hizo posible el desarrollo de parte de la investigación de esta tesis y de la formación del autor.

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RESUMEN

El contexto actual de cambio global está marcado por alteraciones a escala planetaria en procesos clave que impulsan su funcionamiento, como cambios en el sistema climático, y en los ciclos de los elementos y materiales esenciales para la vida. El desarrollo demográfico de la población humana, así como el uso y la explotación de los recursos naturales y el uso y la ocupación del suelo, sitúan a la actividad del ser humano como uno de los principales impulsores de dicho cambio.

En esta cuestión, los suelos agrícolas se encuentran en el centro de atención. Por un lado, el sector es responsable de una parte importante de las emisiones de gases de efecto invernadero que se emiten a la atmosfera. Por otro lado, el papel del sector como agente sumidero de carbono es ampliamente aceptado, por el potencial de la agricultura para secuestrar CO_2 y promover el almacenamiento de carbono en los suelos agrícolas. Tanto los factores edafoclimaticos como los relacionados con el manejo empleado parecen determinantes para que el balance neto de emisiones de gases de efecto invernadero se oriente hacia un sistema emisor o hacia un sistema mitigador. Por otro lado, las diferentes políticas de desarrollo rural, y las necesidades del comercio mundial, llevan asociados cambios de uso de la tierra directamente vinculados a la producción y el manejo agrícola del suelo.

Esta tesis responde a la demanda de conocer, y evaluar con precisión, el funcionamiento del suelo como soporte de los diferentes usos agrícolas en la región de Navarra, y explorar su potencial tanto desde el punto de vista de la mitigación del cambio climático como desde la mejora de la resiliencia de los agrosistemas (adaptación al cambio climático). Con el objetivo de profundizar en estos aspectos, la tesis se estructura en varios capítulos. Los capítulos principales se agrupan en dos partes, una primera constituida por los capítulos II y III, y una segunda formada por los capítulos IV, V y VI.

La primera parte, capítulos II y III, se centra en el estudio de la dinámica del carbono orgánico del suelo, explorando en detalle los mecanismos y controles que regulan este proceso en un suelo Mediterráneo cultivado calcáreo, característico de la región. Además, dado la relevancia que el riego tiene en la misma, se estudió la interacción que la transición del secano al regadío supone en la dinámica de incorporación de carbono orgánico en dicho suelo. Para ello se dispone de un diseño experimental *ad hoc*, que fue implementado en Enériz, Navarra, en 2009, diseñado para realizar un estudio de marcaje isotópico natural a partir de un cambio de plantas C3 a C4. Los resultados indican que los carbonatos presentes en este suelo, parecen comportarse como un factor clave en el proceso de

estabilización de la materia orgánica en el horizonte labrado, promoviendo una rápida incorporación y estabilización de los residuos de los cultivos en agregados estables de diferentes tamaños. Además, se observó que el riego puede inducir cambios, con tendencia positiva, en el stock de carbono del suelo a lo largo del periodo de estudio de 7 años. El tipo de cultivo y la gestión agrícola en secano o regadío, fueron los principales impulsores de este proceso en las condiciones edafoclimáticas de la zona estudiada.

La segunda parte de esta tesis, recogida en los capítulos IV, V y VI, se centra en la evaluación de estrategias de mitigación y adaptación al cambio climático en los sistemas agrarios de Navarra, y su relación con el funcionamiento del suelo.

El capítulo IV, se centra en evaluar el impacto que la introducción del regadío tiene en la región, desde un punto de vista amplio de la calidad del suelo, incluyendo la evaluación de distintos servicios ecosistémicos asociados a dicho uso del suelo, basada en el concepto de *Seguridad del Suelo*. En él, se lleva a cabo el análisis de diferentes sistemas de cultivo vinculados al riego en la región, considerado como herramienta para garantizar un aumento tanto del rendimiento de los cultivos como de las ganancias netas para el agricultor. El análisis incluye la cuantificación de balances de emisiones de gases efecto invernadero, considerando en dicho balance la estimación de una tasa de secuestro de carbono anual vinculada a cada suelo y manejo considerado. Los resultados indican que el potencial del regadío para proporcionar servicios ecosistémicos claves a la sociedad, como son el control de la erosión y la regulación del clima, es variable y dependiente del manejo agrícola que lo acompañe.

Finalmente, los capítulos V y VI de esta tesis se centran en el desarrollo y análisis de una serie de indicadores de suelo de cara a cuantificar la eficacia de diferentes estrategias de adaptación al cambio climático en la vulnerabilidad de los sistemas agrícolas, a escala regional. Las estrategias consideradas son la aplicación de fuentes externas de materia orgánica, la introducción del riego, la agricultura de conservación, el uso de rotaciones de cultivos y el manejo controlado de pastos.

El capítulo V se centra en el análisis del stock de carbono orgánico como indicador edáfico de vulnerabilidad, mientras que el capítulo VI lo hace a partir del análisis de indicadores físicos del suelo, en este caso densidad aparente y la capacidad de retención de agua del suelo. Los resultados obtenidos ponen de relevancia la importancia del clima y del tipo de suelo a la hora de evaluar la vulnerabilidad de los sistemas agrícolas de la región de Navarra. Del mismo modo, a pesar del efecto general positivo observado asociado a las cinco estrategias consideradas, la variabilidad observada en cuanto a la adopción y la eficacia de las mismas parece estar modulada por factores geográficos y de gestión. Esto indica que es necesario realizar investigaciones más detalladas para evaluar la vulnerabilidad del suelo y el posible potencial de adaptación de los sistemas agrícolas a los cambios del clima.

El trabajo realizado en esta tesis aporta una valoración funcional del uso agrícola del territorio de la Comunidad Foral de Navarra. Se muestra como los suelos agrícolas prestan importantes servicios que la sociedad debe poner en valor, no sólo los relacionados con el suministro de alimentos y otros materiales, sino también con otras funciones clave como la regulación del clima, o el control de la degradación y vulnerabilidad del suelo. Al mismo tiempo, estos servicios pueden degradarse bajo determinadas condiciones de manejo. La comunidad científica debe coordinarse y colaborar con los responsables políticos, extensionistas, agricultores y otras partes interesadas para explorar y capitalizar estos servicios, de cara a orientar una transición hacia una agricultura sostenible que permita afrontar los retos del futuro. Este trabajo remarca, además, la importancia de realizar estudios a escala de parcela agrícola, en las que se consideren las características específicas de cada lugar, que permiten profundizar en el conocimiento de procesos básicos, como es la dinámica de incorporación de carbono orgánico en suelo, de cara a definir y desarrollar estrategias que puedan ser aplicadas a nivel regional.

SUMMARY

The context of global change is marked by planetary-scale alterations in key processes that drive its functioning, such as changes in the climate system and in the cycles of elements and materials essential for life. The demographic development of the human population, as well as the use and exploitation of natural resources and land use and occupation, place human activity as one of the main drivers of such change.

Agricultural soils are at the center of this issue. On the one hand, the sector is responsible for a significant proportion of greenhouse gas emissions into the atmosphere. On the other hand, the role of the sector as a carbon sink agent is widely accepted, due to the potential of agriculture to sequester CO_2 and promote carbon storage in agricultural soils. Both the edaphoclimatic factors and those related to the management applied seem to be decisive in determining the net balance of greenhouse gas emissions in favor of an emitting system or a mitigating one. In addition, the different rural development policies and the needs of world trade are associated with changes in land use that are directly linked to agricultural production and soil management.

This thesis addresses the need to know and accurately assess the functioning of soil as a support for different agricultural uses in the region, and to explore its potential both from the point of view of climate change mitigation and from the point of view of improving the resilience of agrosystems (adaptation to climate change). With the objective of exploring these aspects in detail, the thesis is structured in several chapters. The main chapters are grouped into two parts, the first one constituted by chapters II and III, and the second one by chapters IV, V and VI.

The first part, Chapters II and III, focuses on the study of soil organic carbon dynamics, exploring in detail the mechanisms and controls that regulate this process in a calcareous cultivated Mediterranean soil, characteristic of the region. In addition, given the relevance of irrigation in Navarre, the interaction that the transition from rainfed to irrigated land has on soil organic carbon incorporation dynamics in this soil was studied. For this purpose, an ad hoc experimental design was implemented in Enériz, Navarra, in 2009, designed to carry out a natural isotopic labelling study based on a change from C3 to C4 plants. The results indicated that the carbonates present in this soil seem to be a key factor in the stabilization process of organic matter in this soil, promoting a rapid incorporation and stabilization of crop residues in stable aggregates of different sizes. In addition, it was observed that irrigation induced changes, with a positive trend, in soil carbon stocks, both in total and particulate fraction, over the

7-year study period. Crop type and agricultural management were the main drivers of this process under the edaphoclimatic conditions of the studied area.

The second part of this thesis, Chapters IV, V and VI, focuses on the evaluation of mitigation and adaptation strategies to climate change in the agricultural systems of Navarra, and their relationship with soil functioning.

Chapter IV focuses on evaluating the impact of the introduction of irrigation in the region, from a broad point of view of soil quality, including the assessment of different ecosystem services associated with this land use, based on the concept of *Soil Security*. In it, the analysis of different cropping systems linked to irrigation in the region, considered as a tool to guarantee an increase in both crop yields and net profits for the farmer, is carried out. The analysis includes the quantification of greenhouse gas emission balances, considering in such balances the estimation of an annual carbon sequestration rate linked to each soil type and management considered. The results indicate that the potential of irrigation to provide key ecosystem services to society, such as erosion control and climate regulation, is variable and dependent on the accompanying agricultural management.

Finally, chapters V and VI of this thesis are focused on the development and analysis of a series of soil indicators in order to quantify the effectiveness of different adaptation strategies to climate change on the vulnerability of agricultural systems in the region. The strategies considered are the application of external sources of organic matter, the introduction of irrigation, conservation agriculture, the use of crop rotations and controlled pasture management. Chapter V examines the organic carbon stock as a soil indicator of vulnerability, while Chapter VI considers the analysis of soil physical indicators, in this case bulk density and soil water retention capacity. The results obtained highlight the importance of climate and soil type in assessing the vulnerability of agricultural systems in the Navarra region. Similarly, despite the overall positive effect observed associated with the five strategies considered, the variability observed in terms of adoption and effectiveness of the strategies seems to be modulated by geographical and management factors. This indicates that more detailed research is needed to assess soil vulnerability and the potential for adaptation of agricultural systems to climate change.

The work carried out in this thesis provides a functional assessment of agricultural land use in the region of Navarra. It shows how agricultural soils provide important services that society should value, not only those related to the supply of food and other materials, but also to other key functions such as climate regulation, or the control of soil degradation and vulnerability. At the same time, these services can be degraded under certain management conditions. The scientific community must coordinate

and collaborate with policy makers, external agents, farmers and other stakeholders to explore and capitalize these services, in order to guide a transition to sustainable agriculture to address the challenges of the future. This work also highlights the importance of conducting studies at the plot scale, taking into account the specific characteristics of each site, in order to provide a better understanding of basic processes, such as the soil organic carbon incorporation dynamics, which can be used to identify and develop strategies that can be applied at the regional level.

Chapter I

Introduction

Work framework and structure

Objectives

“Porque todavía ha de observar que solo es fértil un terreno cuando la vida microbiana tiene en él suficiente actividad.
Y como el humus es el lecho o medio imprescindible en que aquellos pueden desarrollarse, se desprende que las miríadas de bacterias, zoos, hongos… solo vivirán si aquel existe, y tanto más cuanto mayor sea su proporción.”

Daniel Nagore Nagore
El abono. Resorte vital de la producción agrícola.
Diputación Foral y Provincial de Navarra. Dirección de Agricultura y Ganadería. Editorial Aramburu. Pamplona, 1939

CHAPTER I

Introduction
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CONTENTS

INTRODUCTION

1. Soil and global change

Global change is a multi-factorial phenomenon (Rillig et al., 2019), that refers to planetary-scale changes on the key processes driving the functioning of the Earth system. This includes, among others, the climate system, the stratospheric ozone layer, the cycles of the elements and materials essential to life such as nitrogen, carbon or water, or the balance and distribution of biodiversity and ecosystems. The combination of factors such as the demographic development of human population, the use and exploitation of resources and energy, pollution or land use and land cover, places human social and economic activity as a major driver of this global change. This is evidenced in the fact that, in the last years, food, water and energy security, as well as sustainable integrated land and resource management, have become the central axes of many research (Smith et al., 2016) and development policy programs in recent years as the European *Green Deal* (European Commission, 2019), the United Nations Sustainable Development Goals and the 2030 Agenda for Sustainable Development (Assembly UN, 2015) or different climate change regulations at European, national or regional scale (European Commission, 2020a; Gobierno de Navarra, 2017; Ministerio para la Transición Ecológica y el Reto Demográfico, 2020).

In relation to climate, according to the IPCC (2014), climate change refers to alterations in the state of climate that can be identified by changes in the average condition and/or the variability of climate factors and agents, and that persists for an extended period (decades or longer). Climate changes may be caused by natural internal processes, external forcing, and by anthropogenic activities. In this case, human activity contributes directly or indirectly by altering the composition of the atmosphere. Soil appears at the center of this issue, because of its key role in terrestrial ecosystems, and because it supports agriculture and, therefore, it is related to the changes in land use associated with primary production. This places soil as a cornerstone in climate change, both in terms of causes and effects (Smith et al., 2015).

The role of soil systems in the biogeochemical cycles of C and N, and in particular, in the exchange of these elements between the atmosphere and terrestrial ecosystems, has awaken special interest in recent decades, as this exchange is directly related to greenhouse gases (GHG) in which these elements are involved (CO_2, CH_4, N_2O). Agriculture in general, and agricultural soils in particular, are of special interest in this sense, due to the impact of land use and agricultural management on these cycles, and their consequences on the global balance of GHG emissions. They have been, as a consequence, the focus of attention in emission regulation policies and strategies for some time (IPCC, 2006). Evidence of the current interest in this issue is the European Commission proposal to align the Common Agricultural Policy (CAP) with the EU's environmental, climate and biodiversity protection commitments established in the European *Green Deal* (European Commission, 2020b; European Commission Staff, 2020; Panagos et al., 2020) or the recent support study on the impact of the CAP on sustainable soil management (Augier et al., 2020).

This interest is partly explained by the potential of soils to sequester atmospheric C and to store it in form of organic matter, constituting one of the largest reserves of C on Earth, and thus performing a function of climate regulation (Lehmann and Kleber, 2015). This function has highlighted the importance of studies on the stabilization of organic matter in the soil, and on the effects that different uses or agricultural management strategies can have on this stabilization. This is reflected in the activities of scientific networks such as the Remedia Network (http://www.redremedia.org) or the well-known 4per1000 initiative (Minasny et al., 2017; Rumpel et al., 2020) and by the numerous research papers and official reports at national and international scale (FAO, 2020a, 2020b; Lal, 2004; MAPAMA, 2018; Pellerin et al., 2013; Sánchez et al., 2016; Stockmann et al., 2013).

Additionally, soil represents a fundamental part of terrestrial ecosystems and can be affected by variability and changes in climatic conditions (European Environment Agency, 2015). In addition to the key role of climate as a factor of soil formation and the possible consequences of climate change in this respect in the long term

(Keyvanshokouhi et al., 2016), observed and expected changes in climate can have a significant effect on rapid degradation processes such as erosion or the mineralization of organic matter.

In this context of global change, it is therefore needed to invest efforts in the evaluation and understanding of the impact that this multifactorial phenomenon can have on soils. As such, because of its key role in soil functioning and climate change regulation, it is of paramount importance to improve our understanding of the soil organic C (SOC) dynamics and how these changes can directly affect the performance and quality of agricultural soils. Similarly, developing new agricultural systems, able to propose responses to this change is needed, as well as evaluating their potential mitigation and adaptation strategies to face it. This would lead to progress in the conservation of agricultural soils, reducing the impact that their use implies, and ensuring the support of the diverse ecosystem services they provide.

2. Assessing and managing the risks of climate change: mitigation and adaptation

The IPCC (2014) defined the risk of climate-related impacts as the interaction of climate-related hazards with the vulnerability and exposure of human and natural systems (Figure 2). In this framework, changes in both the climate system and socioeconomic processes (including adaptation and mitigation strategies) are drivers of hazards, exposure, and vulnerability.

Climate change mitigation strategies in agricultural systems can be summarized as those aimed to reduce GHG emissions, and those aimed to increase the potential of soil in the stabilization of atmospheric CO_2 in the form of stabilized organic matter (Sanz-Cobena et al., 2017).

In both directions, the need for understanding the functioning of the soil system is evident. Globally, emissions from agricultural soils, considering emissions from the use of fertilizers and in flooded systems such as some rice fields, account for approximately 23% of those associated with agriculture (Tubiello et al., 2014). Other emissions associated with agricultural soils are those related to livestock residues

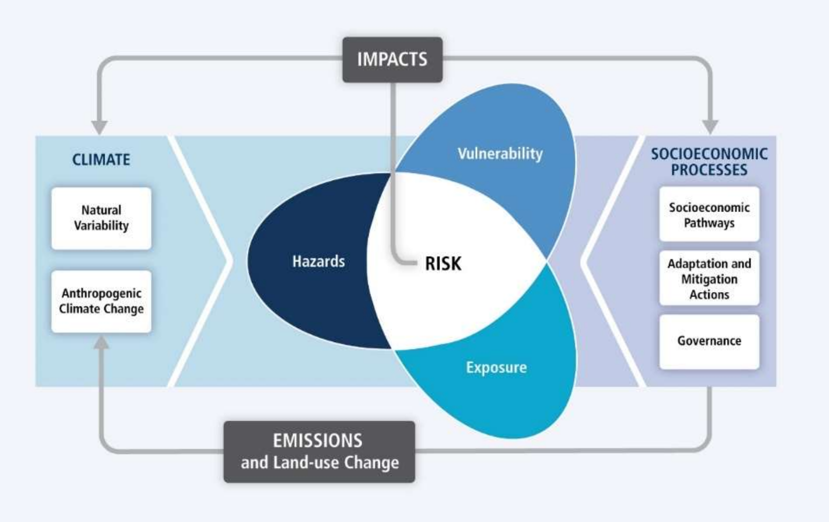

Figure 2. Risk framework for the analysis of extreme event impacts. (IPCC, 2014)

management. For this reason, the development of agricultural and agro-livestock systems capable of supporting production with lower emission rates constitutes a clear line of work in most climate change mitigation plans at different scales. Soil characteristics and management are decisive in this sense, since both factors drive most of the processes responsible for these emissions (Cayuela et al., 2017).

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Our knowledge about the potential of soil management to mitigate climate change has increased significantly in recent years (Paustian et al., 2016). In relation to C sequestration from the atmosphere, the potential of agricultural soils to stabilize photosynthesized C, and therefore contribute to the reduction of CO_2 in the atmosphere, depends largely on the climate and soil conditions considered (Chenu et al., 2019). In this sense, initiatives such as the "4per1000" (Minasny et al., 2017; Rumpel et al., 2020) have used this potential as a basis for promoting strategies that contribute to an increase in SOC stocks in agricultural soils. This is in line with the study developed by the Spanish Ministry for Agriculture and the Environment (MAPAMA, 2018), which concluded that the potential for SOC stabilization into agricultural soils in Spain is high. The strategies considered in this study included the application of different types of compost and organic urban and agricultural sub-products and residues (Torri et al., 2014), and soil management techniques such as conservation agriculture (Lal, 2016), organic agriculture (Altieri et al., 2015), or crop rotations (Land et al., 2017). These strategies imply different ways to increase inputs to the soil, and/or reduce outputs of organic C, therefore driving to a positive net balance in the medium-long term.

The large number of responses and feedback that the 4per1000 initiative has generated (Baveye et al., 2018; Rumpel et al., 2020; Soussana et al., 2019; Van Groenigen et al., 2017; White et al., 2018) are evidence of the need to determine in as much detail as possible the local conditions that may condition SOC stabilization in soils. In this sense, detailed assessments of emissions and mitigation options are needed to provide appropriate responses in each case (FAO, 2013). The site-specificity of the potential response for mitigation (and adaptation) of land-use strategies was indeed explained in detail in the latest IPCC report especially dedicated to land use, agriculture and climate change (Jia et al., 2019).

These authors also noted that strategies focused on improving SOC contents usually require time to show results, as well as limited capacity, in time, and high vulnerability to reverting if management (or climatic) conditions change. The report also recognizes that processes related to SOC and microbial processes, which can interact with vegetation in response to climate, represent a major source of uncertainty for climate model projections.

Therefore, the implementation of these mitigation strategies, and their evaluation, must be assessed at the local level, considering both climatic and soil characteristics. Some aspects of soil functioning, not widely known to date, may be relevant in this sense, such as the sensitivity of different soil organic matter fractions to temperature and other changes (Conant et al., 2011), the maximum potential for organic C storage, or the role of the mineral fraction or the physical-chemical conditions of the soil (Chenu et al., 2019; Dignac et al., 2017). The relevance of deeper understanding of soil organic matter dynamics is particularly important in this context.

Finally, a last point to be considered in relation to potential mitigation strategies is the requirement to synthetically evaluate their effect on the sequestration-emission balance, as well as their possible implications outside the region where they are applied (Fernández-Getino et al., 2018).

Adaptation to climate change is based in reducing the risks associated with climate change, and the adaptive capacity of a system will be determined by the vulnerability of each system and the possibility or not of reducing the exposure to different phenomena (*hazards*) (IPCC, 2014; Jia et al., 2019).

The agricultural sector appears as particularly vulnerable, as it is highly dependent on weather conditions (Iglesias et al., 2012), so there is an increasing interest in exploring different adaptation strategies (see for example the European initiatives at https://climate-adapt.eea.europa.eu/, or projects such as Adaptaclima II (http://www.adaptaclima.eu/) or AgriAdapt (https://agriadapt.eu/). In this respect, the adaptation strategies developed at various levels consider, directly or indirectly, aspects related to the characteristics and condition of the agricultural soils, both in relation to the vulnerability of the agrosystems and to their capacity to adapt to present and future climate changes.

For instance, the IPCC states in the last synthesis report (IPCC, 2014) that increased water demand for irrigation and reduced water availability are recognized as among the main risks in Europe. The assessment of these risks and potential adaptation measures needs to consider the soil resource in relation to its role in the agricultural water cycle, considering for instance the adoption of water-saving strategies, in addition to adapted crop species or appropriate land use.

The EU's 2012 Climate change, impacts and vulnerability report (EEA, 2012) already addressed these issues, emphasizing the need to obtain quality information to identify appropriate adaptation measures. In particular, this report included the relevance of soil in three aspects: its role in providing ecosystem services related to climate regulation; the need (and challenge) to consider soil indicators in relation to mitigation; and the need to establish soil indicators to enable policy-makers to take appropriate adaptation measures.

The specific IPCC report on mitigation and adaptation strategies related to land use (Cosgrove and Curtis, 2018; Jia et al., 2019; Lead et al., 2018) indicates, on the one hand, that it is possible to improve the adaptation and adaptability of agrosystems by using soil management strategies. On the other hand, these authors point out that there are still important sources of uncertainty about the consequences and performance of these strategies. Four actions with different adaptation potential in relation to soil are included in the report: increase in SOC content (with a high potential for mitigation as well), erosion control, and salinization and compaction control, the last two with a lower potential for adaptation. However, the level of confidence associated to these four measures in relation to adaptation is low, due to the high variability observed in the response, and the existing uncertainties.

From the four actions mentioned, the report describes with special relevance the situation of those related to SOC. It states that some of the aspects that contribute to the uncertainty of the effectiveness projections of some measures, and to the response of agrosystems to climate change, include the response of the soil-plant-atmosphere system to climate changes, its sensitivity to humidity and temperature, the distribution of organic C in the soil profile, its relationship with the mineral fraction, and its response to changes in the organic C inputs from plants (natural or cultivated). In this context, the consideration of the role of soil in direct adaptation strategies is variable, and can be sometimes indirectly related to other measures and strategies.

In the EU, the European Climate Change Adaptation Strategy is based on three pillars: (i) encouraging action by Member States, (ii) developing measures at EU level to further promote adaptation in key vulnerable sectors such as agriculture (climate-proofing), and (iii) informed decision-making, addressing knowledge gaps on adaptation and the development of the European Platform for Adaptation to Climate Change (Climate-ADAPT, https://climate-adapt.eea.europa.eu/).

In this context, the most recurrent concepts regarding the role of soil in adaptation include those related to the water cycle, such as improving water retention in agricultural areas, and to organic matter. The FAO report on climate-smart agriculture also remarked the relevance of these two aspects, indicating that the increase in organic matter content should not be considered only from the perspective of mitigation, but also as a tool to increase the resilience of agrosystems and maintain the ecosystem services provided by the soil (FAO, 2013).

The knowledge about this role is wide, and has generated great interest from research policies in Europe in recent decades, as explained below. However, the evaluation of the implementation of this strategy (European Commission, 2020a), recognizes that there are still knowledge gaps on adaptation, despite significant progress reported by EU research and innovation activities since 2013. Areas where a transition from knowledge generation to its application for decision making is encouraged include agriculture in Mediterranean regions.

For instance, in relation to section (iii) of the strategy, there are uncertainties regarding the functioning of agricultural soils in several aspects. Regarding the SOC storage in agricultural soils, and the policies that can lead to its management as an adaptation strategy due to its link with chemical, physical and biological fertility, and its role in the water cycle, Chenu et al. (2019) established knowledge limitations at two levels. First, in the understanding of edaphic mechanisms and agrosystems that can explain and model the processes of organic matter stabilization between two equilibrium states (e.g. current vs. future situation). Second, the major difficulties identified when predictions are made at the local scale include the uncertainty of the initial soil C content, the difficulty to adequately define the size of the different organic C pools, the estimation of the actual organic C inputs associated with the different strategies, the poor consideration of soil typology, the impact of different managements on SOC loss rates, and the lack of consideration of the deep soil horizons.

3. Soil organic C dynamics and its interaction with agricultural management.

Understanding SOC dynamics appears, from the explnataion above, a cornerstone for the assessment of agricultural management strategies. The nature and dynamics of soil organic matter (SOM) has been indeed studied for a long time already (Paul, 2007; Brevik and Hartemink, 2010), and especially since the emergence of Soil Science as a discipline on its own (Hartemink, 2015; Van Baren et al., 2000). As explained above, SOM cycling and storage has numerous implications for the present and future challenges of global change (Paul, 2016), including the implication in the process of climate change mitigation and adaptation.

The conceptualization of this soil fraction has gradually progressed over time, as new knowledge and approaches have been developed, and new methodological tools and concepts have enriched the existing knowledge (Baveye and Wander, 2019; Dignac et al., 2005; Minasny et al., 2017). Considering that the primary origin of SOM are the materials photosynthesized by plants and other organisms living in the soil, when the rate of decomposition of SOM is slightly slower than the new incorporation of these materials into the soil, it may result in an increase in their stock (Paul, 2016). The factors that explain this basic mechanism will ultimately explain the amount and type of organic materials found in different soils.

The model proposed by Lehmann and Kleber (2015), which includes different approaches developed to date, defines SOM as a continuum of materials in progressive decomposition, processed by the decomposer community from large plant and animal residues towards components with smaller molecular size (Figure 1).

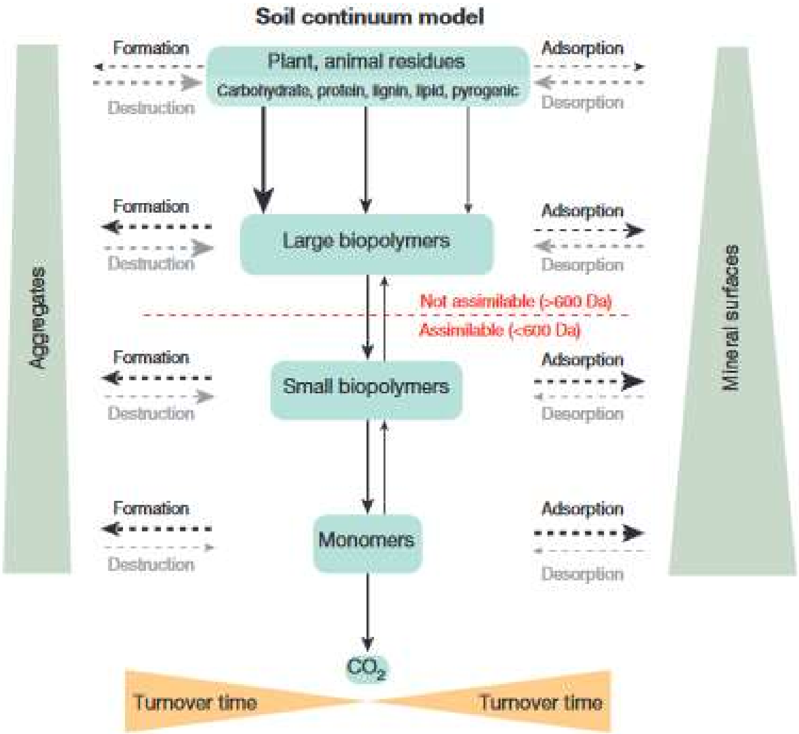

Figure 1. Soil continuum model. Dashed arrow lines denote mainly abiotic transfer, solid lines denote mainly biotic transfer; thicker lines indicate more rapid rates; larger boxes and ends of wedges illustrate greater pool sizes; all differences are illustrative. All arrows represent processes that are a function of temperature, moisture and the biota present. (Lehmann and Kleber, 2015)

According to this consolidated model of the SOM stabilization cycle, the controls of these mechanisms that regulate this process would be similar in all soils. Therefore, it should be the expression of these controls in the different possible soil and climate conditions what results in the individual characteristics of SOM dynamics at each site (Paul, 2016). The nature of SOM can be better understood when these controls are known in each situation. The main controls defined have been the chemical composition of the organic inputs, the physical protection (aggregation) and the interactions with the soil matrix (Lützow et al., 2006).

From them, the relations of organic matter with the mineral components of the soil, constitute the main control of stabilization and/or mineralization in the soil. As described in Figure 1, these mechanisms are manifested mainly at two levels: soil organic matter protected by direct interaction with minerals, and aggregation. In this sense, the evaluation of the interaction between the mineral fraction, the soil structure, and the preservation of organic matter allows to understand the response of the soil to different alterations, such as different agricultural management strategies. The nature and proportion of the different components in the inorganic fraction of the soil is thus a factor of relative importance in the stabilization cycle of organic matter

Therefore, updated visions of the processes and dominant agents in the control of the SOM cycle have proposed different agents depending on the natural conditions of the soil. In two reviews it has been observed, with different approaches, that, under certain conditions, there are agents with greater predictive capacity of SOM storage at the continental scale than the clay content (Rasmussen et al., 2018). These are related to the soil reaction, as is mineralogy at the global scale, so that exchangeable calcium has a strong predictive relationship to SOM content in basic soils or soil horizons of arid and semi-arid zones, while with increasing soil moisture and acidity, iron and aluminum oxyhydroxides appear as the best predictors of total SOM content. In relation to calcareous soils, the presence of carbonates, and in particular $CaCO_3$, can influence both SOM stabilization by occlusion by physically stabilizing aggregates of various sizes, and because they can play a role in direct sorption and SOM inclusion in primary organo-mineral complexes (Rowley et al., 2018).

Agricultural land use and the practices it involves can modify the inputs of organic materials into the soil in space and time, as well as the sensitivity of organic matter to mineralization, by acting on biotic and abiotic mechanisms, such as plant type and density, rotation management, exports of harvest residues, amendments, fertilization or tillage (Dignac et al., 2017).

An example of this is the estimations provided on SOC stocks in the forests, agricultural lands and grasslands of Spain by Rodríguez Martín et al. (2016), who reported 65.2-98.6 Mg C ha^{-1}, 38.1-45.3 Mg C ha^{-1} and 57.0-68.1 Mg C ha^{-1}, respectively. Although it is not possible to extract cause-effect relationships from this observation, it is an example of the globally observed trend that implies a reduction in SOM content associated to agricultural land use. This is commonly associated to a reduction of inputs and/or improvement of the conditions for mineralization, although the response is dependent on both the type of management and the characteristics of the soil (Plante et al., 2010).

Considering the relevance and multifunctionality of SOM, agricultural extension services and research have focused largely in recent decades on the design, implementation, and evaluation of different agricultural management strategies that would reverse this effect and recover and/or increase SOS stocks in agricultural soils (Paustian et al., 2019). Dignac et al. (2017) and Chenu et al. (2019) summarized the practices considered with potential for improving SOC stocks, the mechanisms and indicators involved, and the gaps in current knowledge to understand the relationship between agricultural management and the accumulation of organic matter in the soil. Among the challenges of current knowledge (Chenu et al., 2019), in relation to the techniques that should be reviewed for a better understanding of the processes associated with the organic C cycle, conservation agriculture, irrigation, practices that increase root growth, organic amendments and nitrogen fertilization are the most relevant.

These practices are focused on altering the cycle of SOM through different ways, and therefore moving the balance to a more positive state of equilibrium between inputs and outputs. This is in line with the already mentioned 4per1000 initiative , which takes this figure (4‰) as a reference for the average annual increase of organic C content in the world's soils that would compensate the CO_2 emissions of the agricultural sector (Minasny et al., 2017), assumes that the interest of this increase actually goes further than mere compensation, and aims to improve the condition of the soil and the functioning of agrosystems, as benefits associated with the increase of SOM (Rumpel et al., 2020; Soussana et al., 2019).

When addressing this issues in a regional context, it is necessary to address the change of scale (*up-scaling*) from the experimental plot to the region, which represents one of the main challenges in this type of studies (Chenu et al., 2019; Dignac et al., 2017; FAO, 2013; Paustian et al., 2019). For Paustian et al. (2019) the main challenges for C quantification at territory scale are the high spatial variability and relatively small observable changes relative to the background stock (*baseline*). According to these authors, the high-precision methods used in research are not practical for large-scale monitoring. Therefore, it is necessary to develop sampling strategies based on georeferenced points to optimize the balance between sampling intensity and uncertainty. In the same line, Wiesmeier et al. (2019) highlighted the importance of considering regional approaches to properly estimate organic C storage potential for specific climate and land use conditions, management, and vegetation characteristics, in agreement with Karlen et al. (2014).

4. Soil organic matter fractionation and modelling

A practical consequence of the conception and dynamics of SOM proposed by Lehmann and Kleber (2015) described above, is the identification of SOM components and compounds that represent the different phases of the cycle. This concept represents the basis on which SOM fractionation studies have been developed for decades. This approach has also supported the development of mechanistic models in order to simulate SOM dynamics, in which, in turn, it is necessary to define, quantify and characterize the pools or functional fractions that constitute the SOM (Lützow et al., 2007).

In this sense, physically separated fractions seem more appropriate to characterize the fractions corresponding to the first phases of the cycle (with short return cycles). In contrast, it seems more complex to isolate functional fractions corresponding to the pool called passive, and corresponding to polymers of different molecular weight protected from biological degradation by their relationship with the mineral fraction, according to the model of Lehmann and Kleber (2015).

Within this approach, there are multiple strategies to physically separate fractions of different size and/or density, granulodensimetric fractions, and/or aggregates of different size and stability, or resistance to contact with water and/or mechanical agents. The first ones, such as sequential densimetric fractionation, allow for the separation of organic and mineral components with a greater or lesser degree of union between them (Plante et al., 2010).

Methodologies have also been developed to separate aggregates of different sizes containing physically-occluded organic materials with different levels of protection from biological degradation and return times (Christensen, 2001; Elliott, 1986; Marriott and Wander, 2006; Six et al., 2002). In this regard, various labile fractions of organic matter, occluded within the aggregates but with little direct association to the mineral fraction, and easily biodegradable in nature, have been distinguished, such as the particulate organic matter present in micro and/or macro aggregates (Cambardella and Elliott, 1992; Jastrow, 1996). Some of these fractions have been identified as early indicators of changes in the SOM cycle (Imaz et al., 2010; Marriott and Wander, 2006), which has, by nature, a low density, although it may be heterogeneous in terms of composition and functionality (Chenu et al., 2015; von Lützow et al., 2007).

In addition to allow for a better understanding of the SOC cycle and for the estimation of the return rate for each fraction, these approaches attempt to identify fractions that can explain the functioning of the aggregation cycle, and its response to different alterations. Thus, they allow to evaluate the relate the response of SOC to possible changes with aggregation (Campbell and Paustian, 2015; Paul, 2016).

Numerous models have been developed based on the conceptual division of the soil organic fraction into several pools, which would have different return cycles (von Lützow et al., 2007; Zimmermann et al., 2007). For Campbell and Paustian (2015), the optimal SOM model should be based on a mechanistic understanding of the process, and should use SOM pools that could be estimated by measured data (Cotrufo et al., 2019) and would be valid at multiple scales. For (Paul, 2016), none of the more than 250 models designed and tested in his comprehensive review on the topic, fits this ideal entirely. Some of the limitations identified by these authors are:

- By assuming a material transfer based on first-order exponential kinetics, an increase in inputs implies a continuous and proportional increase in all organic matter fractions considered in the model. There is evidence that this is not always the case in real agrosystems (Stewart et al., 2009).

- Although the complexity of models has increased significantly in recent years, it is difficult to consider all the possible interaction mechanisms within the SOM pool. In this sense, in general, the number of model parameters should not exceed the number of observations, so that the complexity of the models implies a greater source of uncertainty (Derrien and Amelung, 2011).

- Finally, the major challenge is the confluence of the conceptual pools defined in the models with their corresponding SOM fractions, and how the latter can be easily identified or estimated in soil samples (Blankinship et al., 2018; Ellerbrock and Kaiser, 2005; Poeplau et al., 2018; Stockmann et al., 2013; Zimmermann et al., 2007).

For Blankinship et al. (2018), the imbalances among conceptual understanding, measurement, and modeling represents the real challenge in order to integrate microbial decomposition mechanisms and physicochemical protection into predictions of SOM change. In this sense, new models approaches are emerging in order to incorporate and combine the current compartment options with continuous distribution alternatives, based on the interpretation of SOM as a range of organic compounds that microorganisms continuously transform into smaller molecules (Julien et al., 2021).

Isotopic studies combined with field-scale parameter monitoring represent a powerful and widely used methodology to understand the mean residence time (MRT) of the different SOM pools and the total stock. They are based on the study of the isotopic footprint originated by the main elements present in different ecological processes, which can be used to track the interactions occurring in an ecosystem from one end to the other (Derrien and Amelung, 2011). The approach that uses the natural ^{13}C abundance represents a widespread option for temporal and spatial modeling of SOM, with high applicability for assessing its turnover in soil. It is based on differences in the natural abundance of ^{13}C in C3 and C4 plants, and on the assumption that the natural abundance of ^{13}C in SOM is equivalent to that of the plants from which it is derived (Figure 3).

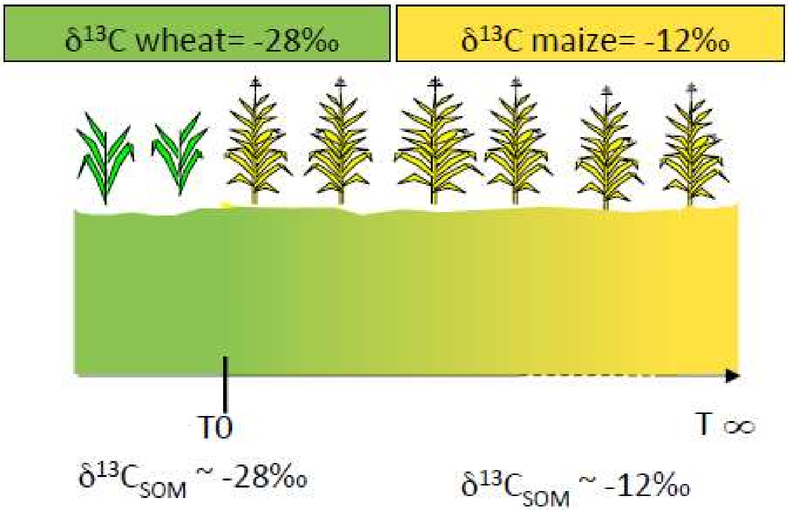

Figure 3. ^{13}C abundance in a conversion from C3 to C4 plants. (Derrien et al., 2017)

In the case of a conversion from C3 to C4 plants grown on a soil, the rate of C loss derived from the original C3 vegetation and the new C incorporation derived from the new C4 vegetation can be deduced from the resulting change in the natural abundance of ^{13}C in SOM, and in its fractions (Kuzyakov et al., 2006; Larionova et al., 2015; Novara et al., 2013).

5. Soil quality assessment

It can be deduced, from the explanations so far, that soils need to be assessed from a holistic perspective, if their role in agrosystems is to be considered as a tool for adaptation to new climate and management conditions. Although the interest on soil quality has followed humanity since the beginning of agriculture (Karlen et al., 2019), the concept evolved throughout the 1990s into a wider concept, more focused on sustainable land management, and providing a more holistic approach (Karlen et al., 2003). In 1994, Doran and Parkin established a formal definition based on soil functionality, which established the basis for studies focused on the evaluation and determination of soil quality indicators. Soil quality also began to be understood as sensitive and dynamic, and responsive to human uses or environmental conditions (Arshad and Coen, 1992; Haberern, 1992; Karlen et al., 2003).

Since then, the literature on soil quality studies has increased exponentially, focusing the efforts on developing a conceptual framework to reflect the complexity and specificity of soil as an element of terrestrial ecosystems (including agrosystems), as well as the many relationships between soil functions and the ecosystem services they provide (Bünemann et al., 2018; Dominati et al., 2010). The importance of considering all dimensions and properties of soil (at least in terms of physical, chemical, biological, and organic matter properties) is intrinsic to any study of this type (Adhikari and Hartemink, 2016; Doran and Parkin, 1994).

In recent years, this concept has been included in ecosystem services studies associated with agriculture or other land uses, within an assessment framework which goes beyond the mere state of soil, attempting to include aspects related to soil capacity, soil condition, soil capital, soil connectivity, or soil codification, as determined by McBratney et al. (2014) within the concept of *Soil Security*.

For these authors, soil capability can be understood in terms of a reference state, soil intrinsic properties, that defines an optimal capacity of the soil to which the current condition of the soil can be compared. Therefore, soil condition refers to the current state of the soil, it can be defined as the capacity of a soil to function at is present state, and can be estimated by measuring specific soil properties. Both soil capability and condition may vary in accordance to how the soil is managed. Soil capital is defined by placing a value on the service delivery soil stocks underpinning. Soil connectivity brings in the social dimension around soil among the different users and stakeholders and the knowledge and resources to manage the soil condition and to use it according to its capability. Finally, the last dimension of soil security, soil codification, is related to public policy, regulation and legal frameworks that support the maintenance and improvement of the world soil resource.

Within the diversity of these approaches, there is consensus on the fundamental stages in the evaluation of soil quality, where the selection of appropriate indicators stands out for its special relevance (Bünemann et al., 2018). For several authors (Bai et al., 2018; Bünemann et al., 2018; Karlen et al., 2019) the most frequently proposed ones are those related to the organic fraction and soil reaction, together with those referring to the status of some nutrients (especially phosphorus) and to porosity (density) and water retention. For these authors, not only soil functions or services associated with them must be considered when selecting the indicators, but also the local conditions imposed by soil-climatic and management characteristics.

Once the most appropriate indicators have been determined, it is necessary to set baselines and possible variation ranges for each of them, in order to give a quantitative or qualitative value to the state of each indicator in a specific agrosystem (Bünemann et al., 2018).

Considering the interrelationship between SOM dynamics, the soil physicochemical conditions, physical state, biological activity and agrosystems productivity, it is possible to understand that indicators related to C dynamics play an important role in the study of soil quality (Bünemann et al., 2018; Coll et al., 2011; Drobnik et al., 2018; Lorenz et al., 2019). The correlation between SOC stabilization and soil quality is, thus, one of the main research goals in agricultural soils in recent decades (ex. Johannes et al., 2017), and remains one of the main areas where regional quantitative tools need to be developed. In this sense, it is important to bear in mind that soil organic C dynamics and their sensitivity to human management (or environmental conditions) imply that agricultural practices, such as the addition of exogenous organic compounds or crop residue and soil management (or extreme climatic events, such as droughts) may therefore alter soil quality (Bai et al., 2018; Bhattacharya et al., 2016; Dash et al., 2019; Yadav and Arora, 2018).

WORK FRAMEWORK AND STRUCTURE

This thesis addresses the demand to understand, and accurately evaluate, the functioning of soil as the support of different agricultural uses of land, and aims to embrace a territorial approach. In the context of agriculture in the region of Navarre, and in many other arid and semi-arid areas, this assessment is necessary, especially considering changes in land use such as the transformation from rainfed to irrigated land, but also in relation to different agricultural strategies included in climate change adaptation or mitigation plans, such as the implementation of crop rotations, the use of organic amendments or the application of techniques linked to conservation agriculture.

The introduction of irrigation in arid or semi-arid regions, such as the study area in this work, implies an important change in soil management (and in its water regime). In addition to having an impact on the economic and social context of the region, this change may also imply a change in soil functioning, resulting in alterations in its dynamic properties, with possible consequences on the biogeochemical and nutrient cycles of the agrosystem, and on the performance of other external ecosystem services such as atmospheric C sequestration.

Irrigation is a particularly relevant issue in the region of Navarre, where the Navarra Canal project represents an example of irrigation expansion in semi-arid Mediterranean lands. The canal, approximately

198 km long, carries water from the Northern part of the region (Itoiz reservoir), with a more temperate climate, to the Southern part of Navarre, which is characterized by a drier climate (Figure 4), and where irrigation is mostly concentrated. The region has a total agricultural area of 341,835 ha, of which more than 108,221 ha correspond to irrigated agricultural use (Gobierno de Navarra, 2020a). More than 22,300 ha of this surface have been transformed in the first phase of the Navarra canal project (2005-2020), and the second phase of the project, to be developed in the coming years, will enable the transformation to irrigation of more than 30,000 ha more in the region.

This explains why this land use change plays a special role in this thesis, being transversally present in 2 chapters (V and VI) of the 5 chapters of the thesis, and being particularly relevant in the other 3 chapters (II, III and IV).

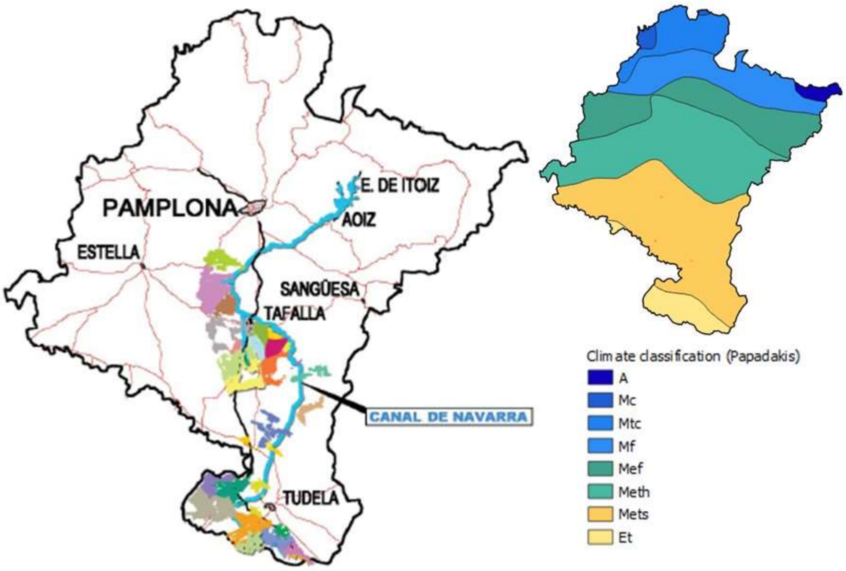

Figure 4. Canal of Navarra itinerary through the region (left) and Papadakis climate classification of Navarre (right). Source: Comunidad General de Regantes del Canal de Navarra (2007) and Gobierno de Navarra (2020b)

In the same way, the region has been focusing for years, and has done an important effort, in terms of adaptation and mitigation to climate change of the agricultural sector. Evidence of this are the actions proposed for the primary sector in the Roadmap for Climate Change in Navarra 2017-2050 (Gobierno de Navarra, 2017) or the LIFE NADAPTA and LIFE REGADIOX projects, which are being developed (or have been developed) in Navarre in recent years, among others. This type of European projects, focused on practical experimentation and demonstrative actions, and usually linked to the agents of the sector, represent an opportunity for the development of research activity in an extensive framework. These two projects are of special relevance since three of the five chapters of this thesis are framed within them. Both projects have allowed for the evaluation, from different points of view, of different agricultural management strategies oriented to mitigation **(Chapter IV)** and adaptation **(Chapters V and VI)** to climate change of agriculture in the region.

With this, the main structure of the present document is divided into two parts. The first one focuses on the study of the soil organic carbon dynamics, exploring in detail the mechanisms and controls that regulate this process in a calcareous cultivated Mediterranean soil, and their interaction with the transition from rainfed to irrigated cultivation of extensive crops. The work carried out in this first part is collected in **Chapters II and III**. The second part of this work is focused on climate change mitigation and adaptation strategies in the agricultural systems of Navarra, and their relationship to soil functioning, which are collected in **Chapters IV, V and VI**.

Chapters II and III of this thesis are developed within the framework of a research project that evaluates the influence of Conservation Agriculture on irrigated crops, funded by the Spanish National Institute for Agricultural and Agri-Food Research (INIA) within the National R+D+i Program "National Subprogram of Agricultural Resources and Technologies in Coordination with the Autonomous Regions" (ref. project RTA2013-00057-C05-03). This project has allowed for the evaluation of the transformation to irrigation effect on the stabilization of organic carbon into the soil, and was the continuation of the first project funded to assess changes in soil following the adoption of irrigation (project RTA2009-00052-C02-02). In the latter, a field with an *ad hoc* experimental design, was implemented in Enériz, Navarre, in

2009, and has been monitored since 2010. This trial is designed to carry out a natural isotopic labeling study from a change from C3 to C4 plants. The monitoring includes crop parameters, such as harvest index or crop yields, and soil parameters, such as bulk density, total soil carbon and particulate soil carbon content, as well as the isotopic signature of ^{13}C in soil organic carbon fractions.

This experiment is designed to evaluate over time the soil response both to a change in crop type and to a change in the irrigation regime. The crops are winter wheat (*Triticum aestivum* L., plant C3) and maize (*Zea mays* L., plant C4), which correspond to the two most widespread extensive crops in the region. Considering, therefore, cultivation and irrigation as factors in the trial, the four combinations considered are: rainfed wheat, irrigated wheat, rainfed maize and irrigated maize. This has made it possible to generate a complete data base with data from a 7-year period of monitoring.

In a first phase, which constitutes **Chapter II** of this thesis, a detailed description of the data obtained in this chronosequence was made. The quantification of the different monitored parameters object of this study in time, is used to describe and explain the possible differences observed between the systems evaluated included in it.

The second phase of this study, on SOC dynamics, constitutes the **Chapter III** of this thesis, and is focused on the development and parameterization of a mechanistic model based on the exponential kinetics of soil organic matter decomposition. This model is based on the C3/C4 isotopic labeling study and is complemented with the chronosequence data addressed in the first phase of this work.

This chapter explores the application of models of this type, in order to understand the performance of the variables involved, under our study conditions. The peculiarity and innovation of this work is that it has been designed to evaluate the differences in the dynamics of SOC incorporation into the soil when the irrigation factor is introduced.

This work was conducted in collaboration with Dr. Delphine Derrien and Dr. Gregory van der Heijden both from INRAE-Nancy center in France, and with Dr. Henar Umeneta (UPNA, Spain).

Chapter IV of this thesis has been developed within the framework of the LIFE REGADIOX project (LIFE12 ENV/ES/000426, https://life-regadiox.es/es/) "Atmospheric CO_2 fixation and reduction of greenhouse gas (GHG) emissions through sustainable management of irrigated agriculture". This project included an important phase of work on soil characterization and land evaluation, in this case focused on areas converted to irrigated land in Navarra. Part of the actions were focused on the analysis of different cropping systems linked to irrigation in the region, and on the quantification of their GHG emission balances. As an important part of these balances, the quantification of the organic C stocks, and the estimation of the annual atmospheric C sequestration rate linked to each soil and management considered were carried out. The project, which lasted 3 years, between 2013 and 2016, allowed the collection and complementation of a large database.

Data collected in this project were used to evaluate the impact of this important land use change in the region, from a wide point of view of soil quality, including the evaluation of ecosystem services associated with agriculture and land use. Within the framework of this evaluation, aspects related to soil capacity, soil capital, soil connectivity, or soil codification, as determined by McBratney et al. (2014) within the concept of *Soil security*, were addressed. This evaluation refers not only to the amount of physical and biological resources present in the soil, but also to the connection between the different users and stakeholders and the public and private use regulation and conservation. This work constitutes **Chapter IV** of this thesis.

This work was conducted in collaboration with the others partners of the project, the Institute for Agrifood Technologies and Infrastructures of Navarre (INTIA) and FUNDAGRO.

Chapters V and VI are framed within the LIFE NADAPTA project (LIFE16 IPC/ES/000001, https://lifenadapta.navarra.es) “Towards an integrated, coherent and inclusive implementation of climate change adaptation policy in a region: Navarra". This project aims to increase resilience to Climate Change in Navarra through intersectoriality, long-term sustainability, participation and networking, contributing to the implementation of the actions included in the Roadmap for Climate Change in Navarra 2017-2050 (Gobierno de Navarra, 2017).

One of the main actions of this project is focused on the evaluation of the adaptation of Navarra's agrosystems to climate change. It proposes, among other things, to carry out a territorial vulnerability study. This assessment was based on the development of a zoning system, based on intrinsic and dynamic aspects of the territory (such as climate, soil type or land use), on which a network of demonstration plots has been defined under different management systems that allow for a diagnosis of the level of vulnerability of the region.

An important part of the work has focused on the development and analysis of a series of soil indicators to quantify the effectiveness of the different climate change adaptation strategies proposed in the project, linked to the management of external sources of organic matter, the introduction of irrigation, conservation agriculture and the use of crop rotations. **Chapter V** summarizes the main results of the zoning phase and the analysis of SOC stocks as an edaphic indicator of vulnerability, and represents a regional approach within the 4p1000 initiative, while **Chapter VI** is focused on the analysis of soil physical indicators, such as bulk density and soil water retention capacity.

This work was carried out in collaboration with INTIA, project partner in the action related to agriculture within the project, and with the support of the Department of Rural Development, Environment and Local Administration of the Government of Navarra, as project coordinator.

Finally, **Chapter I** includes a first part that introduces and contextualizes the work, and a second part that defines the framework, structure and objectives of this thesis and **Chapter VII** contains a general discussion of all the results obtained, as well as a general conclusion.

OBJECTIVES

The general objective of this thesis is to provide an accurate evaluation of different agricultural uses of the territory, from the point of view of soil functioning, in the region of Navarre. To this end, the following specific objectives were established, which are developed in the different chapters:

1. To identify and quantify irrigation-induced changes in soil organic matter incorporation dynamics using isotopic analysis tools and the parameterization of a mechanistic model in a semi-arid Mediterranean calcareous soil (Chapters II and III).

2. To perform a quantitative evaluation of the environmental externalities associated with irrigated agriculture, based on a multidisciplinary study of soil quality and the ecosystem services provided by irrigated soils in Navarra (Chapter IV).

3. To evaluate the vulnerability of Navarra's agrosystems to climate change, based on the monitoring of different soil indicators of vulnerability: SOC stock, bulk density and soil water retention (Chapters V and VI).

4. To evaluate the effectiveness of different management strategies of agriculture at the regional scale from the point of view of both climate change mitigation and adaptation, as proposed in the regional Climate Change Roadmap of Navarre (Chapters V and VI).

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Chapter II

Changes in organic C storage induced by the adoption of irrigation in a cultivated calcareous Mediterranean soil

“Así, pues, se comprende que solo el complejo mecanismo que en el aspecto físico, químico y biológico dan los coloides a la tierra, y en especial el humus, permiten que un suelo laborable pueda convertirse en medio de aceptable fertilidad.”

Daniel Nagore Nagore
El abono. Resorte vital de la producción agrícola
Diputación Foral y Provincial de Navarra. Dirección de Agricultura y Ganadería. Editorial Aramburu. Pamplona, 1939

CHAPTER II

Changes in organic C storage induced by the adoption of irrigation in a cultivated calcareous Mediterranean soil

ABSTRACT

Irrigation is in the spotlight of land-use planning in semi-arid regions. In this study, we measured the changes in soil organic C (SOC) storage in the tilled soil layer (0-30 cm) of an experimental field on a calcareous soil with two different crops (maize, a C4 plant, and wheat, a C3 plant), cultivated with and without irrigation for seven years. We hypothesized that changes in SOC storage occur when introducing irrigation and/or different crops in an agrosystem due, in part, to changes in the amount of organic C incorporated into the soil. Our results validated this hypothesis. Over the 7-year study period, irrigation increased total (TOC) and sand-size (50-2000 μm) particular organic C ($POC_{50\text{-}2000}$) stocks in the tilled layer (0-30 cm): +7.7% TOC and +13.7% $POC_{50\text{-}2000}$ for maize, and +7.5% and 13.9% for wheat, confirming the traditional vision of this labile fraction as an early indicator of long-term changes in SOC cycling. An increase in potential C inputs from crop residues with irrigation, due to increased biomass production, may explain these changes, as less partially.

This study supports the idea that irrigation can be responsible for changes in the SOC cycle when implemented in calcareous semi-arid soils, and opens the path to a deeper exploration of the mechanisms involved in this process.

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INTRODUCTION

Irrigation is a traditional strategy to expand and sustain agriculture in arid and semi-arid regions (Zaveri and B. Lobell, 2019). It allows to increase yields and provides farmers with wider crop farming options and more flexible planting dates (Salmon et al., 2015). It can also be seen as a tool for adapting to climate variability (Patanita et al., 2019; Tanasijevic et al., 2014), although its sustainability in some regions has been questioned (Ricart and Clarimont, 2016; Velasco-Muñoz et al., 2019). Assessing the impact of the adoption of irrigation on soil quality and functioning, and in particular on organic matter storage, seems necessary to better understand its benefits and drawbacks in terms of agricultural sustainability and climate policies. In terms of soil organic C (SOC) storage, irrigation may have positive effects in arid and semi-arid areas (Lal, 2020; Pareja-Sánchez et al., 2020). It is, for instance, one of the measures considered within those proposed in the "4 per 1000" initiative framework (Minasny et al., 2017), which aims to address the global challenge of securing food for a growing population, while ensuring climate change adaptation and mitigation (Chenu et al., 2019; Rumpel et al., 2020).

This effect has not however been clearly demonstrated. For example, only eight out of fourteen long-term field experiments reviewed by Trost et al. (2013) showed higher SOC contents in irrigated plots compared with rainfed plots. These eight experiments were all located in arid or desert regions, in contrast with the other six experiments from wetter regions, which displayed no significant differences. As SOC content depends mostly on C input from plants and decomposition processes, these results were explained by a greater irrigation-induced increase in primary productivity in arid and semi-arid areas compared with wetter regions, while SOC decomposition rates were assumed to be similar at all sites (Chenu et al., 2019). Nevertheless an increase in decomposition rates may be associated with changes in the water regime of the soil, which can favour the soil microbial activity (Moyano et al., 2013). Accordingly, Aguilera et al. (2018) showed that in the Mediterranean region, both soil C inputs and SOC decomposition rates increased with irrigation, obtaining inconsistent results in terms of the net effects on SOC storage. Similar results were observed by Zhou et al. (2016) in a global meta-analysis.

In summary, the variations induced by irrigation in the soil C cycle can be expected to be different depending on the effects of the new water and soil management practices on soil C inputs, and C stabilization mechanisms (Qiu et al., 2018; Trost et al., 2013; Zhou et al., 2016). Despite this evidence, there is still little information available at the regional scale to conduct a detailed analysis of the effect of irrigation adoption on SOC dynamics (Chenu et al., 2019), notably because of the lack of paired irrigated and non-irrigated trials (Bai et al., 2018).

The assessment of SOC changes associated with a land-use change such as a change in crop and/or irrigation regime in a given area requires some considerations. An important one is whether the change of use is likely to imply a transition period in which SOC stocks are not at steady state. For example, in a regional study conducted in Navarre (NE Spain), a positive effect of irrigation was observed in terms of SOC storage, with variable annual rates depending on crops and location (Antón et al., 2019, see Chapter IV). Understanding the mechanisms of SOC dynamics during this transition period remains a major research question (Chenu et al., 2019).

In this study, we aimed to investigate the changes in SOC dynamics in a semi-arid calcareous Mediterranean soil after seven years of irrigation. We hypothesized that irrigation and the crop conversion from less productive crops, such as wheat (a C3 plant) to more productive crops such as maize (a C4 plant) would lead to changes in SOC storage in the case studied. These would be related, in part, to potential gains due to an increase in C inputs to the soil due to enhanced biomass production and accumulation of crop residues.

To test our hypotheses, we took advantage of the introduction of irrigation in an area where rainfed agriculture existed before, and both crops can complete their growing season with and without irrigation, to set a C3-to-C4 plant-shift experiment in Enériz (Navarre, Spain).

MATERIALS AND METHODS

Site description, soil and crops sampling. The study field is located in Navarre, NE Spain (42°40’18.74”N; 1° 45’ 4.65”W) within a sub-humid temperate Mediterranean climate area. The mean annual temperature is 13.4°C, and mean annual rainfall and potential evapotranspiration (PET) are 565 mm and 722 mm, respectively. The average monthly distributions of PET and rainfall are shown in Figure 1. In this field, rainfed maize is in its geographical limit for profitable standard production, but can still be grown.

The soil is a *Calcic Haploxerept* (Soil Survey Staff, 2014), developed on carbonate-rich siltstones and sandstones. It is a fine-loamy deep soil, with 38 % carbonates (pH = 8.2), and average clay content of 29 % in the upper horizon (0-30 cm).

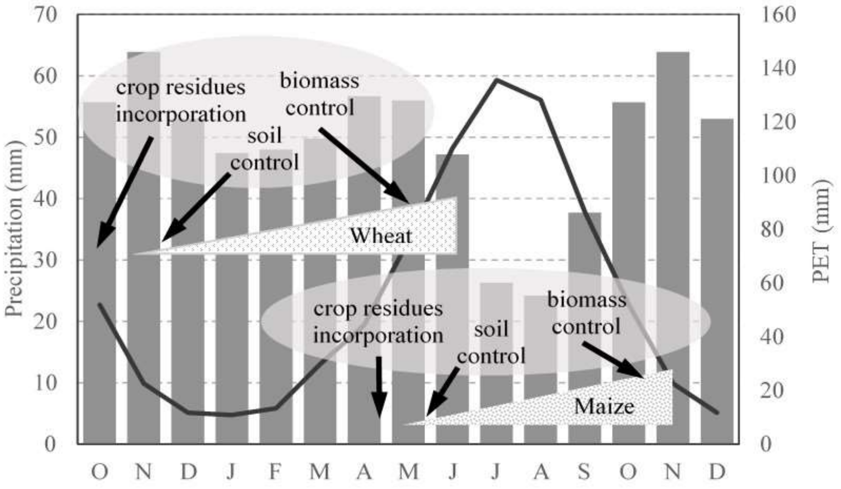

Figure 1. Wheat and maize growing seasons and sampling schedule and monthly average rainfall (bars) and potential evapotranspiration (PET, solid line) data at the study field. Source data series: 1925-2018 (DRMAAL GN, 2019)

This field had been managed for at least five decades as a traditional rainfed dryland field under conventionally tilled C3 crops before the area was converted to irrigated farmland. At this moment, taking advantage of the opportunity of the introduction of irrigation in this area, a C3-to-C4 plant shift experiment was set up with the aim of long-term monitoring the effect of climate manipulation with irrigation under different crop systems. Winter wheat (*Triticum aestivum* L.) and maize (*Zea mays* L.), a C3 and C4 plant respectively, corresponding to the two most widespread extensive crops in the region, were selected for the experiment, and grown for 7 years with and without irrigation. Maize is the most frequently grown crop by extensive farmers when irrigation becomes available, as it is far more productive than wheat or other extensive C3 crops.

Given the impossibility of varying the level of irrigation and of controlling belowground water transfers on a small scale, and the differences in the irrigation regime of both crops, the field was split into two large areas of 2600 m^2, one with irrigation and the other without. Each area was divided into two large subareas, separated by a buffer due to the different irrigation and management schedules of wheat and maize. In these subareas, winter wheat and maize were grown for the 7 years of the experiment. The four subareas considered in this study corresponded, therefore, to the four crop-irrigation combinations: rainfed wheat (W-rf), irrigated wheat (W-irr), rainfed maize (M-rf) and irrigated maize (M-irr). This design was conceived to minimize the boundary effect due to belowground water transfers, and ensured an adequate distribution of irrigation in time and space for both crops.

In order to organize a systematic sampling to ensure complete coverage of the field for good representativeness, and to avoid contour effects of small sampling plots, in each subarea with W-rf, W-irr, M-rf and M-irr, a grid of 6 plots (6 x 10 m) separated by 4 m wide corridors was stablished. The homogeneity of soil properties known to affect crop yields and SOC stabilization among the four subareas (namely texture (Schiedung et al., 2017), carbonates content and available water-holding capacity, AWHC)) was verified in this grid of plots at the onset of the experiment (Table 1). To that end, soil in each plot in the grid was sampled following the protocol described below.

Table 1. Soil particle-size distribution (g 100 g^{-1}), available water-holding capacity (AWHC), carbonates, TOC stock and POC stock in the six plots for the four crop-irrigation combinations (experimental subareas) at year 0 (Mean ± 95% Confidence interval).

	Depth	Sand	Silt	Clay	AWHC	Carbonates	TOC (0-30 cm)	POC$_{50-2000}$ (0-30 cm)
Sub-area	(cm)	(50-2000 mm)	(2-50 mm)	(<2 mm)	(L m^{-2})	(g 100g^{-1})	(Mg ha^{-1})	(Mg ha^{-1})
W-rf	0-5	27.4 ± 3.4	41.9 ± 3.5	30.7 ± 3.0	8.82 ± 1.3	38.8 ± 1.51	39.59 ± 1.35	5.82 ± 0.25
	5-15	28.9 ± 1.6	42.1 ± 2.6	29.1 ± 1.9	17.6 ± 4.0	38.8 ± 0.59		
	15-30	28.1 ± 2.0	42.2 ± 2.7	29.6 ± 2.3	29.9 ± 2.2	38.8 ± 1.01		
W-irr	0-5	25.2 ± 2.5	44.9 ± 2.1	29.9 ± 1.7	9.09 ± 1.3	38.7 ± 0.76	42.32 ± 0.84	6.58 ± 0.21
	5-15	26.1 ± 2.5	44.1 ± 2.3	29.8 ± 1.2	16.4 ± 4.5	38.2 ± 2.20		
	15-30	25.4 ± 2.9	44.7 ± 1.6	29.9 ± 2.0	26.6 ± 3.7	38.8 ± 2.01		
M-rf	0-5	30.0 ± 4.9	41.1 ± 3.8	28.9 ± 2.1	7.71 ± 3.6	37.9 ± 1.42	41.42 ± 0.60	5.53 ± 0.28
	5-15	27.7 ± 2.3	42.3 ± 0.9	30.0 ± 1.6	15.0 ± 6.0	38.0 ± 1.20		
	15-30	28.9 ± 4.1	40.3 ± 3.7	30.9 ± 1.8	26.5 ± 6.4	38.1 ± 2.10		
M-irr	0-5	28.4 ± 5.2	41.7 ± 5.8	30.0 ± 1.8	7.29 ± 3.1	39.0 ± 0.86	40.76 ± 0.60	6.10 ± 0.16
	5-15	25.5 ± 3.9	44.2 ± 3.2	30.3 ± 1.3	16.7 ± 5.2	38.3 ± 0.91		
	15-30	28.2 ± 4.8	42.1 ± 4.5	29.6 ± 2.4	25.7 ± 6.2	38.3 ± 1.15		

Sprinkler irrigation was used in this field for W-irr and M-irr. Because of the local distribution of rainfall (Figure 1), and the cycle and water demands of both crops, the irrigation schedule and amounts was different for W-irr and M-irr. Irrigation in W-irr was used in March, April, May and June, and it was continuous from June to September in M-irr. The average water supply by rainfall within the growing season for the seven years of the experiment in wheat was of 182 ± 70 L m^{-2}, and the average total water supply, complemented by irrigation, in W-irr was of 281 ± 66 L m^{-2}. For maize, the average water supply by rainfall within the growing season for the years of the experiment was of 143 ± 73 L m^{-2} and it was complemented with irrigation in M-irr to get a total average amount of 709 ± 99 L m^{-2} (Aguacanal, 2018).

Crops and soils management were conducted following the local conventional practices (Table 2). Crop residues incorporation was done in early fall for wheat, and early spring for maize (Figure 1), through inversion tillage (0-30 cm). In the case of W-irr and W-rf, the average dose of fertilizers used in the area for wheat were applied. The normal fertilization doses corresponding to irrigated maize were applied in both M-irr and M-rf.

The soil in each of the 6 plots in the grid per crop-irrigation combination subarea was sampled every year except for year 5, after the incorporation of the crop residues biomass into the soil through tillage (in early fall for wheat and early spring for maize, Figure 1). Each year, the sampling date was precisely determined by computing thermal integrals for each crop, so that the number of degree-days accumulated between residues incorporation and sampling was equivalent for both crops (data not shown). Undisturbed (100 cm^3 soil cores for bulk density) and disturbed composite samples were collected at 0-30 cm. For disturbed samples, five sub-samples were collected at random per plot, avoiding the perimeter first meter, and gently pooled to obtain one composite sample, and air-dried. According to Zang et al. (2018), the resulting distance of over 5 m between sampling zones in each plot, ensured that each plot corresponded to an independent statistical experimental unit.

Table 2. Soil and crops management

	Wheat (W-irr and W-rf)	Maize (M-irr and M-rf)
Growing season	November - June	May - November
Soil preparation	Seedbed in early Fall	Seedbed in April
Sowing	450 seeds m^{-2}	8 seeds m^{-2}
Fertilization		
Nitrogen	60 + 120 kg N ha^{-1} (March and April)	40 + 250 kg N ha^{-1} (May and June)
Phosphorous	45 kg P_2O_5 ha^{-1} (November)	101 kg P_2O_5 ha^{-1} (May before sowing)
Potassium	not added	132 kg K_2O ha^{-1} (May before sowing)
Weed control	Conventional herbicides	Conventional herbicides

Crop yields were controlled during the seven growing seasons of the study by harvesting each individual plot with a Haldrup C-85 mechanical harvester (Haldrup, Denmark). Before harvesting, aboveground plant biomass (AGB) was quantified by counting the number of plants in 2 linear meters and collecting and dry-weighing 5 of these plants for maize. For wheat controls, before harvesting, plants were collected and dry-weighed within a sampling frame of 0.1 m^2 in triplicate in each plot. From these plants, the harvest index (HI) was determined as the ratio of grain yield and total AGB. The total amount of aboveground crop residues potentially incorporated into the soil was then determined for each plot using HI and the measured grain yield at harvest. Belowground biomass was estimated using empirical allometric relations given by IPCC (2006), as a percentage of AGB (24 % in wheat, 22 % in maize), and the C concentration in each crop was used to convert AGB and belowground biomass into organic C data, as an expression of crop residue-C potentially incorporated into the soil.

Analytical methods and SOC storage determination. Prior to analyses, air-dried disturbed soil samples were sieved at 2 mm in a device allowing for complete disaggregation of large clods and fragments of organic debris, to ensure the highest possible recovery of aggregates and particles < 2 mm, and thoroughly homogenized.

At year 0, standard methods were used to determine the soil particle-size distribution (Klute, 1986), carbonates (Sherrod et al., 2002) and AWHC (Dirksen, 1999) from disturbed and undisturbed samples, respectively.

Every sampling year, total organic C (TOC) was determined by wet oxidation (Walkley-Black, Tiessen and Moir, (1993)) due to the elevated carbonate content (Apesteguia et al., 2018). The organic C in the particulate size fraction 50-2000 μm ($POC_{50\text{-}2000}$) was isolated by the method described in Virto et al. (2007), where 10 g of air-dry soil (< 2 mm) were dispersed by shaking overnight in 150 mL of a 5% $(NaPO_3)_6$ solution, and sieved to collect the fraction > 50 μm (Cambardella and Elliott, 1992). Organic C concentration in this fraction was measured by wet oxidation after grinding the fraction to a powdery consistency (Tiessen and Moir, 1993).

TOC and $POC_{50\text{-}2000}$ stocks in the tilled layer were calculated for W-rf, W-irr, M-rf and M-irr using concentrations and bulk density data for an equivalent dry soil mass (Ellert and Bettany, 1995) of 4771 kg m^{-2}, corresponding to the soil mass of the lowest recorded average bulk density in the tilled depth (0-30 cm) across plots and years, which was recorded in M-rf at year 7, to avoid corrections based in unknown bulk density and SOC concentrations beyond this depth (Lee et al., 2009; Poeplau & Don, 2013).

Statistical analysis. The experimental design requires a number of considerations to be taken into account regarding the statistical analysis of the experimental data. Reference is made here to TOC measurements, but the same approach was used for POC measurements.

Despite the homogeneity of the total area relative to the TOC initial values and other parameters that could create gradients in TOC storage, namely texture, water-holding capacity and carbonates content (Table 1), the disposition of each combination of type of crop and irrigation in each subarea, results in a dependence between the observations. In addition, the longitudinal observation over time of each plot generates another source of dependence.

In this sense, data should be considered integrated in a hierarchical structure as shown in Figure 2, for the four subzones described above, and designed here as subzones 1 to 4. Figure 2 shows the corresponding plots and measurements for each year shown for subzone 1 (same would be repeated for each subzone 2, 3 and 4). It can be observed that while the 6 different plots are nested within each subzone, the observations over time constitute a cross effect.

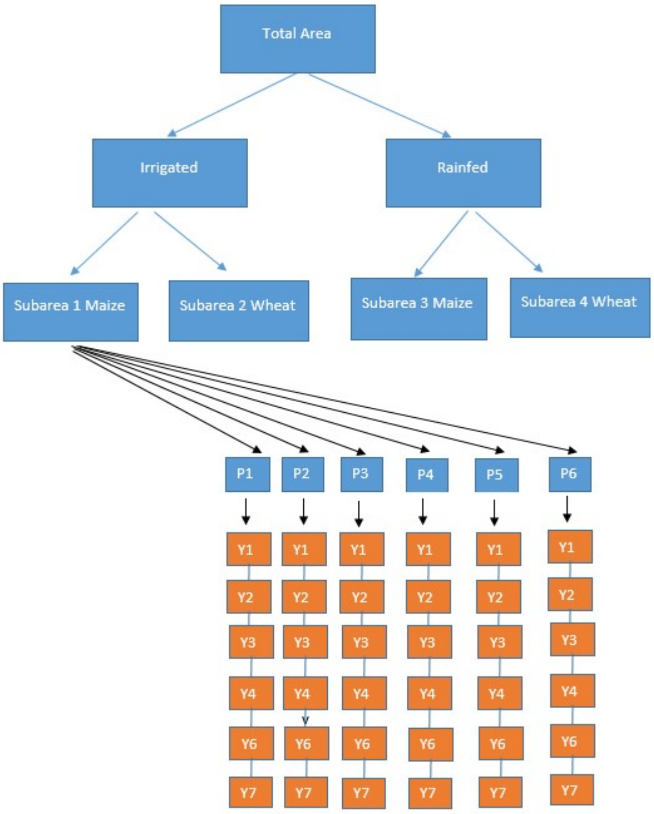

Figure 2: Hierarchical structure data

This structure creates different inertias (dependences): first an inertia for the measurements of the same subarea, second another inertia for the measurements of the same plot, nested in the previous one, and third, another inertia for the measurements of the same year, crossed with the previous ones (Figure 3).

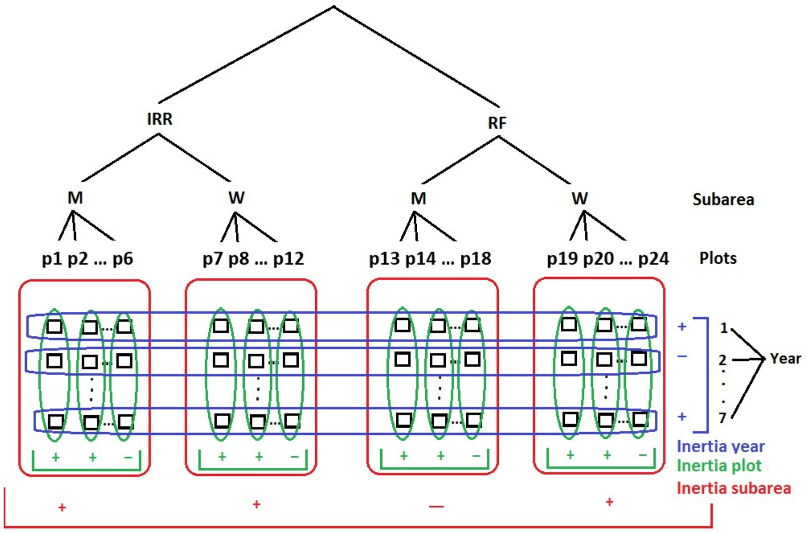

Figure 3. Structure of dependence. Symbols "+" and "-" reflect one possible interpretation of the effects.

To address the analysis of data corresponding to non-independent measurements between units of observation, linear mixed effects models (LMM), also known as hierarchical linear models in the literature (Harrison et al., 2018), were considered. These models contain two parts: a mean structure corresponding to the fixed effects and a random part consisting of a sum of random effects plus residual errors.

The random effects collect the dependence of the observations so that the residual errors maintain, conditionally, the classical assumption of independence and homogeneity of their variances. In addition, they also allow for the combination of random effects with different structures of the variance-covariance matrix of the residual errors, relaxing the assumptions of variance homogeneity (Galecki and Burzykowski, 2013).

An exhaustive work was carried out in order to optimize the trade-offs not only between data and the fit of a model but also the complexity of the structure of the model. In this process, different LMMs were tested with different structures, based initially on the most complete one, with a mean structure based on the three main fixed effects (crop, irrigation and year) with their interactions, and the different ways of observing the existing correlation, and with different variance-covariance residual random error structures (autoregressive correlation structure with different lag or with (potentially) different correlation coefficients), adding the possibility of a subarea-specific, plot-specific, and year-specific intercepts. The latter allows the model to explain the existing correlation in the measurements explained above.

The selection criteria for the final model valued simplicity and clarity, also considering the possible future evolution of TOC and POC, so that the model would be valid for future studies on the same experimental field. That means that among the models that were statistically more significant, those with the simplest structure and that provided a clearer interpretation were prioritized. At the same time, considering the relatively short time period of the series of data, a flexible approach was followed with respect to the (minimum) significance level for discarding or including a possible effect, considering that a trend observed in year 7 may become significant in year 20, for instance.

Therefore, the mean structure of the selected model, which takes into account only the significant effects, considered the main effects crop, irrigation and year, and the interaction of the crop and year (year-specific crop effect). In the same way, random effects associated with measurements in the same subzone and between measurements in the same year were discarded, and a model that only takes into account a specific plot random intercept as random effect, was finally considered. It can be expressed as:

$$TOC_{it} = \beta_0 + \beta_1.\mathrm{Year}_t + \beta_3.\mathrm{Irrigation}_i + \beta_{2t}.\mathrm{Crop}_i + \delta_{0i} + \varepsilon_{it}$$

(Equation 1)

Where TOC_{it} is the value of TOC measured for plot *i* (*i* = 1, . . . ,24) at year *t* (*t* = 1,2,3,4,6 and 7) with β_0 denoting the intercept, β_1 the year continuous effect, B_{2t} the year-specific crop effect and β_3 the constant irrigation effect. Finally, the random part of the model included the random plot intercept effect δ_{0i}, and a residual random error ε_{it}. The random plot intercepts δ_{0i} were distributed with mean 0 and constant variance. The same approach and model were also applied for $POC_{50\text{-}2000}$ stocks data analysis. These changes in TOC and $POC_{50\text{-}2000}$ over time were analyzed, using the *nlme* package of R (Pinheiro et al., 2020).

The conditional distribution of the residuals, $\varepsilon_{it}|\delta_{0i}$, were distributed with mean 0 ($E(\varepsilon_{it}|\delta_{0i})$), and year-specific variance ($Var(\varepsilon_{it}|\delta_{0i}) = \sigma_t^2$), and independent of the random plot intercept. The estimated standard deviation of the random base effect of zero mean for each plot (δ_{0i}), as well as the conditional standard deviation of the random residue (ε_{it}) for each year *t*, are shown in Table 3.

Table 3. Estimated standard deviation of the random base effect of zero mean for each plot (d_{0i}) and the conditional standard deviation of the random residue (ε_{it}) for each year *t* from the mixed-effects model (LMM)

Standard deviation of	d_{0i}	ε_{i1}	ε_{i2}	ε_{i3}	ε_{i4}	ε_{i6}	ε_{i7}
TOC *	0.78	2.99	1.12	2.25	2.25	1.95	3.13
$POC_{50\text{-}2000}$ *	0.08	1.26	0.77	0.97	1.11	0.81	0.95

*estimated

The residual errors of the model conditionally maintained the classical assumption of independence, an assumption that was checked with a subsequent analysis, by studying the distribution of Pearson residuals against the fitted values of the model for each subarea (Supplementary Figure S1). No correlation among them related to the subareas was observed, which supports the assumption of independence between subareas. Finally, the normality of errors was tested by studying their deviation from a linear trend in a Q-Q plot. Only small deviations were observed, supporting the hypothesis of normality.

Finally, a LM was used to analyze annual organic C in crop residues, derived from yield and HI data, to study the effect of crop, irrigation as well as their interaction during the 7 years of the experiment, as described above, conducted with R (R Core Team, 2019).

RESULTS

Potential C inputs to the soil. As hypothesized, annual and accumulated C in crop residues after 7 years (Tables 4 and 5) were significantly higher in the irrigated than in the rainfed subareas, both in wheat and maize subareas.. No effect of crop type was observed but the interaction of crop and irrigation was significant for both parameters. Carbon in annual crop residues was also significantly affected by year, which reflects the variability of the data between years. These data corresponded to differences in yield (on average, maize yielded more than wheat, and irrigated crops more than rainfed systems) and HI (higher values were observed for maize compared with wheat, and for irrigated compared with rainfed systems (Table 4 and 5). Also, a significant interaction was observed for crop and irrigation for these last parameters (Table 5).

Table 4. Annual and accumulated C (7 years) in crop residues, yields and HI. Mean ± standard deviation. Standard deviation refers to that corresponding to the different years (n =7), and plots per year (n=6), except for accumulated crop residues C, where it only refers to year 7 (n=6).

	M-irr	M-rf	W-irr	W-rf
Annual C in crop residues (Mg ha^{-1})	3.17 ± 1.60	2.52 ± 1.14	3.09 ± 0.85	2.81 ± 0.65
Accumulated C in crop residues (Mg ha^{-1})	23.60 ± 0.93	14.25 ± 4.60	21.60 ± 2.22	19.67 ± 0.58
Yield (Mg grain ha^{-1})	8.64 ± 3.82	5.23 ± 2.16	4.25 ± 1.49	3.46 ± 1.14
HI	0.59 ± 0.05	0.52 ± 0.04	0.41 ± 0.04	0.38 ± 0.07

Table 5. Significance results of the effects in the linear model (LM) for annual potential C inputs and accumulated potential C inputs from crop residues after 7 years, annual yield and harvest index (HI). F-value of the analysis of variance and p-value considering a significant difference p-value < 0.05.

	Annual C in crop residues		Accumulated C in crop residues		Yield		HI	
	F-value	P-value	F-value	P-value	F-value	P-value	F-value	P-value
Intercept	3617.72	<.0001	2689.94	<0.0001	13676.03	<.0001	8072.09	<.0001
Year	8.42	<.0001	-	-	5.53	<.0001	8.21	<.0001
Crop	0.09	0.7634	0.58	0.4576	2246.46	<.0001	230.90	<.0001
Irrigation	25.17	<.0001	26.96	0.0001	192.32	<.0001	17.99	<.0001
Crop:Irrigation	12.21	0.0017	19.93	0.0008	166.12	<.0001	5.07	0.026

Changes in TOC and POC$_{50\text{-}2000}$. Figure 4 and 5 show the change in TOC and POC$_{50\text{-}2000}$ for each plot, as well as the average evolution in the subareas (W-rf, W-irr, M-rf and M-irr). The TOC and POC$_{50\text{-}2000}$ stocks at year 0 showed no significant differences between these four subareas (Table 1). According to the LMM model used (Equation 1), the average effects of the studied factors (crops and irrigation) on TOC and POC$_{50\text{-}2000}$, are shown in Table 6.

Table 6. Estimations from the linear mixed-effects model (LMM) for the changes in time of TOC and POC$_{50\text{-}2000}$.

	TOC		POC$_{50\text{-}2000}$	
	Estimated (Mg ha^{-1})	P-value	Estimated (Mg ha^{-1})	P-value
Intercept	41.1	< 2.2e^{-16}	5.29	< 2.2e^{-16}
Year effect	1.02	4.45e^{-10}	0.49	8.43e^{-13}
Irrigation effect [if rainfed]	-3.44	1.53e^{-04}	-1.05	1.69e^{-03}
Crop effect [if wheat]	4.54	3.10e^{-03}	3.10	9.53e^{-06}
Year:Crop interaction [if wheat]	-0.51	4.64e^{-03}	-0.46	1.22e^{-05}

The use of the LMM model in Equation 1 allowed for the identification of a significant trend of TOC (and POC$_{50\text{-}2000}$) to increase over the years in the four subareas, confirming the increasing trends observed in Figures 4 and 5. The correlation observed in TOC and POC$_{50\text{-}2000}$ measurements in adjacent years for all W-rf, W-irr, M-rf and M-irr, supported the use of a LMM model. This observation implies that none of them could be considered to be at steady-state in terms of C storage after 7 years of experimentation. However, a different effect on the trend in the subareas with wheat and maize, was detected (mean of crop-year interaction, Table 6), so that the increasing trend was more pronounced in the subareas with maize than in those with wheat. Also, a crop average effect was observed. In addition, an irrigation average effect was also confirmed, equal for all years, so that lower values were obtained if the plot was not irrigated.

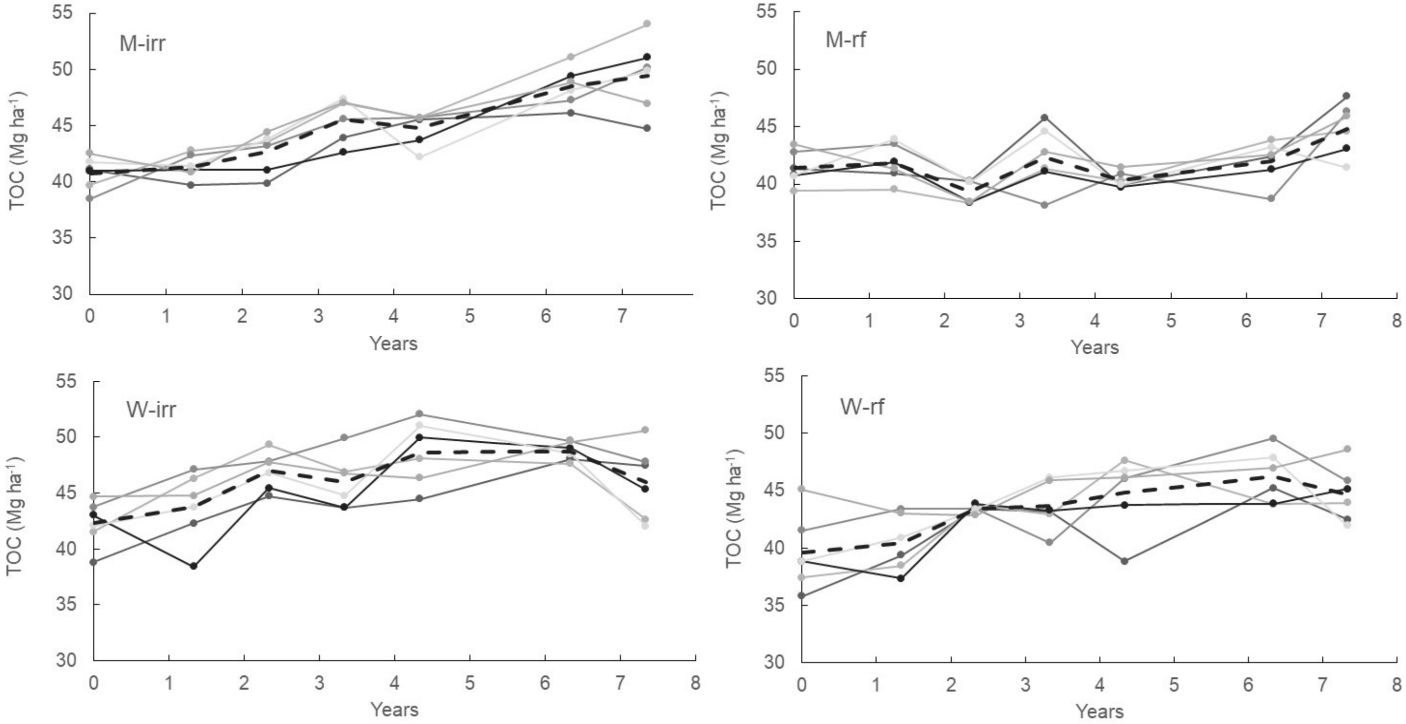

Figure 4. Total organic C (TOC) stocks (Mg ha^{-1}) in the six plots per crop-irrigation combination, and average values over time (dashed line). M-irr: maize, irrigated; M-rf: maize, rain-fed; W-irr: wheat, irrigated; W-rf: wheat, rainfed.

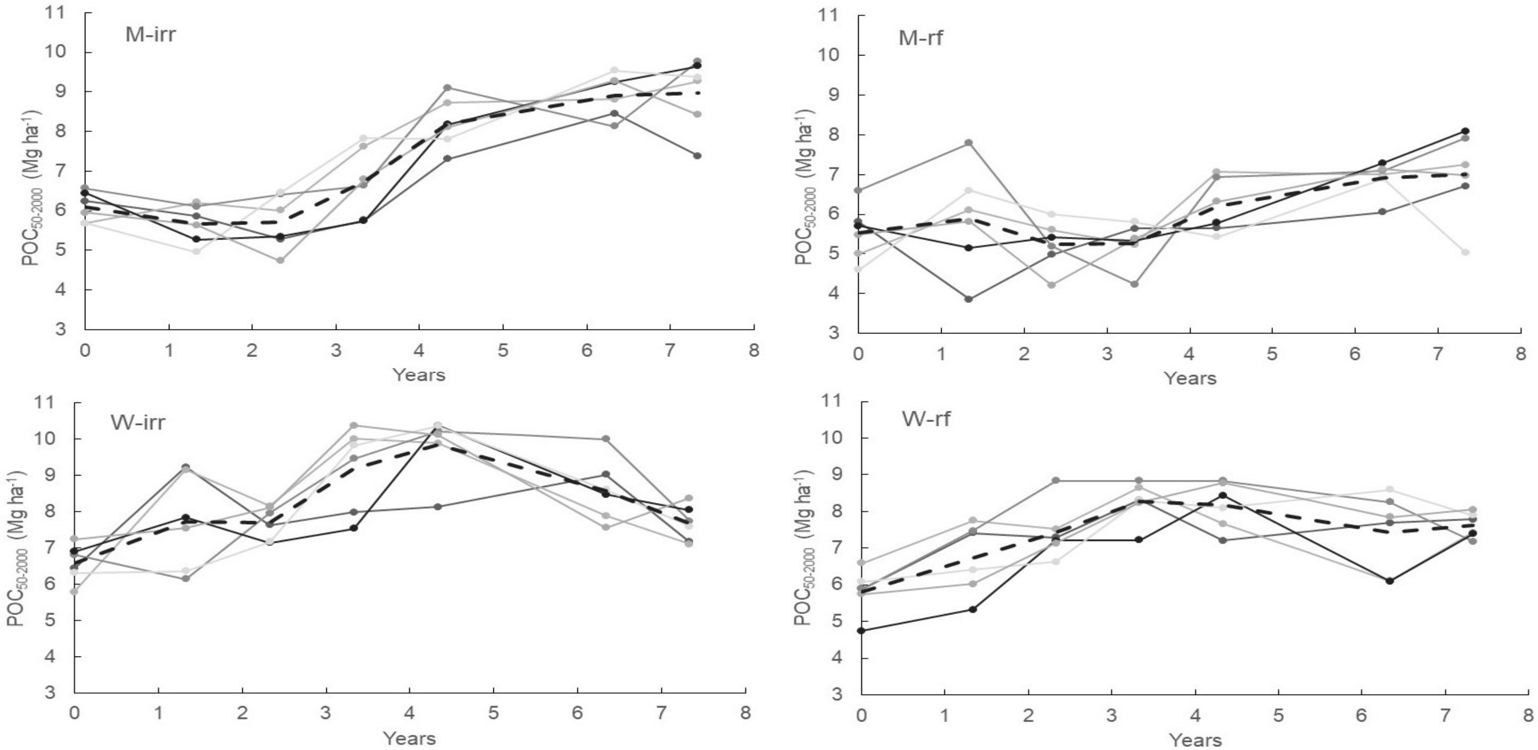

Figure 5. Particulate organic C (POC$_{50\text{-}2000}$) stocks (Mg ha$_{-1}$) in the six plots per crop-irrigation combination, and average values over time (dashed line). M-irr: maize, irrigated; M-rf: maize, rainfed; W-irr: wheat, irrigated; W-rf: wheat, rainfed.

Specifically, in the case of TOC (Table 6), in the maize subareas (M-rf, M-irr), an average effect of 41.1 Mg TOC ha^{-1} was identified, with an annual growth of 1.02 Mg TOC ha^{-1} year^{-1}. In wheat subareas (W-rf, W-irr), the average effect was of 45.64 Mg TOC ha^{-1}, with a modulated annual growth of 0.51 Mg TOC ha^{-1} year^{-1}. In both cases, the effect of irrigation in any year was valued at -3.44 Mg TOC ha^{-1} year^{-1} for non-irrigated subareas (M-rf and W-rf) vsersus irrigated (M-irr and W-irr). Following this trend observed in the LMM model, the overall significant positive effect of irrigation on TOC stocks in year 7 would be of +7.7% between M-irr and M-rf, and of +7.5% between W-irr and W-rf.

In the case of POC$_{50\text{-}2000}$, in the maize subareas (M-rf, M-irr), an average effect of 5.29 Mg POC$_{50\text{-}2000}$ ha^{-1} was identified, with an annual growth of 0.49 Mg POC$_{50\text{-}2000}$ ha^{-1} year^{-1} (Table 6). In wheat subareas (W-rf, W-irr), the average effect was of 8.39 Mg POC$_{50\text{-}2000}$ ha^{-1}, with an almost nil modulated annual growth of 0.03 Mg POC$_{50\text{-}2000}$ ha^{-1} year^{-1}. In both cases, the effect of irrigation in any year was valued at -1.05 Mg POC$_{50\text{-}2000}$ ha^{-1} year^{-1} for non-irrigated subareas (M-rf and W-rf) versus irrigated (M-irr and W-irr). According to the trend observed in the LMM model, this would be reflected in a difference between M-irr and M-rf of +13.7 %, and of +13.9% between W-irr and W-rf in year 7.

Overall, according to this model, the greatest observed difference of POC$_{50\text{-}2000}$ with TOC data was that the changes in POC$_{50\text{-}2000}$ were faster than those of TOC in all W-rf, W-irr, M-rf and M-irr, with an average annual increase estimated for POC$_{50\text{-}2000}$ of 7.7 ± 1.6% compared with 2.1 ± 0.7% for TOC (Table 6).

DISCUSSION

Potential C inputs to the soil. The results observed in terms of yield corresponded to the expectable differences considering the type of crops and cultivation systems, and were within the normal values observed in the region (Gobierno de Navarra, 2019). In terms of HI, the observed differences between wheat and maize were in agreement with those reported in the literature (Brancourt-Hulmel et al., 2003; Costa et al., 2002; Dai et al., 2016). The higher values of HI in maize

(M-rf and M-irr) than in wheat (W-rf and W-rf) implied that the amount of C in crop residues per unit yield was smaller on average in maize than in wheat. Our data also indicated an overall positive effect of irrigation on HI. Similar results were reported by Apesteguía et al. (2015) for the two first years of the study, and can be explained by the fact that modern varieties prioritize a bigger partitioning of assimilates to the grain (Araus et al., 2008), so a higher increase in grain yield compared to aboveground biomass occurs when the cropping conditions are improved (Giaveno et al., 2002). As a result of the interaction between changes in yield and HI, differences in annual and accumulated crop residues between treatments did not directly correspond to the observed yield differences. These results highlight the importance of adequately determining the HI when potential C inputs to the soil from crops are to be determined from crop yields (Unkovich et al., 2010).

In terms of potential C inputs from crop residues assessment, in agreement with our working hypothesis, both annual C inputs and accumulated C inputs were higher in the irrigated subarea after 7 years. Higher plant biomass production observed in this subarea can explain this observation. Even so, from the results obtained, it can be pointed out that the amounts of potential C inputs from crop residues were not dependent only on yield, but also on the type of crop and irrigation management used.

In particular, in our case study, introducing a crop that multiplied the yield by two (ex. M-irr vs. W-irr, Table 4), did not automatically imply multiplying the organic C inputs to the soil (i.e. biomass in crop residues) by the same factor. In the same way, increasing the yield of a crop with irrigation (M-irr vs. M-rf or W-irr vs. W-rf), did not necessarily imply increasing crop residues by the same proportion (Table 4).

Observed changes in TOC and $POC_{50\text{-}2000}$. The first observation in the assessment of TOC and $POC_{50\text{-}2000}$ storage was that none of the four subareas (W-rf, W-irr, M-rf and M-irr) was at steady state: all showed increments of both TOC and $POC_{50\text{-}2000}$ stocks in the 7 years of the study. In our hypothesis, this behavior was however only expected for the subareas including a change (irrigation and/or the introduction of maize, as in W-irr, M-rf and M-irr) from the original situation (rainfed C3 plants cropping, as in W-rf). An explanation for this general increment in SOC and $POC_{50-2000}$ stocks can be the fact that cropping conditions were standardized when the experiment was designed, and carefully applied during the 7 years of the experiment. In contrast, in the previous situation, the most extended rainfed agricultural practices in the area included low fertilization rates and frequent crop residues removal from the field (Apesteguía, personal comm.). In this sense, although it is not possible to determine if yield increases occurred since the setup of the study, wheat yields were in line with those observed in the region (Gobierno de Navarra, 2019), as mentioned above. In terms of the general assessment of organic C stabilization, this would imply that an improvement in fertilization routines and the restitution of crop residues can effectively increase SOC stocks in this region. Other studies have shown that adequate fertilization, especially with N, can result in improved SOC storage (Ladha et al., 2011; Qiu et al., 2018).

Second, the most relevant observation in relation to the objective of this study was that, unlike other studies reporting losses of SOC upon the adoption of irrigation (Da Gama et al., 2019; Mudge et al., 2017; Nunes et al., 2007), the gains in TOC and $POC_{50-2000}$ stocks in the irrigated subareas was higher than in the rainfed subareas over the time period considered in the studied field.

Thirdly, the fixed crop effect observed from the LMM (Table 6), which resulted in higher stocks of both TOC and $POC_{50-2000}$ in the wheat subareas, seemed to indicate that this crop may be more effective for short-term C storage. Indeed, gains in TOC and $POC_{50-2000}$ were observed earlier in the time series considered (Figures 4 and 5) in the wheat subareas (W-rf and W-irr) than in the maize subareas (M-irr and M-rf). Wang et al. (2015), while studying the contribution of wheat and maize residues to SOC on calcareous soils with irrigation in N China, observed a more efficient incorporation of wheat residues, which they related to lower lignin and smaller C:N rations in maize compared with wheat, as suggested by Fuentes et al. (2010). However, in our study the higher annual increase observed for maize (Table 6), compensated the fixed crop effect of wheat. This was a consequence of the crop-year interaction, which was two-fold higher for TOC and 107% higher for $POC_{50-2000}$ in maize vs. wheat (Table 6). This indicates that maize would be more effective than wheat for long-term C storage in the conditions of the studied field. The short period of the data series of this experiment did not enable to verify the reasons explaining the different behaviors of maize and wheat in this case.

Finally, it was observed that the change over time of $POC_{50-2000}$ was greater than that of TOC (Figures 4 and 5; Table 6). This confirmed $POC_{50-2000}$ as a fraction behaving as an early indicator of SOC changes in the conditions of this study (Apesteguía et al., 2017; Imaz et al., 2010). In a global analysis, Cotrufo et al. (2019) have recently described this fraction as useful to inform on organic C storage at different levels of protection, and as predominantly of plant origin and persisting in soil through physical protection in aggregates and/or microbial inhibition.

From these observations, it can be deduced that both the type of crop and the presence or not of irrigation had a role in the net final evolution of TOC and $POC_{50-2000}$ stocks in the four subareas. This implies that, under the conditions of the experimental field studied here, it is reasonable to consider that the introduction of irrigation was a driver for the changes observed in SOC storage in the different subareas, as stated by the main hypothesis of this work.

CONCLUSIONS

The hypothesis of the study was that SOC storage changes may occur when introducing different crops or/and irrigation in an agrosystem, as a result of changes in the amount of organic C incorporated into the soil from increased biomass production and accumulation of crop residues.

In agreement with the working hypothesis, in terms of potential C inputs from crop residues assessment, both annual C inputs and accumulated C inputs was higher in the irrigated subarea after 7 years.

Even so, the expectable amounts of C inputs to the soil from crop residues were not dependent only on yield, but also on the type of crop and irrigation management used.

The adoption of irrigation in the calcareous soil of this study induced changes in SOC and $POC_{50-2000}$ stocks over the 7-year study period, with overall greater increments in the irrigated areas. Crop types and agricultural management were key drivers on this process in the soil and climate conditions of the studied area. The greater change over time observed on $POC_{50-2000}$ confirm the traditional vision of this fraction as an early indicator of long-term changes in SOC cycling.

This study represents a contribution at the regional scale to deepen our understanding of SOC dynamics associated with the introduction of irrigation on calcareous soils. Our observations allow to support the idea that irrigation can be responsible for this type of changes when implemented in calcareous semi-arid soils, and opens the path to a deeper exploration of the mechanisms involved in this process.

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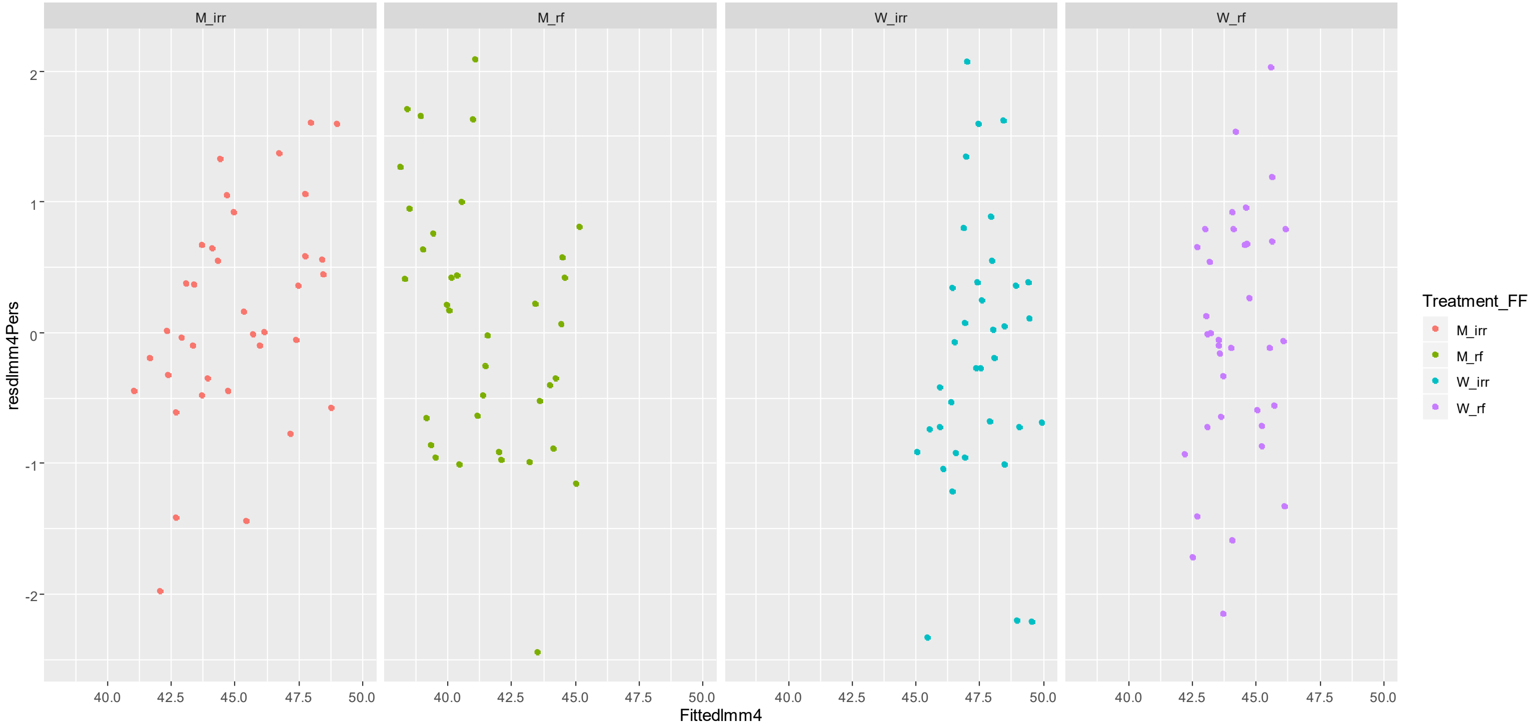
Supplementary Figure S1. Pearson residuals versus fitted values of the model for each subarea



Chapter III

Modelling the effect of the conversion to irrigation on mid-term soil organic C dynamics in a semiarid Mediterranean agrosystem. An approach using C natural isotopes

“Este suelo que mi copa está cubriendo se halla fijo,

porque yo con mis raíces te lo tengo bien sujeto.

Si me arrancas bien pronto se marchará por los ríos mar adentro.”

Daniel Nagore Nagore
Plegarias del árbol. Enseñanza ambulante.
Diputación Foral y Provincial de Navarra. Dirección de Agricultura y Ganadería. Editorial Aramburu. Pamplona, 1939

CHAPTER III

Modelling the effect of the conversion to irrigation on mid-term soil organic C dynamics in a semiarid Mediterranean agrosystem. An approach using C natural isotopes

ABSTRACT

Irrigation is an increasing strategy of agricultural land-use planning in many semi-arid regions. In this study, we modelled the changes in soil organic C (SOC) storage and dynamics in the tilled soil layer (0-30 cm) of an experimental field on a calcareous soil with two different crops (maize, a C4 plant, and wheat, a C3 plant), cultivated with and without irrigation for seven years. We hypothesized that changes in SOC storage occur when introducing irrigation and/or different crops in an agrosystem due to changes in the amount of organic C incorporated into the soil, a change in SOC turnover rates, and an alteration of the stabilization processes of SOC. Our results validated theses hypotheses only partially.

A parallel two-pool SOC model based on TOC and $POC_{50\text{-}2000}$ fractions and the C3-C4 plant shift allowed understanding that the observed changes in SOC storage were most likely related to an increase in C inputs from crop residues with irrigation, due to both increased biomass production and a more efficient incorporation of these residues. The mean residence time of SOC in the two modelled pools did not allow however to support our hypothesis of a systematic acceleration of mineralization with irrigation. The interaction of the carbonate-rich mineral phase of this soil can explain at least partially this observation.

We conclude that irrigation can contribute to effectively increase SOC storage in the mid-term, but its effect might be dependent upon the type of crops and soil.

Part of this chapter, combined with chapter II is to be submitted to *International Soil and Water Conservation Research* as: Antón, R.; Derrien, D.; Urmeneta, H; van der Heijden, G; Enrique, A; Virto, I. *Organic carbon storage and dynamics as affected by the adoption of irrigation in a cultivated calcareous Mediterranean soil*.

INTRODUCTION

The land use change that implies the introduction of irrigation may involve changes in soil organic C (SOC) dynamics depending on the effects of new water and soil management practices on soil C inputs, and C stabilization mechanisms (Qiu et al., 2018; Trost et al., 2013; Zhou et al., 2016). The role of these aspects as drivers of SOC dynamics is widely accepted (Lehmann and Kleber, 2015; Schmidt et al., 2011), as well as the critical interaction of the soil physical-chemical characteristics and the nature of the mineral phase of the soil with them (Rasmussen et al., 2018; Vázquez et al., 2020). In this sense, the protective nature of carbonate-rich soil matrixes could play a significant role in irrigated calcareous soils. In addition to the well-known higher stability of organic forms in Ca-rich soils compared with other soils in similar conditions (Fernández-Ugalde et al., 2011; Rowley et al., 2018) carbonates can be sensitive to both moisture changes and acidification by increased roots respiration (Bughio et al., 2016; Bughio et al., 2017), which should be accounted for when studying irrigation in calcareous soils.

Despite these evidences, there is still little information available at the regional scale to conduct a detailed analysis of the effect of irrigation adoption on SOC dynamics (Chenu et al., 2019), notably because of the lack of paired irrigated and non-irrigated trials (Bai et al., 2018). Therefore, a site-specific research to correctly assess this effect in the long term is needed (Aguilera et al., 2018; Apesteguía et al., 2015; Cayuela et al., 2017; Sanz-Cobena et al., 2017).

Different approaches have been developed to assess the potential changes in SOC storage and dynamics in agricultural soils. Isotopic studies combined with the monitoring of field-scale parameters represent a powerful method, and are frequently used (Balesdent, 1987; Balesdent et al., 2017; Balesdent and Mariotti, 1996). The ^{13}C natural abundance approach represents a widespread option for temporal and spatial modelling of SOC, with great applicability to evaluate its turnover (Derrien et al., 2006; Derrien & Amelung, 2011; Dignac et al., 2005; Liu et al., 2019).

This approach, when used in chronological studies, allows for testing models aiming to estimate the turnover, or the mean residence time (MRT) of SOC. These models simulate the processes driving SOC dynamics, the balance between the soil C inputs and outputs, and the influence of land use and management on this dynamics (Aalde et al., 2006; Chenu et al., 2019; Novara et al., 2013). They can have a variable degree of complexity (Campbell and Paustian, 2015). Identifying the best choice of model structure is essential to get as closer to the natural system evaluated with a minimal error as possible (Derrien & Amelung, 2011). The decomposition of crop residues in the soil and their progressive incorporation into the soil organic pool represent an extremely complex process (Lehmann and Kleber, 2015) to which, at least, two-pools models may give a closer representation over the first few years, offering good fits to this decay process (Jenkinson, 1990). In these two-pools models, a fast- and a slow-cycling pool are considered, according to their biological stability towards decomposition (Batlle-Aguilar et al., 2011; Trumbore, 1997) and, therefore, representing SOC pools with contrasting turnover rates.

In this context, when different pools are considered in the model, a well-defined SOC fractionation protocol is required to separate and analyse fractions corresponding to these modelled pools (Stockmann et al., 2013). Indeed, in many cases, the convergence of the conceptual pools defined in models with their corresponding fractions of SOC can be considered the real challenge in their parametrization (Blankinship et al., 2018; Ellerbrock and Kaiser, 2005; Zimmermann et al., 2007). As such, Six et al. (2000) already observed that the isolation of functional pools of soil organic matter sensitive to land use changes can be elusive.

Poeplau et al. (2018), in a study comparing fractionation methods to recover fractions with varying turnover rates, concluded that none of the twenty methods tested was able to properly isolate the most labile fractions representing the fast-cycling labile C pools described in biogeochemical models. In their study, the fraction most enriched in C recently arrived into the soil, was the coarse (sand size) light organic fraction or particulate organic matter. In fact, the organic C in the size fraction 50-2000 μm has been often considered as functionally representing the fast cycling / labile organic C pool (Haile-Mariam et al., 2008; Mazzilli et al., 2014; Paul, 2016).

Carbon inputs from crop residues are also a critical parameter in these models (Derrien & Amelung, 2011), as observed by Keel et al. (2017), who reported large uncertainties in the simulated changes of SOC by applying different approaches to estimate C inputs with the same decomposition model. In addition, it is known that the proportion of these residues which actually enters the soil at a given depth may depend on the physical distribution and fate of crop residues between harvesting and incorporation with tillage (Schiedung et al., 2017), and that changes in moisture conditions in the soil can affect the proportion of C actually incorporated per unit C in crop residues (Coppens et al., 2006).

Based on the results obtained in terms of SOC storage (see Chapter II), and the 7 years database defined in it, in this study we aimed to model the changes in mid-term SOC dynamics in a semi-arid calcareous Mediterranean soil following the introduction of irrigation and the crop conversion from wheat (a C3 plant) to maize (a C4 plant).

We hypothesized that changes in SOC storage observed would be related not only to potential gains due to an increase in C inputs to the soil (confirmed in Chapter II), but also to (i) potential losses as a result of an acceleration of the turnover rate of the labile and stable fractions because of an enhanced microbial activity due to the improved moisture conditions during the growing season, and (ii) changes in the parameters regulating the partitioning of fresh plant input between the labile and the stable fraction in the studied calcareous soil.

To test our hypotheses, we took advantage of an isotopic labeling study based on vegetation change from C3 to C4 plants, setup in an experimental field in Eneriz (Navarre, Spain) where both types of vegetation are grown with and without irrigation.

MATERIALS AND METHODS

Site description and experimental design.The study field is located in Navarre, NE Spain (42°40’18.74”N; 1° 45’ 4.65”W) within a sub-humid temperate Mediterranean climate area. The mean annual temperature is 13.4°C, and mean annual rainfall and potential evapotranspiration (PET) are 565 mm and 722 mm, respectively.

The soil is a *Calcic Haploxerept* (Soil Survey Staff, 2014), developed on carbonate-rich siltstones and sandstones. It is a fine-loamy deep soil, with 38 % carbonates (pH = 8.2), and average clay content of 29 % in the upper horizon (0-30 cm).

This field had been managed for at least five decades as a traditional rainfed dryland field under conventionally tilled C3 crops before the area was converted to irrigated farmland. At this moment, taking advantage of the opportunity of the introduction of irrigation in this area, a C3-to-C4 plant shift experiment was set up with the aim of long-term monitoring the effect of climate manipulation with irrigation under different crop systems. Winter wheat (*Triticum aestivum* L.) and maize (*Zea mays* L.), a C3 and C4 plant respectively, were selected for the experiment, and grown for 7 years with and without irrigation.

Within this field, four different subareas were defined corresponding to the four crop-irrigation combinations: rainfed wheat (W-rf), irrigated wheat (W-irr), rainfed maize (M-rf) and irrigated maize (M-irr). Different crop and soil parameters were monitored in detail for 7 years on each of these four subareas. Yield and harvest index (HI) were the crop parameters, which allowed for the estimation of C inputs from crop residues potentially incorporated into the soil each year. Soil parameters monitored were total organic C (TOC) and the organic C in the particulate size fraction 50-2000 μm ($POC_{50-2000}$). Additional details about the field site, the experimental design, as well as the sampling protocol and analytical methods employed can be found in Chapter II.

Isotopic analytical. The natural abundance of ^{13}C was analyzed in TOC and $POC_{50\text{-}2000}$ samples from three plots out of six in each maize subarea (chosen at random), as well as in maize tissues. This was done with a CN elemental analyzer (NC 2500, Carlo Erba, Milano, Italy) coupled to a mass spectrometer (Thermo Quest-Finningan Delta Plus, Bremen, Germany). Acid fumigation (Harris et al., 2001), which was reported by previous studies to not affect the organic C concentration or isotopic signature (Fernández-Ugalde et al., 2011), was used before analysis to remove soil carbonates.

For modelling purposes, the proportion of maize-C at time *t* in the chronological study (*F*(*t*)) in both TOC and $POC_{50\text{-}2000}$ was quantified in M-rf and M-irr samples considering that the isotope composition of SOC after the introduction of maize (δ_{sample}) can be expressed as (Balesdent and Mariotti, 1996):

$$\partial_{sample}.(C_{old} + C_{new}) = \partial_{sample}(C) = \partial_{old}.C_{old} + \partial_{new}.C_{new}$$

(Equation 1)

where C_{old} and C_{new} are the soil C contents from the old and the new crops (former C3 vegetation and maize, respectively), δ_{sample} is the δ^{13}C of the soil studied sample, δ_{old} is the δ^{13}C of the original SOC (*t* = 0) and δ_{new} is the average δ^{13}C of new maize plant material, (-12.7 ± 0.1 ‰ in M-irr, and -13.5 ± 0.2 ‰ in M-rf).

F(*t*), the proportion of C derived from the new C4 crop is calculated as:

$$F(t) = \frac{C_{new}}{C_{new}+C_{old}} = \frac{\partial_{sample}-\partial_{old}}{\partial_{new}-\partial_{old}} \qquad \text{(Equation 2)}$$

Values of *F(t)* were calculated for each plot independently, for TOC and $POC_{50\text{-}2000}$, in relation to the average value of δ^{13}C in the W-rf plots (δ_{old} = -26.6 ± 1.2 ‰) which is considered to be representative of previous soil condition (Rasse et al., 2006). For verification, δ^{13}C from

TOC and $POC_{50\text{-}2000}$ in W-rf and W-irr samples was measured at years 0, 2 and 7, and no significant differences were observed. The amount of C4-C stored in any fraction and moment in time (C4-C stock) can be calculated as the product of C in that fraction and $F(t)$. Thus, this amount for TOC (C4-TOC) and $POC_{50\text{-}2000}$ (C4-$POC_{50\text{-}2000}$) was calculated for the 7 years of study, except for year 5, in the M-rf and M-irr.

Modelling of SOC dynamics. Soil organic carbon dynamics in M-irr and M-rf were simulated with a two-pool modeling approach, with both pools submitted to exponential decomposition kinetics. Pool 1 (P1) consists of rapidly-decomposable organic matter with a fast decay rate (k_1) and, consequently, a short MRT_1 ($MRT_1 = 1/k_1$). Pool 2 (P2) represents a pool with a slower decay rate (k_2) and a longer MRT_2 ($MRT_2 = 1/k_2$).

There are different options for coupling the two pools. We tested a sequential two-pools model (sequential) and a parallel two-pools model (parallel) (Figure 1), as those described by Derrien and Amelung (2011), adding a new parameter (Incorporated fraction, *IF*) to account for the increasingly acknowledged possibility that only a proportion of crop residues would be effectively incorporated as C inputs into the soil (Jackson et al., 2017). In the sequential option, C inputs are first directed into P1. When C leaves P1, a proportion (*tr*) is transferred to P2 and the rest is lost as CO_2. The C eventually leaving P2 is fully lost as CO_2. In the parallel option, it is assumed that C inputs are directed into both pools P1 and P2. A proportion (*s*) is allocated to the pool P1, and the remainder ($1 - s$) enters the pool P2. There is no C exchange between the two pools. Carbon leaving P1 and P2 is lost as CO_2.

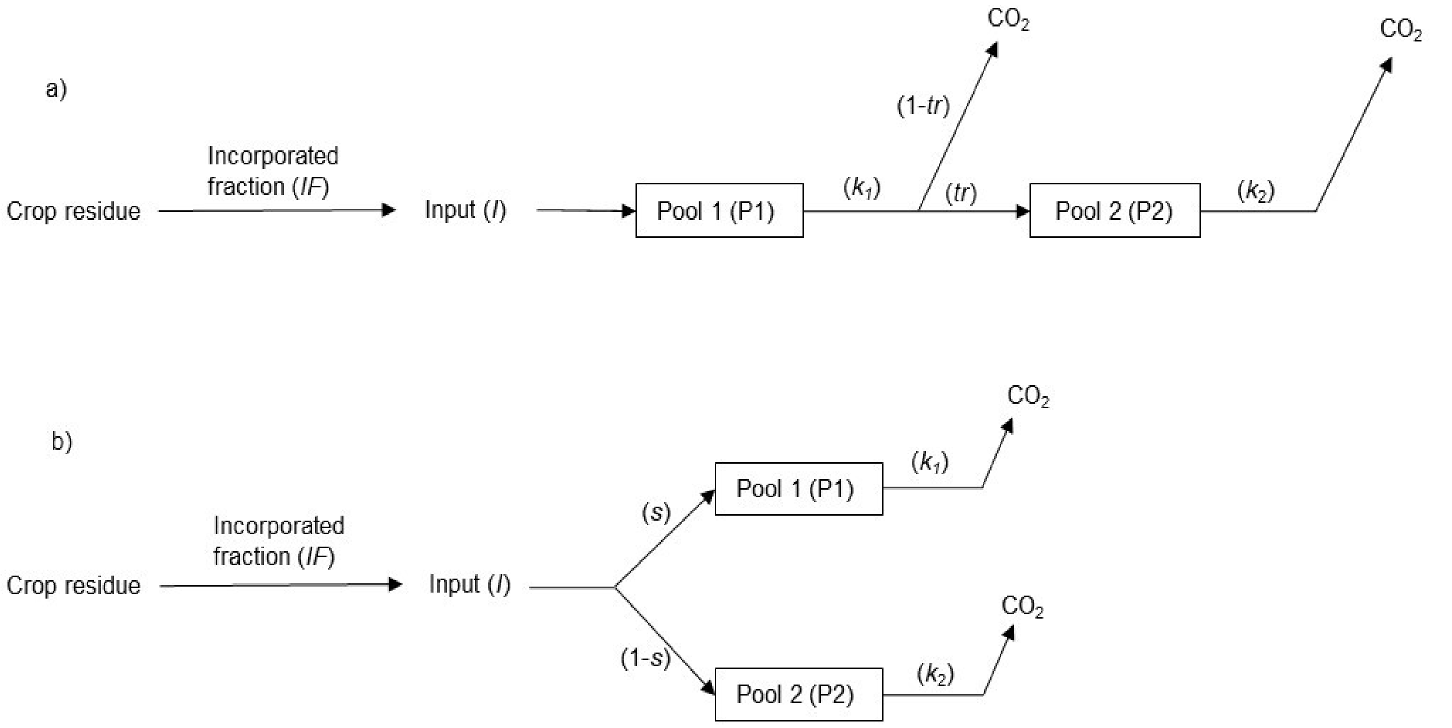


Figure 1. Flow chart of the two two-pools models considered in this study for soil organic C dynamics, two-sequential pools model (a) and two-parallel pools model (b), where Pool 1 cycles more rapidly than Pool 2

At steady state, the SOC stocks in the two pools, C_{ss_P1} and C_{ss_P2}, can be calculated as follows (Derrien & Amelung, 2011), for the sequential model:

$$C_{ss\_P1} = \frac{I}{k_1} \quad \text{(Equation 3)}$$

$$C_{ss\_P2} = I \times \frac{tr}{k_2} \quad \text{(Equation 4)}$$

and for the parallel model:

$$C_{ss\_P1} = I \times \frac{s}{k_1} \quad \text{(Equation 5)}$$

$$C_{ss\_P2} = I \times \frac{(1-s)}{k_2} \quad \text{(Equation 6)}$$

where *I* is the average amount of C inputs, and k_1 and k_2 are the decay rates of P1 and P2, respectively (Figure 1). The calculation of the mean or equivalent residence time in the whole system (MRT_{eq}) is also possible from MRT_1 and MRT_2, plus *tr* or *s* data. In the case of the sequential model is calculated as:

$$\mathrm{MRT}_{eq} = MRT_1 + tr \times MRT_2 \quad \text{(Equation 7)}$$

and for the parallel model:

$$\mathrm{MRT}_{eq} = s \times MRT_1 + (1-s) \times MRT_2 \quad \text{(Equation 8)}$$

Model calibration. A modelling approach was performed to quantitatively assess the impact of irrigation on C cycling. Model parameters were estimated by calibrating the model with the 7-year dataset from the three plots monitored for their isotopic composition in M-rf and M-irr, and assuming that the $POC_{50\text{-}2000}$ fraction represented the fast-cycling pool P1. A General Likelihood Uncertainty Estimation (GLUE) (Beven, 1993; Beven and Binley, 1992) calibration procedure was applied. This approach enables to simultaneously i) optimize the model parameters in order to obtain the best fit between the modelled and empirical datasets and ii) quantify the uncertainties associated with parameter estimates. This Monte Carlo type of approach is "*based upon making a large number of runs of a given model with different sets parameter values, chosen randomly from specified parameter distributions. On a basis of comparing predicted and observed responses, each set of parameter values is assigned a likelihood of being a simulator of the system"* (Beven and Binley, 1992).

The amounts of simulated total SOC (P1 + P2) and C in the labile fraction (P1) were initialized using the average measured values of TOC and $POC_{50\text{-}2000}$ before the onset of the experiment (year 0), respectively. For each of the model parameters to optimize (*IF*, MRT_1, MRT_2, *tr* or *s*), an initial interval of possible values was defined: [0-1] for the proportions *IF*, *tr* and *s*, [0-50 years] for MRT_1, and [50-200 years] for MRT_2. Each model parameter was assigned a random value within its interval. The model was then run and the performance of the model output was determined using the Root Mean Square Error (RMSE):

$$RMSE = \frac{100}{\overline{O_i}} \times \sqrt{\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{n}} \qquad \text{(Equation 9)}$$

where n is the number of observation dates, and O_i and P_i are the observed and predicted proportions of C for each observation date i, respectively (Derrien and Amelung, 2011).

This process was repeated 6000 times. Within these 6000 combinations of model parameters, all parameter combinations leading to a calculated new steady-state total carbon pool (TOC_{ss}) greater than

2.5-fold the initial carbon pool were rejected, on the basis of a regional-scale study conducted in the same area by Antón et al. (2019) (see Chapter IV). In this study, it was observed that SOC stocks in agricultural fields converted to irrigation were up to 1.8 times greater than those in similar soils under rainfed cropping conditions after 20 years.

Finally, the 50 combinations of parameters that resulted in the lowest values of total RMSE (Equation 9), were used to define a new interval of possible values for each parameter for the next cycle. The modeled parameter intervals obtained after 5 cycles were used to estimate the range of optimal model parameters and quantify their associated uncertainty. The number of cycles and the random parameter combinations were defined in order to ensure the repeatability of the GLUE-optimization procedure.

Differences in mean residence time (MRT_1 and MRT_2), incorporated fraction of crop residues (*IF*) and in the proportion of C input allocated to the pool P1 (*s*) or transferred to P2 (*tr*) between M-irr and M-rf were assessed by comparing the intervals of possible model parameters values obtained through the GLUE procedure. Differences were only considered as significant when these intervals did not overlap. All model analyses were conducted with R (R Core Team, 2019).

RESULTS

Two-pool models testing. The sequential model, built on the assumption that $POC_{50\text{-}2000}$ corresponds to the fast-cycling pool P1, was not able to satisfactory reproduce SOC dynamics in the maize plots (Figure 2). Although it correctly reproduced the change in stocks in TOC and $POC_{50\text{-}2000}$, it could not reproduce the C4-C incorporation patterns. Whatever the time after conversion, observations indicated larger C4-TOC stocks than C4-$POC_{50\text{-}2000}$ stocks, which is contradictory to simulations with a sequential model of SOC dynamics. In a sequential model, during the first years after crop conversion, the new C4 carbon should be entirely incorporated in P1, and access P2 over time, which is not observed in Figure 2..

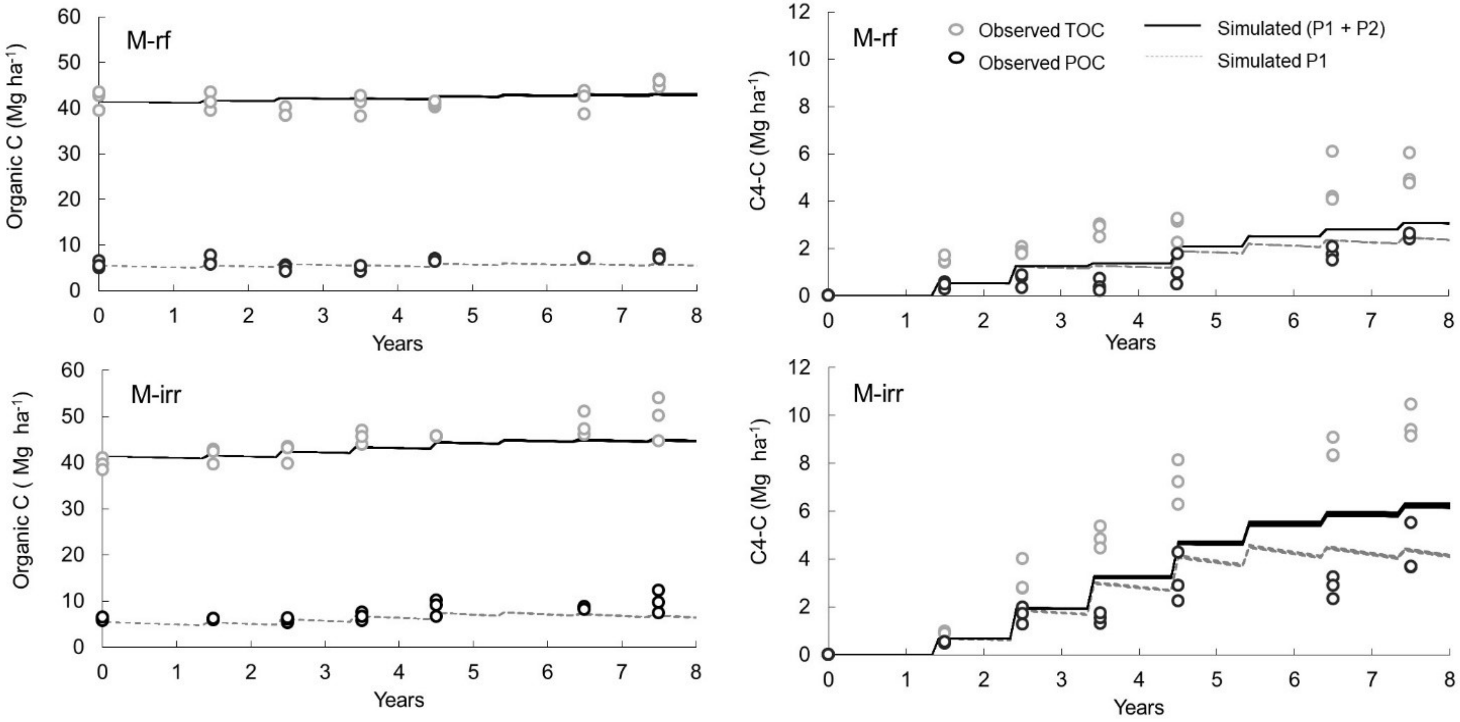


Figure 2. Simulations of organic C and C4-C stocks dynamics in P1 (grey dashed lines) and (P1+P2) (dark lines) with the sequential model. The 50 best fits are represented. TOC (grey dots) and $POC_{50-2000}$ (dark dots) observed data are also displayed (n=3). Top panels show organic C and C4-C stocks in M-rf (maize rainfed). Bottom panels show organic C and C4-C stocks in M-irr (maize irrigated).

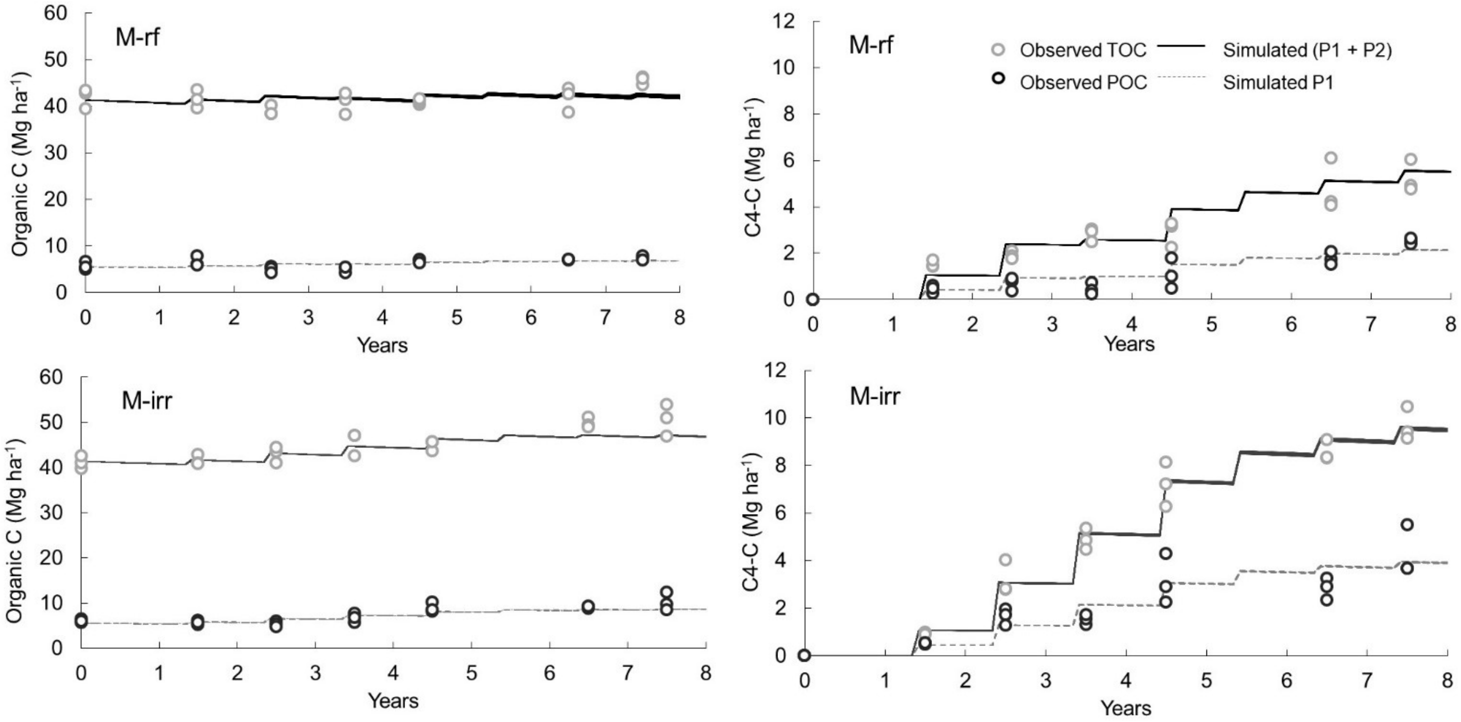


Figure 3. Simulations of organic C and C4 stocks dynamics in P1 (grey dashed lines) and (P1+P2) (dark lines) with the parallel model. The 50 best fits are represented. TOC (grey dots) and $POC_{50-2000}$ (dark dots) observed data are also displayed (n=3). Top panels show organic C and C4-C stocks in M-rf (maize rainfed). Bottom panels show organic C and C4-C stocks in M-irr (maize irrigated).

Unlike the sequential model, the parallel model successfully reproduced the dynamics observed for TOC and $POC_{50-2000}$ in the maize plots, both for total stocks and for the kinetics of new C4-C incorporation (Figure 3). The 50 best combinations of parameters provided by the GLUE approach for this model were used to gain quantitative insights into the effect of irrigation on SOC dynamics, and are explained in the following section for M-rf and M-irr plots.

Soil organic carbon dynamics in maize plots. The intervals of possible model parameters generated by the GLUE optimization procedure for the irrigated and rainfed plots for MRT_2, the split *s* parameter, and the incorporation factor of crop residues, *IF* (Figure 4) did not overlap. The proportion of C from crop residues incorporated into the soil (*IF*) was approx. 19% higher in the irrigated plots, from 0.36 (M-rf) to 0.43 (M-irr).

MRT_2 was also significantly higher in the irrigated plots: 67.2 ± 3.6 years in -M-rf against 86.3 ± 1.1 years in M-irr. No effect was observed for MRT_1: mean MRT_1 obtained for the 50 best sets of parameters in M-rf was 49.8 ± 0.05 years against 49.3 ± 0.31 years for M-irr.

Finally, the split of plant input (*s*) between P1 and P2 was slightly but significantly higher for the irrigated plots, favoring the incorporation into P1 by 8% in average over the whole set of parameters (0.39 ± 0.00 for M-rf against 0.42 ± 0.00 for M-irr).

The MRT_{eq} value was of 70.8 ± 0.5 years 60.4 ± 4.0 years for M-irr and M-rf respectively (Table 1). In terms of projected SOC stocks in the new steady state equilibrium, C_{ss_P1} and C_{ss_P2} values were 29.8 ± 0.4 Mg ha^{-1} and 72.3 ± 1.5 Mg ha^{-1} respectively for M-irr, and 16.4 ± 0.1 Mg ha^{-1} M-rf and 34.4 ± 3.3 Mg ha^{-1} respectively for M-rf. The projection was 2.5 times the initial value of TOC in M-irr, and 1.2 times in M-rf.

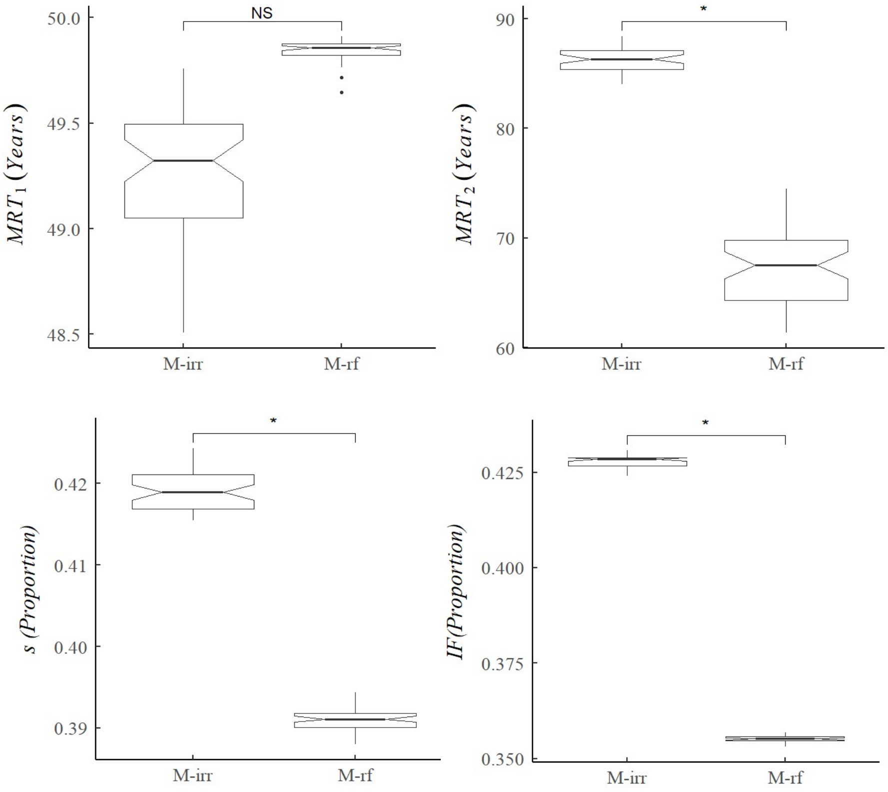


Figure 4. 50 best sets of parameters obtained for the parallel model with the GLUE procedure. Values of MRT_1 (a) MRT_2 (b), the split *s* parameter (c), and the proportion from crop residues incorporated into the soil (*IF*) in the parallel model for rain-fed maize (M-rf) and irrigated maize (M-irr). The boxplots represent the median (n=50), 25th and 75th percentiles with the whiskers extending to the most extreme data points within the 1.5x of values generated by the model for each parameter. * represents significant differences (no overlapping of the intervals of possible model parameters).

Table 1. MRT_{eq} values and parallel model projections of stocks at steady state for P1 (Css_p1), P2 (Css_p2) and P1 + P2 (TOCss) and ratios between initial stock (observed) and the steady state stock estimated for rainfed maize (M-rf) and irrigated maize (M-irr). (Mean ± Confidence interval).

	M-irr	M-rf
MRT_{eq} (years)	70.80 ± 0.50	60.40 ± 3.98
C_{SS_p1} (Mg ha^{-1})	29.80 ± 0.45	16.38 ± 0.07
C_{SS_p2} (Mg ha^{-1})	72.28 ± 1.50	34.42 ± 3.31
TOC_{SS} (Mg ha^{-1})	102.08 ± 1.13	50.80 ± 3.32
C_{SS_p1} / $C_{p1initial}$	4.49 ± 0.07	2.88 ± 0.01
C_{SS_p2} / $C_{p2initial}$	2.08 ± 0.04	0.96 ± 0.09
TOC_{SS} / $TOC_{initial}$	2.50 ± 0.03	1.23 ± 0.08

DISCUSSION

SOC fractionation parametrization. As observed in the Chapter II, observed changes over time on $POC_{50\text{-}2000}$ fraction were greater than those on TOC. This confirmed $POC_{50\text{-}2000}$ as a fraction behaving as an early indicator of SOC changes in the conditions of this study (Apesteguía et al., 2017; Imaz et al., 2010), and therefore, which can be considered as the fast cycling pool (P1) in the mechanistic two-pools modelling approach used here, in agreement with results from Poeplau et al. (2018). These authors concluded, that the separation of particles > 50 μm and < 50 μm, recovered after chemical dispersion as described in Sanderman et al. (2013), yielded the strongest contrasts in terms of turnover rates. Cotrufo et al. (2019) have recently described this fraction as useful to globally inform on organic C storage at different levels of protection, and as predominantly of plant origin and persisting in soil through physical protection in aggregates and/or microbial inhibition.

Nevertheless, regardless of the maize systems considered, irrigated or rainfed, the difference between the ranges of MRTs obtained for C in the two pools (P1 and P2, corresponding respectively to $POC_{50\text{-}2000}$ and the fraction <50 microns) was relatively small (Figure 4). In particular, MRT_1 values found in our calcareous soil were close to 40 years, which seems relatively long if we consider that the pool P1 conceptually represents a labile fraction of rapid renewal.

Other studies based on the natural abundance of ^{13}C in soil samples and conducted on C3-C4 plant-shift experiments in other soil types and climate conditions, have found MRTs in the same order of magnitude, but smaller than our data, associated with the fraction 50-2000 μm and with $\rho > 1$ g cm^{-3} recovered after chemical dispersion. These range from 13.8 years to 28 years calculated from Balesdent (1996) and Derrien et al. (2006) on silty soils in humid temperate France, or 20.6 years from Dalal et al. (2013) in warmer and more arid conditions in Queensland (Australia). Haile-Mariam et al. (2008) reported between 5.6 and 12.8 years in three studies with 30 years of maize cultivation on three carbonate-free soils (Typic Fragiudalf, Mollic Ochracqualf and Typic Haplustoll) in the MidWest of the US, and of 11.4 years in a Typic Hapludalf after 8 years of maize cultivation for this fraction. Paul (2016), combining incubations and field samples data, described MRT values between 12 and 7.8 years in two Mollisols in Canada and Ohio. None of these soils was calcareous.

Therefore, although our results confirm the traditional vision of $POC_{50\text{-}2000}$ as a fraction with a faster turnover than bulk soil, and therefore a potential predictor of long-term changes in SOC cycling (Cambardella and Elliot, 1993; Cotrufo et al., 2019; Jastrow, 1996; Paul, 2016), they also open questions on the concept of precocity when referring to $POC_{50\text{-}2000}$, and on the interaction of soil and climate factors in this sense.

Incorporation of C from crop residues in soil and SOC dynamics. The fact that the parallel model (Figure 3) was a closer approximation to actual SOC dynamics in the studied soil than the sequential model option (Figure 2) suggested that, in the soil and cropping conditions of this experiment, the protection of organic C from crop residues can be direct, once they are incorporated into the soil. This observation does not completely match the general understanding of SOC stabilization processes, which considers a progressive sequence of interaction of fresh organic C from crop residues with the soil biota and the mineral fraction (Lehmann and Kleber, 2015; Six et al., 2004, 2000).

In this sense, there is consensus on the fact that the interaction of the organic and mineral components of the soil represents a major factor controlling its stabilization in the soil, although one of the greatest weaknesses of most SOC models is the lack of adequate representation of edaphic characteristics (Schmidt et al., 2011). This interaction is closely linked to the reactivity of organic and mineral surfaces (Gao et al., 2019) and to the development of soil structure (Banwart et al., 2019). The nature and proportion of the mineral compounds in the soil largely determine their functioning as stabilizers of organic matter (Creamer et al., 2019; Kaiser and Guggenberger, 2003; Torn et al., 1997). In semi-arid regions, for example, alkaline carbonates can be an important factor of aggregation (Fernández-Ugalde et al., 2014, 2011), which can result in longer-term organic matter protection in comparison to carbonates-free soils (Boix-Fayos et al., 2001; Bouajila and Gallali, 2008; Six et al., 2004). In fact, it is a long known observation (Duchaufour 1982) that, in calcareous soils, SOC contents are usually higher than in soils without carbonates under equal conditions, especially in agricultural soils with low SOC levels (Lopez-Sangil and Rovira, 2013; Romanyà and Rovira, 2011). The soil of this study had a carbonates content of 38% in the upper layer (0-30 cm). Carbonates can promote the fast incorporation of crop residues into stable aggregates with slow cycling in comparison with non-calcareous soils, as observed by Fernández-Ugalde et al. (2011), very likely as a result of carbonate dissolution and re-precipitation cycles. As explained by Rowley et al. (2018), in such situations, part of the residues incorporated would be directly protected within aggregates of different sizes stabilized by carbonates. The elevated content of alkaline carbonates of the studied soil could therefore at least partially explain this observation, as well as the relatively long MRTs of the fraction $POC_{50-2000}$ observed in this study, discussed above.

Another relevant result from the modelling approach was that, in all cases, the optimized fitting of the observed TOC and $POC_{50-2000}$ data indicated that a large proportion of crop residues was not actually incorporated into the soil (parameter *IF* < 50%).

Different reasons can explain this observation. First, a loss of crop residues left on the ground is possible before they are actually incorporated into SOC, as part of these residues (aerial crop parts) remained on the surface of the soil after harvest for a period of 4-5 months before tillage (see Chapter II). It has indeed been reported by local extension agents that wind and intense meteorological events, as well as the activity of wild fauna, can exert a significant reduction in the amount of biomass during this time (Apesteguía, personal comm.). Second, direct mineralization of aerial crop residues compared with belowground residues has been frequently reported as the cause of belowground crop biomass contributing more to SOC than aboveground biomass. For instance, Jackson et al. (2017) analyzed 6 maize field experiments with a duration ranging between 2 and 15 years, and observed that, on average, 47 ± 20% of belowground C inputs were stabilized as SOC compared with 11 ± 4% of aboveground C inputs, showing great variability depending on different agroclimatic conditions or management. These authors emphasized that, although many models for C balances generally assume a direct relationship between crops biomass production, crop residues inputs, and SOC accumulation, there is yet little direct evidence for such a relationship.

Irrigation and SOC dynamics. In agreement with our working hypothesis, our investigation showed that the input of plant material into the soil was higher in the irrigated subarea, which can be explained by both the higher plant biomass production (see Chapter II) and by a higher incorporation of crop residues in the studied layer (0-30 cm) (*IF* data, Figure 4). This highlights the importance of adequately determining C inputs to the soil from crops when studying SOC dynamics (Unkovich et al., 2010).

One explanation for this increased effective incorporation of crop residues could be that irrigation could induce a difference in the root distribution with depth resulting in a higher proportion of roots concentrated in the studied 0-30 cm soil layer compared with rainfed management. In rainfed systems within areas where water availability is limited, the soil exploration for available water results in crop root systems tending to expand, usually in depth (Lynch, 2013), notably in the case of maize (Kondo et al,. 2000), while irrigation tends to increase maize root density in the topsoil (Mahgoub et al., 2017). It is also possible that the granted moisture conditions during the growing season of maize in the irrigated subarea (see Chapter II) would provide better conditions for an effective incorporation of crop residues (which were incorporated with tillage shortly before seeding, see Chapter II) into the soil matrix by earthworms and other soil fauna.

According to the modelling results, however, our hypothesis about the expected acceleration of the organic matter turnover rate in the irrigated subarea due to a possible enhancement of microbial activity, was not verified: MRT_1 was not significantly different in M-irr than in M-rf, and contrary to our expectation, MRT_2 was higher in M-irr than M-rf. In this sense, the increase in MRT_2 associated to irrigation would favor SOC stabilization.

Finally, our third hypothesis (stabilization processes would be altered by irrigation in the studied calcareous soil) can be at least partially confirmed from the results of the parallel model. The slight increase in s in M-irr compared to M-rf (Figure 4), indicated that slightly less crop residues would be protected in the slow-cycling pool P2, but their protection would occur over a longer time with irrigation, because MRT_2 in M-irr increased with respect to M-rf. Investigations about the processes responsible for such a response in calcareous soils merit further attention. Recent observations in the region have shown that irrigation can also induce changes in the dynamics of carbonates (de Soto et al., 2019, 2017), although the interactions with the organic fraction of the soil remain to be studied.

The calculation of the mean residence time in the whole system (MRT_{eq}, Equation 8) and the stock of SOC at the new steady state projected with the parallel model (Equations 5 to 6) enabled to balance the apparent diverging effects of irrigation on mineralization and stabilization processes. The MRT_{eq} was 17% higher for M-irr versus M-rf (Table 1), which indicates that an enhanced stabilization of SOC could be an effective consequence of the introduction of irrigation, as observed above. This dominance of stabilization over mineralization was related to the observed difference in MRT_2 between the irrigated and rainfed maize subareas (+28% in M-irr than in M-rf, Figure 4).

In terms of projected SOC stocks in the new steady state equilibrium (TOC_{ss}), the projection was 2.50 times the initial value of TOC in M-irr, and 1.23 times in M-rf (Table 1 and Figure 1S in Supplementary Material), in line with the trend observed in TOC data in the first 7 years of this study, and within the range of field observations in a previous study in the region on calcareous soils (Antón et al., 2019, see Chapter IV). The different steady-state stocks between irrigated and rainfed plots can be related to the raise in MRT_{eq} associated to irrigation, but were mainly explained by the amount of crop residues entering the soil (66% more of accumulated C in crop residues in 7 years (see Chapter II) and 19% more crop residues incorporated in M-irr vs M-rf (Parameter *IF*, Figure 4)). Interestingly, the projections at steady state for P1 (C_{ss_p1}) and P2 (C_{ss_p2}) (Table 1), indicated a leading role of P1 in SOC accumulation in M-rf, and a leading role of P2 in SOC gains in M-irr. However, these projections need to be considered with care as the original dataset of observed values of TOC and $POC_{50-2000}$ accounted for a period of 7 years (Schiedung et al., 2017).

In summary, and as a general response to our working hypotheses, the modeling results indicated that the greatest difference between irrigated and rainfed maize subareas in SOC storage in the study field, seemed related to crop residues incorporation, and not to SOC mineralization rates. Carbon inputs would therefore be here the major driver responsible for the observed and projected increase in SOC storage in the irrigated subarea, as increasingly claimed (Chenu et al., 2019; Keel et al., 2019; Virto et al., 2012). A careful determination of the actual amount of crop residues entering the soil is then of the uttermost importance to accurately predict changes in C stocks in soil. New tools for monitoring root systems and *in situ* organic C incorporation from crops in the field are needed, and these should be integrated into simulation models (Jackson et al., 2017; Molon et al., 2017). Adequate allometric functions for estimating C inputs seem in this sense critical to select the appropriate modelling approach (Smith et al., 2019).

CONCLUSIONS

The hypothesis of the study was that the observed changes in SOC and $POC_{50-2000}$ stocks over the 7-year study period would be related not only to potential gains due to an increase in C inputs to the soil (see Chapter II), but also to potential losses as a result of an acceleration of the turnover rates because of an enhanced microbial activity due to the improved moisture conditions during the growing season, and to changes in the parameters regulating the partitioning of fresh plant input between the labile and the stable fraction in the studied calcareous soil.

The modelling approach based on the C3-C4 natural isotopic labeling study, allowed understanding that these changes were most likely due to an increase in C inputs from crop residues associated to irrigation, not only because of the increased productivity, but also because of a more efficient incorporation of these residues into SOC, in the studied topsoil layer. However, the differences simulated in terms of the MRTs of the two SOC pools considered (MRT_1 and MRT_2), did not support our hypothesis of an acceleration of mineralization with irrigation in the study field.

The parallel two-pool model option seemed to be a closer representation of the agrosystem evaluated. The interaction of the mineral phase of this soil, with 38% carbonates in the studied depth, could explain at least partially this observation, because carbonates are known to directly promote the protection of fresh organic matter in the soil. This highlights the relevant need for site-specific investigation to properly understand the response of soil and SOC to major management changes such as the implementation of irrigation. In particular, the overlapping between a carbonate-rich matrix, irrigation and organic matter protection, suggested here as an explanation for the results, needs to be verified with more empirical observations.

This study represents a contribution to deepen our understanding of the consequences of these land-use change on SOC cycling on a Mediterranean calcareous soil. Annual contributions of crop biomass incorporated into the soil, and agricultural management were observed as the most important drivers of this process in the soil and climate conditions of the studied field. The use of SOC cycling modelling showed to be a useful approach in this assessment.

The challenges associated to the expansion of irrigation remain significant and need to be carefully considered when such a strategy is considered at a regional or national scale. Our observations support the idea that this expansion can increase biomass productivity and favor SOC storage, but they should be considered in the context with other environmental and socioeconomic issues such as the competition for water use, greenhouse gasses emissions and/or food sovereignty.

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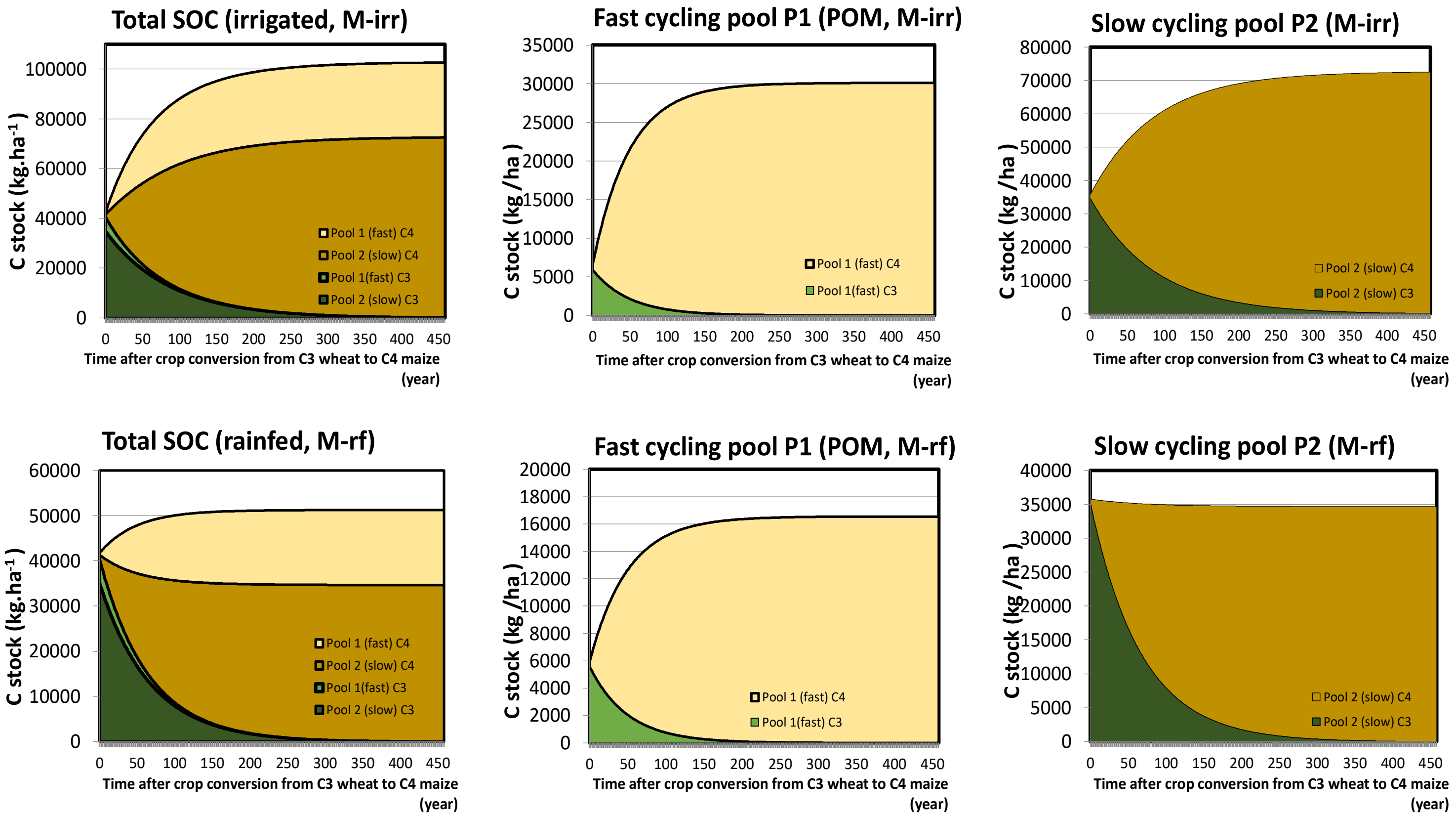

Supplementary Material Figure S1. SOC stocks projection in the new steady state equilibrium (TOC$_{ss}$

Chapter IV

Extension of irrigation in semi-arid regions: What challenges for Soil Security? Perspectives from a regional-scale Project in Navarre (Spain)

“Que la tierra que así conducida a los abismos del océano es en su mayor parte la removida por el hombre en su necesidad de pulverizarla a los fines del cultivo, y debido a su impotencia para retenerla defendida de los efectos de la erosión por las lluvias torrenciales que se la quitan, es evidente.”

Daniel Nagore Nagore
Plegarias del árbol. Enseñanza ambulante.
Diputación Foral y Provincial de Navarra. Dirección de Agricultura y Ganadería. Editorial Aramburu. Pamplona, 1939

CHAPTER IV

Extension of irrigation in semi-arid regions: what challenges for soil security? Perspectives from a regional-scale project in Navarre (Spain)

ABSTRACT

The conversion from dryland to irrigation in semi-arid land is a widespread strategy to grant agricultural profitability and food security. The trade-offs of this transformation for soil security remain unclear. Soil security has been defined as soil capacity to support functions providing planetary services and human wellbeing. It comprises five dimensions, namely soil *capacity,* soil *conditions,* soil *capital,* soil *connectivity,* or soil *codification.* The project LIFE REGADIOX, based on the establishment of a regional-scale network of representative plots in three irrigation districts in Navarre (NE Spain), allowed for a rational evaluation of soil security by using the soils *capability* to establish fair comparisons in terms of soil *condition*, *capital* and *connectivity* in irrigated vs rainfed plots. The results showed a clear influence of irrigation in soil condition and capital, arising from greater SOC storage. Differences in other soil indicators were uneven, and related to the natural limitations of the sites studied (soil and climate), and to the time under irrigation. The translation of these changes into the soil capital showed that irrigation adoption can alter the soils capacity to provide key ecosystem services beyond biomass production, as enhanced greenhouse emissions and moderated changes in soil erodibility were recorded. Connectivity was studied from differences in the major driver for farmers' decisions on soils (gross gains) and compared to SOC gains. Results showed that economic (income) and environmental (SOC gain) drivers did not always match. All in all, our results indicate that soil security can be affected in opposite directions when irrigation is implemented in semi-arid dryland. The dimension of these changes depends on the natural soil characteristics, and the management conditions of the agrosystems. Optimizing soil management under irrigation seems essential for ensuring a positive evolution of soil security in this and other semi-arid regions.

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INTRODUCTION

The challenge of transforming agriculture to feed a growing population without harming natural resources such as soil, requires a transition towards agricultural systems able to supply enough goods without losing sustainability. This implies a more efficient use of inputs, more yields stability and greater resilience to risks, crises and climate variability in the long term (FAO, 2017). The conversion from dryland to irrigation in semi-arid land is a widespread strategy in this sense, and is often seen as an efficient tool towards food security (Darko et al., 2016), as it reduces yield loss caused by drought and water stress, and increases flexibility in crop planting dates and crop types (Salmon et al., 2015).

Globally, 2.3–4.0 Mkm² or 15–26% of the global croplands are equipped for irrigation (Erb et al., 2017). This accounts for 33–40% of global food production (Salmon et al., 2015), including 44% of total cereal production, 30% of the global wheat fields (0.7 Mkm^2), 20% of the maize fields (0.3 Mkm^2) and half of the global citrus, sugar cane and cotton crops (Portmann et al., 2010).

Although the expansion of irrigation has slowed down in the last years, due to higher competition for water resources (FAO, 2017), this declining trend was diverse at the regional level, where regions with the highest shares of irrigated land generally showed a lower decrease between this period (Eurostat, 2016). In 2016, the total irrigable area in the EU-27 was 15.5 million ha, of which 10.5 million ha were actually irrigated. That represents a decrease of 3.5% in the irrigable areas, while irrigated areas decreased by 6.1 % compared to 2003. In 2016, Spain (15.7 %) and Italy (32.6 %) had the largest shares of irrigable areas in the agricultural areas of the EU, with 3.6 and 4.1 million ha, respectively. In addition to surface extension, the average irrigation requirements estimated by Wriedt et al. (2008) are highest in the Mediterranean area, reflecting the general climatic characteristics of this region, as well as soil attributes and crops demands.

The region of Navarre (NE Spain) is an example of the expansion of irrigation in semi-arid Mediterranean land. For a total agricultural surface of 341,835 ha, more than 22,300 ha of rainfed land was converted to irrigation in the period 2000-2015, which added to the previous existing irrigated area make a total of 108,221 ha of irrigated land in 2016 (Gobierno de Navarra, 2017a). In 2009, irrigated land production in Navarre already accounted for 35% of agricultural gross domestic product (GDP).

In general, irrigation adoption implies major changes in agrosystems, as it means changes not only in crop yields and profitability, but also in fertilization, rotations and soil management, and in the use of water and energy. For instance, irrigation affects the energy and radiation balance at the surface (Salmon et al., 2015). As such, irrigation has been identified within the ten important land management activities that may impact the Earth system profoundly (Erb et al., 2017).

Many of these changes can affect soil security, concept defined as the maintenance and improvement of soil to produce food, fiber and fresh water, contribute to energy and climate sustainability, and maintain the biodiversity and the overall protection of the ecosystem (McBratney et al., 2012), from which a set of dimensions have been defined: soil *capacity,* soil *conditions,* soil *capital,* soil *connectivity,* or soil *codification.* Following these authors, soil *capacity* is the reference state of the soil, it defines an optimum soil capacity against which the current state of the soil can be compared. Soil *condition* refers, therefore, to the current state of the soil, defined as the capacity of a soil to function. It can be estimated from specific soil properties. Both are susceptible to vary depending on land management. Soil *capital* can be defined by assigning a value to the service delivery from soil stock. Soil *connectivity* provides the social dimension around soil, linking the different users and stakeholders, as well as the knowledge and resources to manage soil condition and use it according to its capability. Finally, soil *codification* is concerned with public policy, regulation and legal frameworks that support the maintenance and improvement of the world soil resource. In this sense, irrigation can indeed alter soil functions related to global societal challenges: food, water and energy security, climate change abatement, biodiversity protection, and the maintenance of ecosystem services (McBratney et al., 2014).

Because of these sometime conflicting consequences, the role of irrigation in rural development can have contradictory views, arising from the heterogeneities between the preferences of stakeholder groups regarding water resources management, agricultural practices, and irrigation challenges. Although for some, irrigation can be the cornerstone of future adaptation strategies in face of climate and socio-economic changes in Europe (Dunford et al., 2015), integrating the assessment of the trade-offs between different services (e.g. energy and food security (Hurford and Harou, 2014)), and the provision of ecosystem services other than productivity is needed for a better understanding of these issues (e.g. (Aspe et al., 2016; Ricart and Clarimont, 2016)). For instance, Dominati et al. (2017) showed that including the modifications of soil condition following the adoption of irrigation was necessary for an accurate assessment of ecosystem services and their net present value at a regional scale.

In this context, the project LIFE REGADIOX (http://life-regadiox.es/en/) aimed to design, test, and spread the impact that an improved model of sustainable management of irrigated agriculture can have in climate change in the region of Navarre (NE Spain). The project was designed to assess the potential consequences of different management strategies in irrigated agriculture at a regional scale, including greenhouse gases (GHG) balances in irrigated soils, and the optimization of energy, water and other inputs consumption, based in the establishment of a network of representative agricultural fields.

In relation to the main global environmental challenges defined by McBratney et al. (2014), this project allowed for a rational evaluation of soil security in at least four of its five dimensions (*capability*, *condition*, *capital* and *connectivity*), as it provided a multi-disciplinary framework including the study of inherent and manageable soil properties (Dominati et al., 2010), monitoring of environmental outcomes of different management strategies in irrigated land, and socio-economic analyses.

In this work, as described above, the impact associated to an improved model of sustainable management of irrigated agriculture in the region of Navarre (NE Spain) was evaluated from the soil security perspective in three irrigation districts in Navarre, in which different agricultural managements exist, including rainfed and irrigated crops, using an approach based in the assessment of soil condition, capital and connectivity, after defining the local reference state of soil capability at each location.

MATERIALS AND METHODS

Irrigation districts and network of agricultural plots. The study was conducted in three irrigation districts of Navarre (North of Spain): Miranda, Funes and Valtierra. Considering the climatic gradient of the region from north to south (Figure 1), determinant in the development of agriculture in the region, the three districts were representative of the area where the aridity index is highest and where irrigation is concentrated, in the south of the region. As it can be seen in Table 1, there is a slight climate gradient between the three selected districts, especially in terms of precipitation.

At each of these districts, representative agricultural plots were selected to stablish a network. This was done by identifying plots with a known historic management, including rainfed cereal cropping since at least 50 years, and the most widespread cropping systems in irrigated land in the region. In particular, the plots selected included rainfed wheat and irrigated annual maize at the three sites, plus organic rainfed barley in Valtierra and fodder (alfalfa) in Miranda (Table 1). The irrigation system in all cases was sprinkler irrigation. Furthermore, the three districts were transformed to irrigation in different periods, allowing for the evaluation of the effect over time associated to the different management strategies considered. In the case of Miranda, irrigation had been implemented for 6 years at the time of this study, in Funes for 13 years and in Valtierra for 20 years (Table 1).

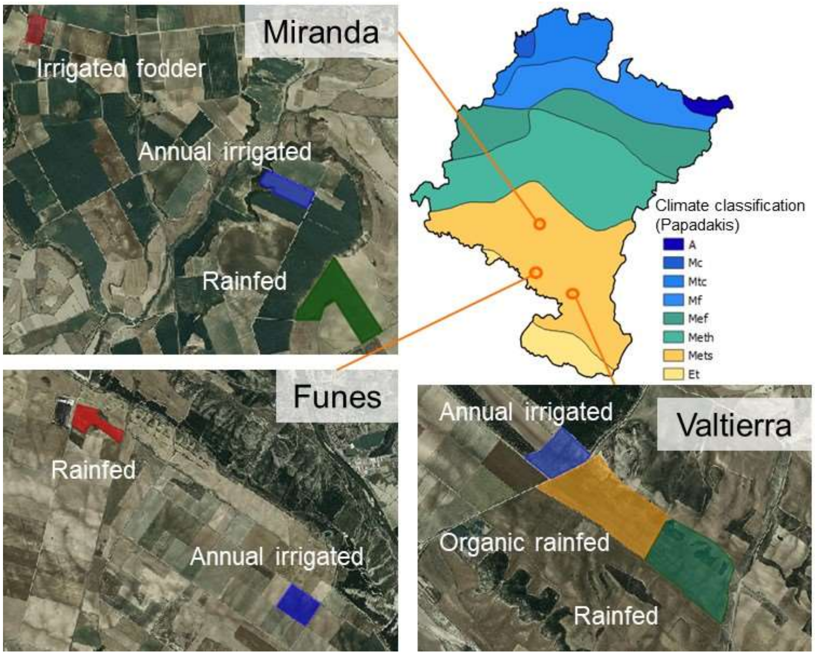

Figure 1. Climate zones in Navarre, according to Papadakis (1952), location and description of irrigation districts and network of agricultural plots.

Soil *capability* and sampling design. Following McBratney et al. (2014), soil capability was studied at each site for an adequate assessment of the other dimensions of soil security, and the local reference state was defined by considering both the so-called *genoform* and *phenoform* of soils (*sensu* Droogers & Bouma, 1997). Genetic information of the soils at each site was collected from available public databases on soil, including soil cartography (Soil Map of Navarre 1:25,000), geology (Geologic map of Navarre 1:25,000) and orto-photographs 1:5,000 available at the regional public database (https://idena.navarra.es/Portal/Inicio), and from soil pits sampled for this study. From these data, pedological criteria were used to ensure that the selected plots included soil from the most representative taxonomic unit at each site (Xeric Haplocalcid in Valtierra and Funes, and Typic Calcixerept in Miranda, (Soil Survey Staff, 2014).

Table 1. Situation, soil and climate characterization, managements included and years since conversion to irrigation for the three irrigated districts.

Site	Miranda	Funes	Valtierra
Coordinates	42°28′59″N 1°49′36″W	42°18′51″N 1°48′10″W	42°11′43″N 1°38′03″W
Mean Annual Precipitation (mm)	437	390	379
Mean Annual Temperature (ºC)	13.9	14.0	13.9
Potential evapotranspiration (Thornthwaite) (mm)	738	740	740
Reference soil (S.S.S., 2014)	*Typic Calcixerept*	*Xeric Haplocalcid*	*Xeric Haplocalcid*
Managements included in the study	Rainfed Annual irrigated Irrigated fodder	Rainfed Annual irrigated -	Rainfed Annual irrigated Organic rainfed
Years since conversion to irrigation	6	13	20

Then, the reference state was set for soils under permanent non-irrigated cereal cropping, because rainfed agriculture has been practiced for decades (or centuries) in these areas, inducing non reversible changes in soils due to erosion and soil organic matter losses, and resulting in a phenotypical alteration of the taxonomically defined *genoform* (Droogers and Bouma, 1997).

Within these plots, a sampling strategy was developed to ensure that only soils with similar capabilities were compared at each site. That for, since many of the selected plots in each district included soils from more than one cartographic unit, a sampling area was defined for each plot by adjusting it only to the area corresponding to the most characteristic soil type for each district (example at Figure 2). In all cases, the process was completed with a field visit to verify the final result and with extra analysis when necessary. Hence, the sampling network for soils included at each plot only those areas within the reference soil within each irrigated district. All the processing of cartographic information was performed with QSIG 2.18 (QGIS.org, 2021. QGIS Geographic Information System)

Finally, to ensure a representative sampling, a protocol was especially designed from the one proposed by Stolbovoy et al. (2007), as described by de Soto et al. (2017). This includes a sampling scheme based on a randomized template that is adjusted to the sampling area of the studied plot. As a result, a georeferenced grid was established including three representative areas (n = 3) per sampling zone and plot. At each area, one composite soil sample from 25 sub-samples and other intact soil core for bulk density (BD) were collected in the tilled layer at 0–15 cm and 15–30 cm (Figure 2).

Soil analyses (Soil *condition* and *capital*). A minimum dataset of soil physical, biological and organic matter-related properties was defined for assessing soil condition based on previous studies developed in the region for the selection of soil quality indicators (Fernández-Ugalde et al., 2009; Imaz et al., 2010). These included BD, soil available water holding capacity (AWHC), microbial biomass C (MBC) and an index of soil functional biodiversity, total (SOC) and particulate organic C (POC).

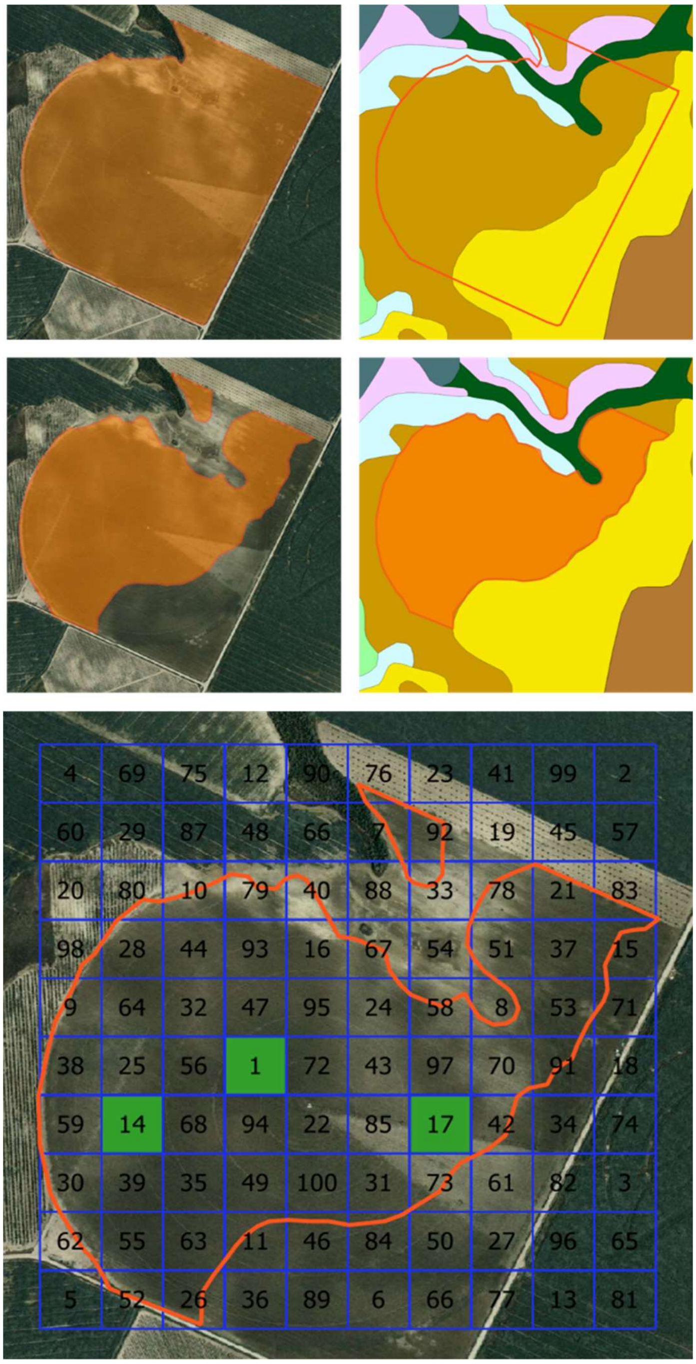

Figure 2. Sampling area definition, sampling template adjustment and representative sampling areas determination.

Pressure plate extractors (Soil Moisture Equipment Corp., Santa Barbara, CA) were used for AWHC determinations, as described by Dirksen (1999). The AWHC was calculated from the difference in soil moisture at field capacity (-33 kPa) and permanent wilting point (-1500 kPa). Volumetric values were calculated from the gravimetric measures using BD.

Because of the presence of carbonates, wet oxidation (Walkley-Black) was used to analyse total oxidizable C (Tiessen and Moir, 1993), from which we calculated SOC and POC, considered that contained in the fraction >53 μm (Cambardella and Elliott, 1992).

Microbial biomass C was determined by the fumigation-extraction method of Vance et al. (1987). The functional diversity of the soil microbial population was studied through the analysis of the community-level physiological profiles (CLPLs). The C source utilization patterns observed using a Biolog Ecoplate^{TM} microplating system (Biolog, Hayward, CA, USA) were used to determine functional diversity of soil microorganisms. These plates comprise 31 C substrates that are major ecologically relevant compounds. The number of substrates used by the soil microbial community (NSU) was used as soil functional biodiversity indicator.

The assessment of soil condition was done by comparing the set of soil indicators, namely BD, AWHC, MBC, NSU, SOC and POC, for irrigated management (and organic dryland in Valtierra) with the reference state, soil under conventional rainfed cropping, at each district.

Finally, soil erodibility, included in the soil capital assessment (see below), was determined by calculating the K factor of the Revised Universal Soil Loss Equation (RUSLE) model (Renard et al., 1991). This factor represents the susceptibility of soil to erosion or erodibility, and depends on inherent and dynamic soil properties (texture, organic matter, structure and permeability).

Within each district, data were analyzed using a univariate ANOVA to determine significant differences among the irrigated (and organic rainfed) systems considered in relation to reference system (rainfed wheat). Post-hoc analysis was performed using Duncan's test (P= 0.05).

Data collection for dry biomass production and GHG emissions (Soil *capital*). Soil natural capital is determined by the compositional state of the soil system, which affects the functions provided by the soil for the whole ecosystem (McBratney et al., 2014). In this work, we focused on three major ecosystem services of agricultural soils, considering the characteristics of the region: two regulating services (climate regulation and erosion control), and the most significant provisioning service in agrosystems (biomass production).

Farmers responsible for the management of the selected plots participated in a survey designed to collect all management data relative to one average season. An exhaustive database including yields and all production factors such as tillage and other operations, fertilization and irrigation doses and other inputs, was completed. From yield data in the survey, the annual production of dry biomass was calculated based on relative humidity of each product (14% for maize and 12% for wheat, barley and alfalfa).

The GHG emission rates were estimated with a software developed in the framework of a regional project for C footprint calculations in agriculture (EURENERS3, 2017). According to the requirements of PAS 2050 (2011), the calculation includes both direct (generated directly during the production process), and indirect emissions (those occurring in a different location but linked to the production process, such as the generation of electric power, production and transport of inputs or treatment of plastic waste). This tool was powered by the database of farmer surveys. Results were provided in eq Mg CO_2 ha^{-1} y^{-1} corresponding to emissions associated to soil respiration, N fertilization, tillage, crops residues burning, energy for irrigation and those associated to other inputs.

From SOC stocks data, comparing those measured in each irrigated (and organic rainfed) system with those measured in the reference system (rainfed wheat), and considering the years since the introduction of irrigation in each of the districts, an average annual sequestration rate was estimated associated to each management. The net annual emissions balance, expressed in eq Mg CO_2 ha^{-1} y^{-1}, was obtained from the difference between the annual GHG emission and this estimated annual sequestration rate previously converted to eq Mg CO_2 ha^{-1} y^{-1}.

Cost-efficiency (Soil *connectivity*). Connectivity was evaluated considering the changes in gross monetary gains associated to each agrosystem, compared to the reference conventional rainfed situation.

Financial information on the gross gains of each studied plot was obtained from the farmer survey, and completed from market prices (Gobierno de Navarra, 2017b) when not provided. This allowed for a comparison in income (gross gain) of the different management systems studied at each location, in relation to the reference state (rainfed cereal).

Previous studies on the introduction of irrigation (Dominati & Mackay, 2015) showed that the final impact on soil connectivity needs to address not only the monetary benefits of improved production, but also the evaluation of such benefits in relation to the changes observed in soil condition. Therefore, a cost-efficiency indicator was obtained by calculating the ratio between the changes observed in gross economic gain and in SOC:

$$Gross\ gain\ \left(\frac{€}{ha}\right) per \frac{Mg}{ha} of\ C\ sequestered =$$

$$\frac{\Delta gross\ gain\ (irrigated - reference)}{\Delta SOC(irrigated - reference)}$$

Where the variation of gross economic gain and of SOC are the gross economic gain and sequestered SOC for each irrigated (and organic rainfed) system compared to the reference system (conventional rainfed wheat), represented by € per unit (Mg of SOC) on a *per ha* annual basis.

RESULTS AND DISCUSSION

Condition. Irrigation is known to potentially affect soil health (e.g. Adejumobi et al., 2016), although this affection is site-and management-dependent. Among other consequences, introducing irrigation implies changes in the soil water regime, alters nutrients cycling and significantly modifies the C cycle (Apesteguía et al., 2015).

The conversion to irrigation had different consequences in these soil parameters. In general, an increase in SOC, considered a 'universal' indicator for soil condition (McBratney et al., 2014; Stockmann et al., 2013) was observed in all soil types (Figure 3). This trend was also observed, to a lesser extent, in the rainfed plot with organic amendments.

This increase may be explained by a greater productivity and crops residues incorporation into the soil (e.g. Denef et al., 2008; Gillabel et al., 2007) although the effect size may depend on climate and initial SOC content (Erb et al., 2017). In this sense, in the review of Zhou et al. (2016) based on 179 published studies, irrigation increased SOC by 1.27% on average. For these authors, this was related to an increment in aboveground and belowground net primary production of 25.5% and 31.4%, respectively. Trost et al. (2013) compiled 5 studies and reported an average net SOC gains 17.6% in irrigated land vs. rainfed in semi-arid conditions, with a high variability. Our data, with an average increase of 41%, range between 73.9% and 28.3% in annual irrigation in Valtierra and Miranda respectively, fell above those values in Valtierra and Miranda respectively, fell above those values increase of 41%, range between 73.9% and 28.3% in annual irrigation in Valtierra and Miranda respectively, fell above those values.

The site-dependency of these changes was however seen when studying POC (Figure 3), which can be considered an earlier and more sensitive indicator of changes in soil organic fraction than total soil C (Apesteguía et al., 2017; Cotrufo et al., 2019; Imaz et al., 2010). POC increased with irrigation, but not in all cases: no differences were observed in Miranda, the district with the shortest time after conversion, but also the one with the most reduced water deficit (Table 1). This site also showed losses in MBC at 15-30 cm (Figure 4), while Zhou et al. (2016) reported average gains of 42.2%. As for POC, changes in soil biodiversity (NSU) were also uneven among sites (Figure 5), with the Miranda site showing none or negative effects, and Funes and Valtierra positive effects in annual crops. Seasonal and site-dependent differences in the soil microbial community gains with irrigation were also observed by Calderón et al. (2016), when comparing two sites with different irrigation doses in the US.

Finally, in relation to the soil physical condition, we did not observe significant differences in BD at any site (Figure 6), which could be explained because all the soils studied, were under a similar soil tillage management. AWHC results were however uneven, showing better condition in irrigated land only in Miranda (Figure 7).

Overall, this results showed that soil condition was affected by the adoption of irrigation, and that this affection was site- and management-dependent.

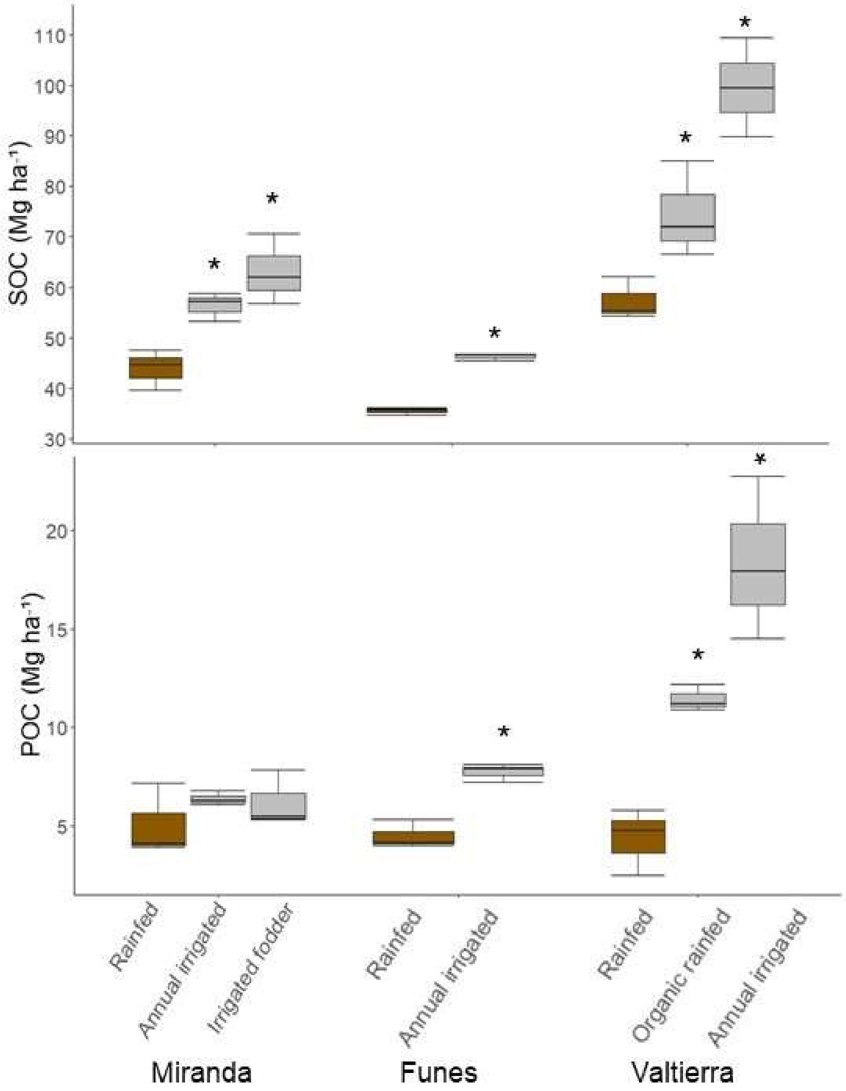

Figure 3. Total soil organic C (SOC) and particulate organic C (POC) stocks (Mg ha^{-1}) measured in the network of agricultural plots. Center lines show the medians, box limits indicate the 25th and 75th percentiles, whiskers extend 1.5 times the interquartile range from the 25th and 75th percentiles. Cases marked with an asterisk (*) show significant differences (P<0.05) in relation to the reference system within each district (rainfed, in brown) according to ANOVA.

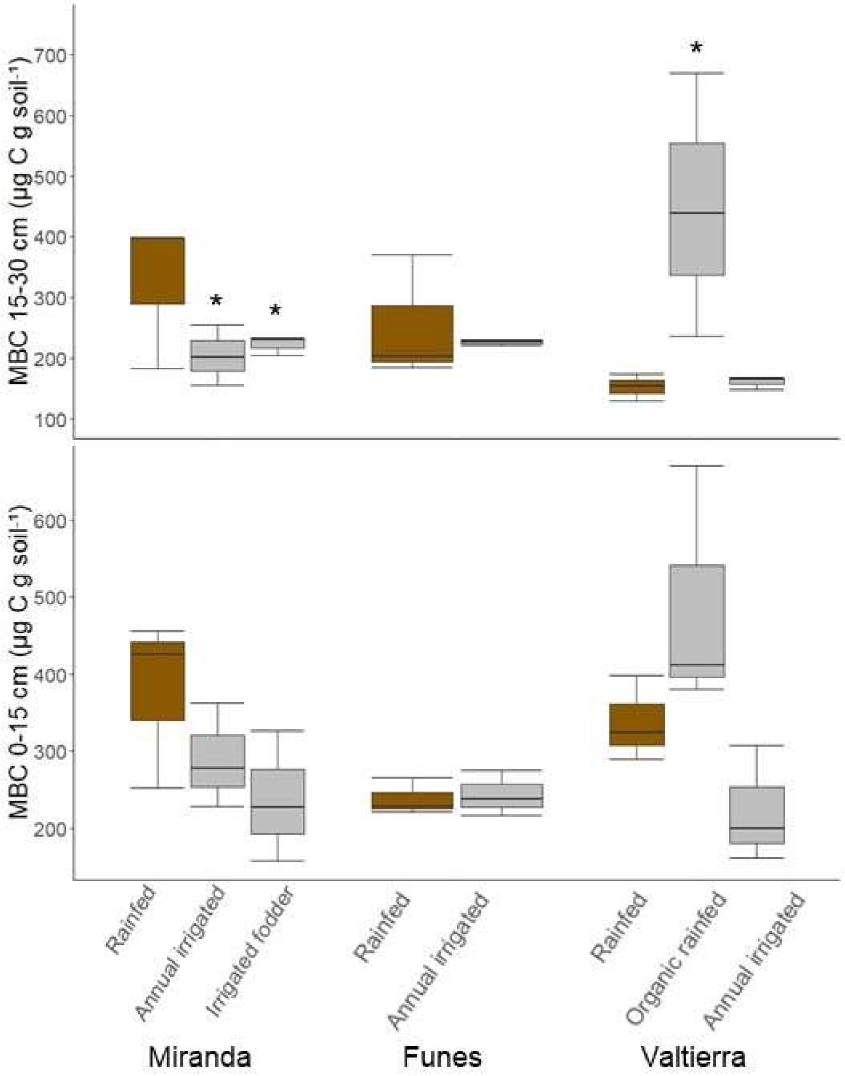

Figure 4. Microbial biomass C (MBC) measured in 0-15 cm and 15-30 cm in the network of agricultural plots. Center lines show the medians, box limits indicate the 25th and 75th percentiles, whiskers extend 1.5 times the interquartile range from the 25th and 75th percentiles. Cases marked with an asterisk (*) show significant differences ($P<0.05$) in relation to the reference system within each district (rainfed, in brown) according to ANOVA.

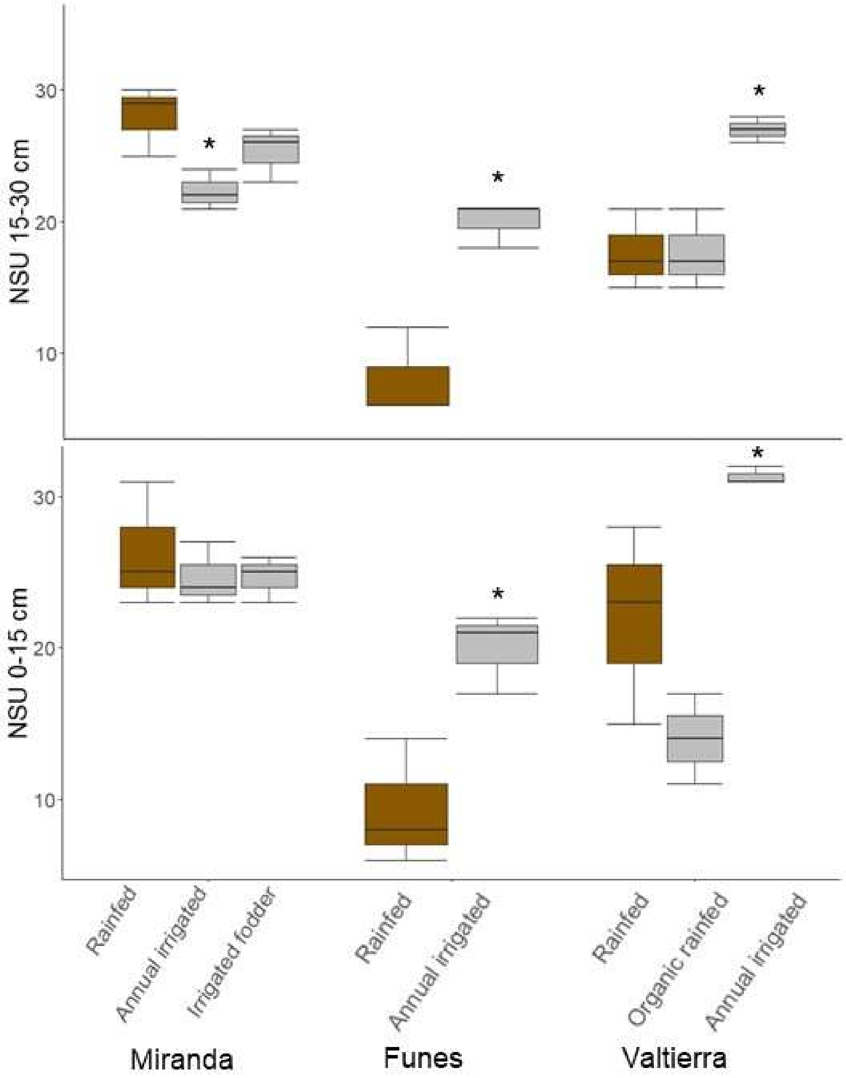

Figure 5. Number of substrates used by the soil microbial community (NSU) measured in 0-15 cm and 15-30 cm in the network of agricultural plots. Center lines show the medians, box limits indicate the 25th and 75th percentiles, whiskers extend 1.5 times the interquartile range from the 25th and 75th percentiles. Cases marked with an asterisk (*) show significant (P<0.05) differences in relation to the reference system within each district (rainfed, in brown) according to ANOVA.

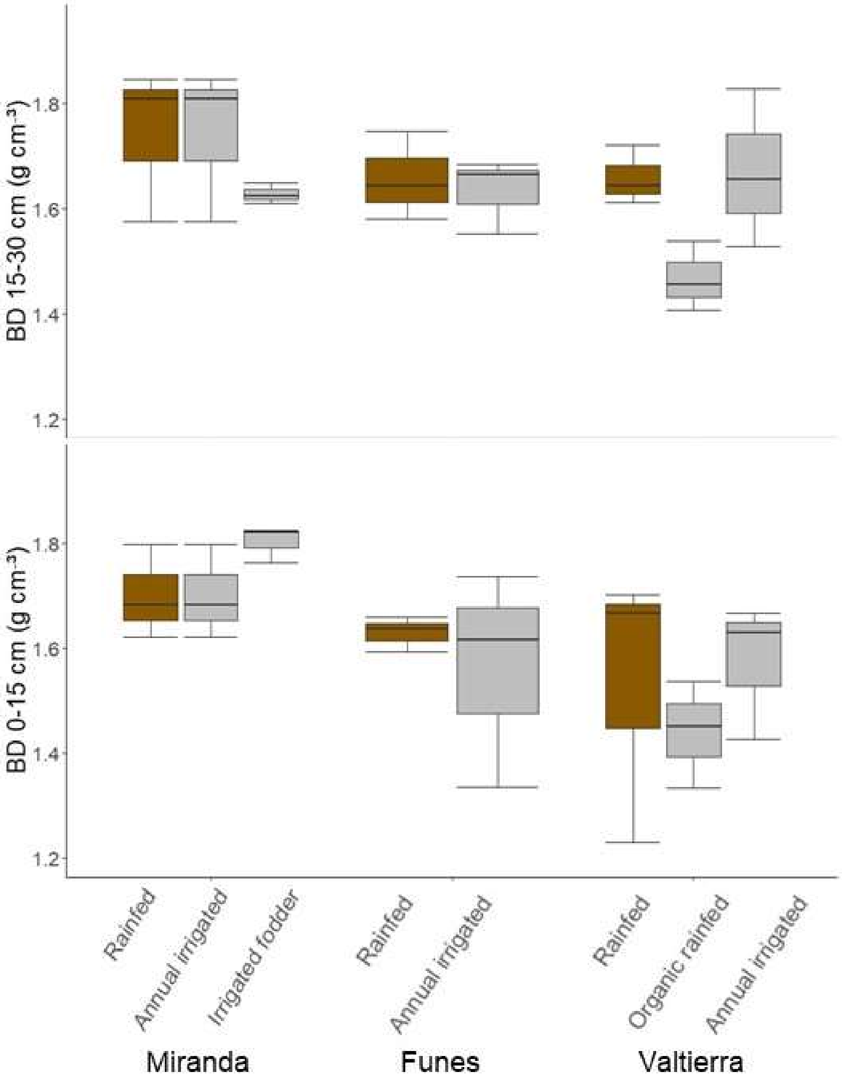

Figure 6. Bulk density (BD) measured in 0-15 cm and 15-30 cm in the network of agricultural plots. Center lines show the medians, box limits indicate the 25th and 75th percentiles, whiskers extend 1.5 times the interquartile range from the 25th and 75th percentiles. Cases marked with an asterisk (*) show significant differences ($P<0.05$) in relation to the reference system within each district (rainfed, in brown) according to ANOVA.

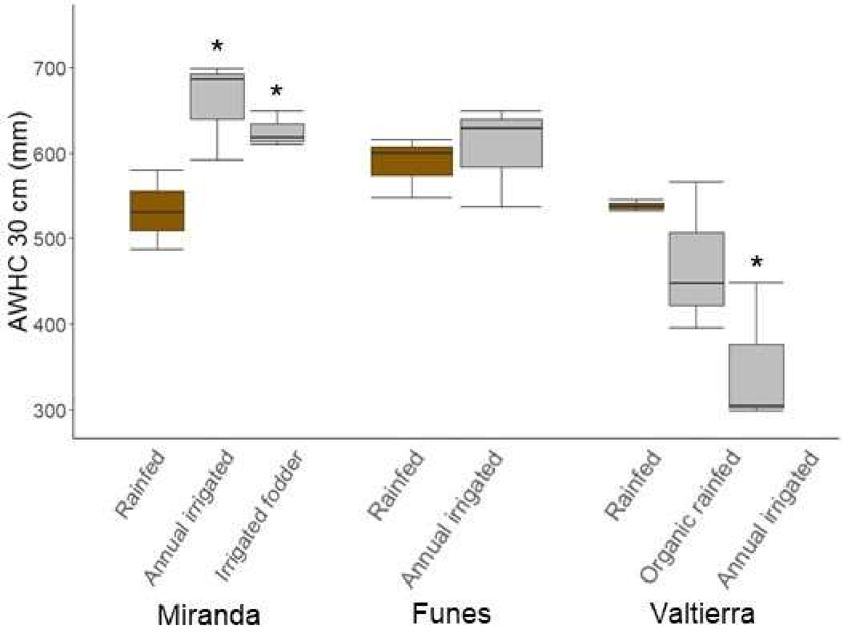

Figure 7. Soil available water holding capacity (AWHC) 30 cm measured in the network of agricultural plots. Center lines show the medians, box limits indicate the 25th and 75th percentiles, whiskers extend 1.5 times the interquartile range from the 25th and 75th percentiles. Cases marked with an asterisk (*) show significant differences (P<0.05) in relation to the reference system within each district (rainfed, in brown) according to ANOVA

Soil *Capital*. Soil natural capital is determined by the compositional state of the soil system, which affects the functions provided by the soil for the whole ecosystem (McBratney et al., 2014). In this work, we focused on three major ecosystem services of agricultural soils, considering the characteristics of the region: two regulating services (climate regulation and erosion control), and the most significant provisioning service in agrosystems (biomass production).

In relation to biomass, as expected, the conversion to irrigation implied a remarkable increase in yields and dry biomass production (Table 3). In contrast, the adoption of organic production without irrigation in Valtierra resulted in reduced yields.

Table 3. Soil capital & connectivity. K coefficient (soil erosion indicator), Biomass Production, SOC* annual gains, GHG annual emissions, monetary gross gain and cost-efficiency indicator obtained by calculating the ratio between the changes observed in gross gain and in SOC for the three irrigated districts.

Site	Management	Erodibility (*K*)	Biomass Production	SOC** gains		GHG emissions	Annual GHG balance***	Gross gain	Δ gross gain /ΔSOC
		(Kg ha h ha^{-1} $MJ^{-1}mm^{-1}$)	(kg dry matter ha^{-1})	(Mg $ha^{-1}y^{-1}$)	(Mg $eqCO_2$ ha^{-1} y^{-1})	(Mg $eqCO_2$ ha^{-1} y^{-1})	(Mg $eqCO_2$ ha^{-1} y^{-1})	(€ ha^{-1})	(€ Mg-C^{-1} ha^{-1} y^{-1})
Miranda	Rainfed (Reference)	44.9 ± 0.8	3872	-		1.24		545.4	-
	Annual irrigated	49.9 ± 0.5*	13149.4	2.07 ± 0.4	7.59 ± 1.5	4.50	-3.09	1911.5	661.0
	Irrigated fodder	57.9 ± 2.5*	11440	3.20 ± 0.8	11.73 ± 2.9	0.83	-10.9	1132.9	183.6
Funes	Rainfed (Reference)	63.3 ± 0.1	3918			0.67		376.2	-
	Annual irrigated	61.8 ± 0. 5*	11591	0.84 ± 0.3	3.08 ± 1.1	7.44	4.36	1569.0	1422.5
Valtierra	Rainfed (Reference)	52.5 ± 0.5	4840			0.67		755.0	-
	Organic dryland	49.5 ± 2.3*	290	0.86 ± 0.3	3.15 ± 1.01	0.77	-2.38	508.3	-
	Annual irrigated	44.3 ± 3.9*	11610	2.12 ± 0.3	7.77 ± 1.01	5.36	-2.41	1434.5	321.3

For erodibility (*K*), cases marked with * show significant differences ($P<0.05$) in relation to the reference system within each district (rainfed) according to ANOVA. ** Annual SOC gains shown in Mg SOC ha^{-1} per year and converted to $eqCO_2$ (Mg $eqCO_2$ ha^{-1} y^{-1}). *** Annual GHG balance: GHG annual emissions - SOC annual gains

Climate regulation can be evaluated by comparing the annual gain in SOC resulting from the change in management associated to atmospheric CO_2 sequestration, with GHG emissions generated by each agrosystem. The results indicated that irrigation increased SOC, but also GHG emissions (Table 3, Figure 8).

The average estimated annual sequestration rate associated to annual irrigation management ranged from 0.84 ± 0.3 Mg SOC ha^{-1} y^{-1} in Funes to more than 2 Mg SOC ha^{-1} y^{-1} in Miranda and Valtierra. Irrigated fodder presented the high annual sequestration rate, 3.20 ± 0.8 Mg SOC ha^{-1} y^{-1}. For comparison, average SOC gains following NT adoption in Spain were set at 0.72 ± 0.16 Mg SOC ha^{-1} per year by (González-Sánchez et al., 2012), suggesting that irrigation adoption is a more efficient strategy in this sense.

Related to GHG emissions, previous studies (Erb et al., 2017) have already pointed out that irrigation can induce greater GHG emissions than rainfed agriculture because it affects soil moisture, temperature and N availability, which are all drivers for the production and evolution of GHG emissions from soils. Sanz-Cobena et al. (2017) explored the different strategies for GHG emissions mitigation in Mediterranean agriculture, and remarked that irrigated systems create favorable soil conditions for N_2O production. Although in this study, GHG emissions were estimated from surveyed data associated to different inputs and soil management system, and not from actual soil measurements, emissions associated to soil and to fertilization represented the most important emission source on our study plots (Figure 8), and were similar to those measured fluxes associated to soil in other studies for annual irrigated maize (Álvaro-Fuentes et al., 2016; Franco-Luesma et al., 2019; Maris et al., 2018). Because emission factors in these systems fluctuate greatly according to water management and the type and amount of fertilizer used, water management practices and the adjustment of N fertilization seem the most promising practices for mitigation (Karimi et al., 2012; Maris et al., 2018; Patle et al., 2016; Zornoza et al., 2016).

From the difference between annual SOC gains and the annual GHG emissions, the net annual GHG emissions balance for the periods considered in each irrigation districts (6, 13 and 20 for Mianda, Funes and Valtierra, respectively) associated to each system evaluated could be completed. The average value of the systems with annual irrigation evaluated presented a slightly negative value (-0.83) and two of them (Miranda and Valtierra) presented a clearly negative emissions balance, performing as C sinks. Irrigated fodder in Miranda showed the clearest result, with a net sequestration potential of more than 10 Mg of SOC per ha and year in the 6 years since the conversion to irrigation. Other studies provided evidence that adequate management of both tillage and the application of fertilizers can keep low net GHG emissions from agricultural systems, and redirect the balance towards C sink agrosystems (Adviento-Borbe et al., 2007; Ghimire et al., 2017; Mosier et al., 2006, 2005; Sainju et al., 2014).

In this respect, it remains to be observed if C accumulation rates decrease over time in the irrigated systems, as concluded by Mosier et al. (2005). As explained by Chenu et al. (2019), the carbon storage potential of a soil could be limited, and is determined by climate, soil type and timeline. Therefore, the potential of these soils to sequester C may be limited, although the estimated annual sequestration rates in the districts did not seem to show differences associated with the time since transformation to irrigation of each of them (Miranda 6, Funes 13 and Valtierra 20 years). Finally, if a possible mitigating effect is considered, it should be noted that, in addition to not being unlimited, the storage process is irreversible, so that the C accumulated over the years in the soil can be re-emitted when both management or climate changes (Chenu et al., 2019; Follett, 2001).

Soil erosion is a key indicator in the assessment of ecosystem services provision in irrigated land (Herzig et al., 2016). The K coefficient in the RUSLE equation is usually reduced with SOC gains. However, as its calculation also depends on soil texture and structure, some interference with these factors made that the observed gains in SOC were translated in reduced erodibility only in Valtierra. It has to be added that irrigation changes also at least the R (rainfall erosivity) and C (crop cover) factors in the equation, so that the final effect on erosion should also consider these changes.

All in all, these results showed that irrigation adoption can alter also the soil capital and its capacity to provide key ecosystem services beyond biomass production, as observed by (Dominati et al., 2016). The net effect will depend on multiple factors, including soil management strategies. The optimization of the soil capital will therefore depend on the optimization of these parameters.

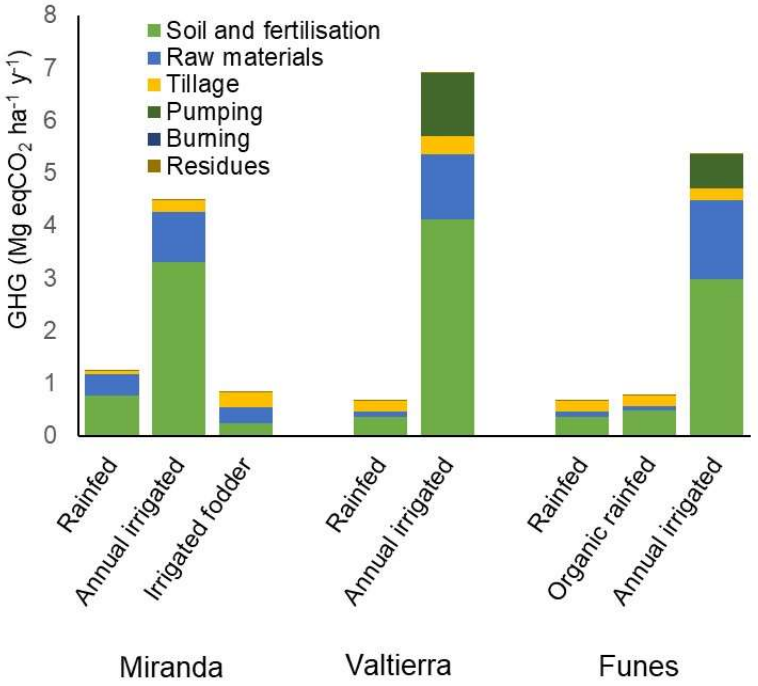

Figure 8. Annual GHG emissions associated to each system considered in the study.

Soil *Connectivity*. Connectivity was evaluated considering the changes in gross monetary gains of each agrosystem, as it represented the major driver for decisions related to soil management in the context of this study. While the transformation to organic management resulted in net losses, very likely due to the reduction in yields, irrigation represented a net increment of income in all the studied sites (Table 3).

When this gain was compared to SOC gains, it was observed that there was not a direct correlation between management strategies resulting in SOC gains and economic gains (for instance, irrigated fodder vs. annual irrigated in Miranda). This means that higher absolute and relative income increase (which represent the best option for farmers) did not correspond to higher SOC gains. Similarly, in Valtierra, organic farming, which represented the lowest increase in GHG emissions in comparison to reference state, displayed negative gross gains. These two cases are an example of how economic and environmental drivers of farmers decisions can induce different results in soil security. Soil codification through regulation can be important in this sense if win-win strategies, implying gains in income and ecosystem services, are to be implemented. Policies encouraging the adoption of managements increasing soil capital and condition should consider the need for financial compensation if this is the major driver for decision makers in relation to soil management.

Another observation is that values for the same soil use (annual irrigated) were different for different sites and time under irrigation, because SOC gains were site- and time-dependent (Table 3) for similar biomass productions. The evaluation of soil connectivity should therefore account for these conditions.

CONCLUSIONS

This work showed that the major changes in management occurring when rainfed agricultural soils are converted to irrigation can induce significant changes in soil condition, capital and connectivity, and therefore in the soils functionality (McBratney et al., 2014) and their ability to provide adequate ecosystem services.

The most evident change in soil condition were net gains in SOC. Given that SOC may play a role in mitigating GHG emissions and in delivering major soil ecosystem services and functions (Ogle and Paustian, 2005), policymakers are increasingly focusing their attention on measures for SOC conservation. However, this study shows that other changes in the capacity of soils to provide ecosystem services need to be accounted for when a holistic evaluation of the consequences of irrigation adoption are to be assessed at a regional scale, especially from the perspective of optimizing soil security in all its dimensions. On the other hand, other management strategies, such as organic agriculture, can have similar consequences in soil condition and capital, but worse performances in terms of biomass production and profitability. Soil codification, as represented by regulations affecting the decisions of soil managers, seems an interesting tool to ensure soil security in this and other semi-arid regions where irrigating is being expanded.

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Chapter V

Soil organic C monitoring for the assessment of a regional-scale strategy for climate change adaptation of agriculture in Navarre, Spain.

“Al despojar el ambiente

del carbónico homicida

llevo engastado en mis hojas

el talismán de tu vida.”

Daniel Nagore Nagore
Plegarias del árbol. Enseñanza ambulante.
Diputación Foral y Provincial de Navarra. Dirección de Agricultura y Ganadería. Editorial Aramburu. Pamplona 1939

CHAPTER V

Soil organic C monitoring to assess agricultural climate change adaptation practices in Navarre, Spain

ABSTRACT

Climate change adaptation strategies are needed for agriculture, one of the most vulnerable human activities. In Navarre, North of Spain, ongoing adaptive management practices were identified and promoted in the framework of a regional adaptation strategy. Most include practices aiming to increase topsoil organic carbon (SOC) in agricultural land. In this work, the effectiveness of these practices (conservation agriculture, crop rotations, additions of organic matter, irrigation and controlled grazing management) was assessed by means of monitoring SOC in a network of 159 agricultural fields across the region. These fields were selected across bioclimatic zones, where soil vulnerabilities and land-uses were previously assessed, to represent the most widespread conditions in the region. A sampling protocol designed to compare SOC stocks in plots with equal soil conditions within each zone, and with or without adaptive practices, allowed to determine their effect size (measured as response ratios, RR). Exogenous organic matter addition was the most effective practice for SOC storage (RR 95% confidence interval (CI) [1.25-1.37]) across the region. Controlled grazing also resulted in net SOC gains (RR CI [1.13-1.42]) in temperate and semi-arid grasslands. Conservation agriculture seemed to be more effective in the driest zone (RR CI [1.30-1.53]) than in the more humid ones (RR CI [0.98-1.21]). Irrigation also displayed a net positive effect (RR CI [1.17-1.34]), modulated by irrigated crops management, whereas crop rotations had an overall negative impact vs. monoculture (RR CI [0.84-0.96]), likely by their interaction with irrigation. These results confirm the variability in SOC responses to changes in management, and SOC as an indicator for assessing regional adaptation practices, although other biophysical, agronomic and socio-economic factors also need to be accounted for.

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INTRODUCTION

Soil appears as a key element in global change. Soils play a crucial role in the biogeochemical cycles of carbon (C) and nitrogen (N), and in particular, in the exchange of these elements between the atmosphere and terrestrial ecosystems (Lal, 2020). Soil is of special interest because of its role as a sink of atmospheric C, and therefore in climate change mitigation. The interference of agricultural management in this process has merited attention in policies and mitigation guidelines since long ago (IPCC, 2006). In this regard, initiatives such as the well-known "4per1000" (Minasny et al., 2017; Rumpel et al., 2020), use this potential as a basis for promoting management strategies that contribute to an increase in soil organic C (SOC) stocks in agricultural land.

In addition, SOC dynamics has also a role in climate change adaptation (IPCC, 2014; Jia et al., 2019), as it is related to soil properties and functions that can reduce the vulnerability of agrosystems to changes in climate, such as water retention, resistance to erosion, or high fertility (Adhikari and Hartemink, 2016; FAO, 2017).

Because the agricultural sector is particularly vulnerable (Iglesias et al., 2012), there is growing interest in studying different adaptation strategies in this sector (FAO, 2018; IPCC, 2014). The most recent IPCC report on mitigation and adaptation strategies related to land-use and land-use changes (Jia et al., 2019; Olsson and Barbosa, 2020), indicates that increasing SOC should be considered a tool to improve the resilience of agrosystems, and to maintain the ecosystem services provided by soils. According to IPCC, the most relevant management practices affecting SOC stocks in croplands are the management of crop residues, tillage and fertilization (both mineral and organic) and irrigation, the choice of crops and the intensity of cropping management, including mixed systems with crops and pasture (Lasco et al., 2006).

Despite this growing interest, most reports recognize that there are still significant sources of uncertainty about the consequences and efficiency of SOC storage strategies (Jia and Shevliakova, 2019).

Uncertainties are associated to the high variability observed in SOC responses to the different strategies, and to gaps in our understanding about the relationship between agricultural management and the accumulation of organic matter in soils (Chenu et al. 2019).

In general, the possibility of increasing SOC through agricultural management is related to its capacity to modify the inputs of organic materials into the soil, and/or the sensitivity of organic matter to mineralization (Dignac et al., 2017). The final effect is dependent on time and local conditions. For instance, some meta-analysis and long-term studies have shown that the effect of tillage suppression on SOC can be dependent on the actual change induced by this practice on crop yields, and therefore C inputs to the soil from crop residues (Mary et al., 2020; Virto et al., 2012) , and on climate conditions (Dimassi et al., 2014), which can be inter-related. Net SOC gains following manure applications have also been seen as likely dependent on climate (Maillard and Angers, 2014). Another major variable in this sense is soil type. Although the role of soil mineralogy in SOC protection is increasingly acknowledged (Barré et al., 2014; Fernandez-Ugalde et al., 2016; Rowley et al., 2018), and it has been seen to be relevant at regional (Wiesmeier et al. 2013, 2020; Gartzia-Bengoetxea et al. 2020) and national scales (Chen et al., 2019), few studies account for this variable when assessing SOC strategies (Jia and Shevliakova, 2019). Francaviglia et al. (2019) recently revised SOC storage rates under different managements in field experiments with Mediterranean climate, and found that results were influenced, among other factors, by the initial SOC content, soil texture, and climate regime. In this sense, it is considered good practice (Aalde et al., 2006) to run stratified analysis for climate zones and soil types when assessing changes in SOC stocks with management in croplands (Lasco et al., 2006).

Furthermore, there are still technical limitations for the systematic assessment of SOC changes at the regional scale, such as the high spatial variability or the small annual SOC response to management in comparison to background levels (Paustian et al., 2019). Up-scaling from laboratory or experimental field studies to landscape or regional-level evaluations is a major challenge in this sense (Chenu et al., 2019;

Dignac et al., 2017; FAO, 2013; Paustian et al., 2016). For instance, a study conducted to assess SOC changes with cropland management in Mediterranean conditions observed greater SOC gains in experimental fields than commercial farms (Aguilera et al., 2013). Reducing uncertainty in the evaluation of agricultural management practices for climate change adaptation needs therefore to move towards strategies that consider local and regional characteristics (Chen et al., 2019; Jia and Shevliakova, 2019), and take these limitations into account. Adequate sampling designs, including geo-referenced sampling networks, are crucial for adequate regional-scale comparisons in time and space (Smith et al., 2019; Tugel et al., 2008).

In this process, it is important to consider that increasing SOC through agricultural management has not only agronomic and environmental consequences, but also sociological, economic and ethical dimensions (Chenu et al., 2019). Collaboration with land users and the experience of extension agents are major tools for a comprehensive assessment of these practices at the regional scale (Altieri et al., 2015; Demenois et al., 2020; Karlen et al., 2014). In particular, studying the efficiency of those strategies which are already common practice in a region can help to overcome the general problem of implementing new strategies that farmers would be reluctant to adopt (Rumpel et al., 2020).

Within the framework of a regional-scale project (Nadapta) launched in 2017 in the region of Navarra (North of Spain), a vulnerability study of agricultural soils to projected regional climate change was developed. For that, various adaptive management strategies, already implemented by farmers in the region and included in the regional roadmap for climate change adaptation were considered (Gobierno de Navarra, 2017).

The main objective of this work was to carry out a quantitative assessment of the effectiveness of these adaptive agricultural practices to achieve an increase in SOC storage at the scale of the region of Navarre. For this purpose, a first objective was to define the baseline of SOC storage under conventional management conditions in zones of the territory with homogeneous conditions for plant growth. Then, we aimed at studying the effect of the most relevant adaptive agricultural practices promoted in the regional roadmap on topsoil SOC storage, in a selection of representative agricultural fields in each homogeneous zone.

MATERIAL AND METHODS

Study area. The region of Navarre, North of Spain (Figure 1), has a high climatic variability created by the distance to the sea and differences in altitude (from 2434 m.a.s.l. in the Pyrenees to 18 m.a.s.l. at the lowest point).The most significant natural division derives from the gradient in rainfall and evapotranspiration between the North and the South. Annual precipitation ranges between >2500 mm in the North and <350 mm in the South-East (Pejenaute Goñi, 2017). Mean annual temperatures vary from 14.5 ºC (Buñuel, 41º58’47”N; 1º26’38”W) to 9.3 ºC (Irabia, 42°59'07"N; 1°09'28"W) (Gobierno de Navarra, 2020). The territory is thus divided into two major biogeographical regions, the Eurosiberian and the Mediterranean (Peralta et al., 2013) (Figure 1). Limestone massifs in the North and Center of the region, and carbonaceous materials of sedimentary origin in the South, are the most relevant lithologies, as they explain topography soil formation.

Due to this heterogeneity in terms of climate, topography and geology, the conditions for the development of plants, and therefore agriculture, differ considerably within the region. At present, 39% of the total area is used as agricultural land (90.7% cropland and 9.3% grassland).

Zoning and zone characterization. In a first step, a study of climate and soil characteristics in zones with homogeneous conditions for plant growth was conducted. To this end, the biogeographic units defined in the region (Peralta et al., 2013) were further divided using information on vegetation series for the identification of ecologically homogeneous territories (Rivas-Martinez, 2005). Biogeographical, climate and soil characteristics were obtained from the available cartographic information (IDENA, 2020), and a new analysis of the regional soil map 1:50,000 (Iñiguez 1982-1992). This allowed for the determination of the

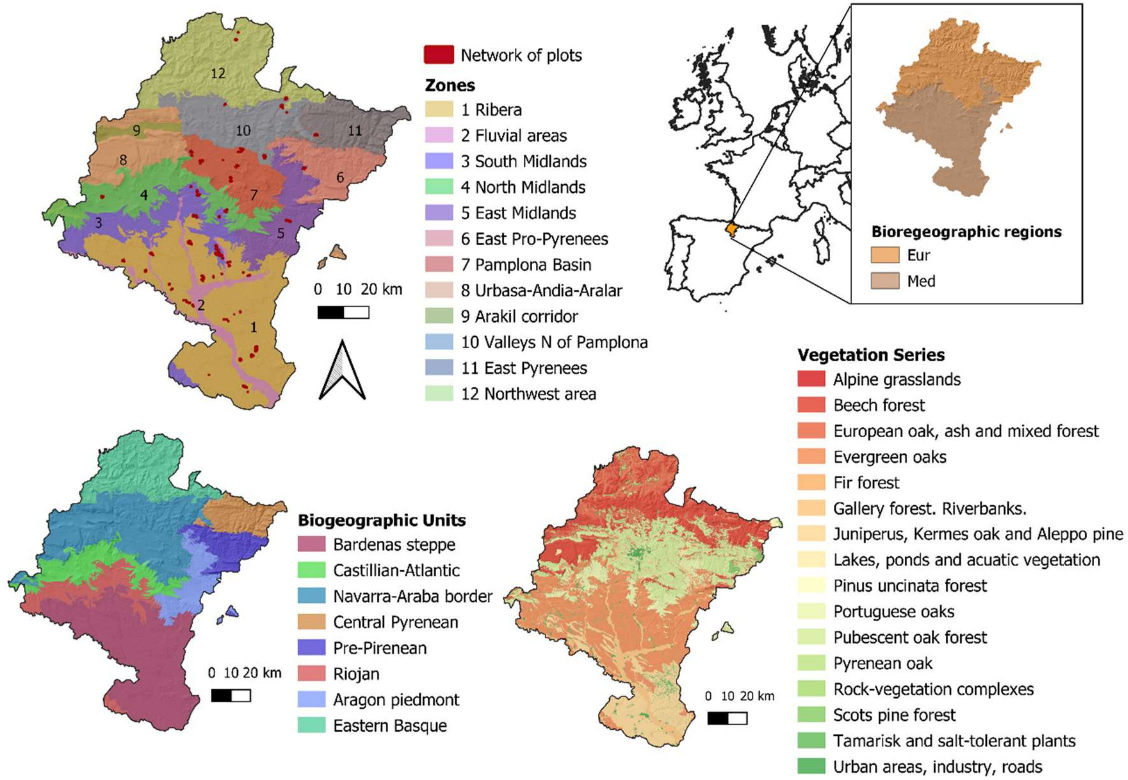

Figure 1. Homogeneous zones and network of plot defined for this study (top left), location of the region of Navarre and biogeographical regions (top right), vegetation series (bottom right) as in Peralta et al. (2013) and biogeographical units (bottom left).

most limiting soil vulnerability traits in each zone. Twelve homogeneous zones were defined (Figure 1). Their climate and soil characteristics appear in Table 1. Information on soil types (Soil Survey Staff, 2014) and vulnerability traits can be found as Supplementary material (Supplementary material 1). The most relevant ones were stoniness and limited depth. In the North of the region, acidity and slope were also relevant. In the Central and South zones, low organic matter content, carbonates concentration, water deficit, and, in some cases, salinity were also identified. Papadakis (1952) climate types, corresponded to the regional gradient, from the driest and warmest conditions in the South (zones 1, 2 and 3), to moist temperate conditions in the Central part of the region (zones 4, 5 and 7) and fresher and moister conditions corresponding to maritime climates in zones 8 to 12, with some Mediterranean traits in zones 8, 9 and 10.

Inceptisols and Entisols are widely distributed throughout the region. Those in the Central and South areas (zones 1, 2, 3, 4, 5 and 7) have a *xeric* soil moisture regime. Aridisols appear in zone 1, corresponding to the *aridic* moisture regime. In the Central-Western and North zones (8, 9, 10, 11 and 12), the *udic* soil moisture regime dominates. Entisols with fluventic characteristics are widespread, corresponding to the hydrological network of the region. Entisols and Inceptisols are dominant in mountain areas with frequent high slopes (zones 6, 8, 11 and 12). Some Mediterranean red soils (*Palexeralfs*) exist on relatively old river terraces, especially in zones 4 and 5. Other Alfisols with moister soil water regime conditions, as well and Ultisols, dominate in the more humid zones 10 and 12.

The distribution of the most widespread land uses for the 12 zones varied greatly (Table 1), from zones with very little agricultural use, such as zones 6 and 8 to zones 1, 2 and 3, with more of 65% of their surface used for agriculture. In terms of the type of agricultural uses, zones 1, 2 and 3 represented 94% of the region's irrigated area, with the maximum in zone 1 (60% of the total irrigated area in the region).

Table 1. Land-use, management strategies, number of groups and plots and major soil groups. Managements are conservation agriculture (CA), addition of exogenous sources of organic C (ExO), rotations (ROT), irrigation (IRR), and controlled grazing and/or rotation in grasslands (GSS).

Zone	Land-use		Management strategies and plots			Soil groups
	Total area (ha)	Agricultural use (%)	Strategies	Groups	Plots	(S.S.S., 2010)
1. Ribera	254 140	66.7	CA	5	12	Fluventic Inceptisols and Entisols, Orthents, Xerepts, Xerolls, Ustolls, Calcids, Gypsids
			ExO	8	26	
			ROT	3	13	
			IRR	4	16	
			GSS	2	6	
2. Fluvial areas	39 625	81,9	-	-	-	Inceptisols and Entisols
3. South Midlands	79 700	67.7	CA	3	9	Fluventic inceptisols and entisols, Other Xerepts, Xerepts with depth limitations, Ustolls
			ExO	4	13	
			ROT	4	12	
4. North Midlands	95 679	39.3	ExO	1	4	Xerepts with depth limitations, Other Xerepts
			IRR	2	4	
5. East Midlands	64 764	40.1	ExO	1	4	Orthents, Xerepts with depth limitations
			GSS	1	5	
6. East Pre-Pyrenees	56 949	3,4	-	-	-	Entisols

7. Pamplona Basin	67 857	46.5	CA	2	6	Xerepts, Orthents, Fluventic inceptisols and entisols
			ExO	2	7	
			ROT	2	6	
8. Urbasa-Andia-Aralar	69 165	7,5	-	-	-	Inceptisols, Entisols, Spodosols
9. Arakil corridor	13 457	42,8	-	-	-	Inceptisols and Entisols
10. Valleys N of Pamplona	87 669	21.4	GSS	3	8	Orthents, Udepts
11. East Pyrenees	63 016	7.2	GSS	1	5	Orthent, Fluventic Udepts
12. Northwest area	144 324	9,8	-	-	-	Alfisols, Ultisols

Selection of soil management strategies and network of plots. The agricultural managements considered were those included in the regional roadmap for climate change adaptation (Gobierno de Navarra, 2017), and most commonly found in the region. They were conservation agriculture (CA), management of exogenous sources of organic C (ExO), and rotations (ROT), as cropping strategies in cultivated plots. Other managements of regional interest, i.e. the implementation of irrigation (IRR), and optimized grasslands management (GSS), were also included. CA included no-till in cultivated plots and permanent grass cover in permanent woody crops. ExO included the regular addition of different sources of organic matter at agronomic doses, ROT included different crops in the regular sequence of cultivation, either on annual basis in rainfed systems, or with several crops per year in irrigated land. IRR was tested in plots under sprinkler irrigation, and GSS included mostly controlled grazing strategies, and in some cases, in combination with lay or lay/crops rotations.

The establishment of a network of agricultural plots representative of these systems was carried out in a procedure that involved extension agents, farmers and researchers (Tugel et al. 2008). First, the most common land uses were identified within those zones representing the highest proportion of agricultural land (1, 3, 4, 5, 7, 10, and 11; Figure 1). Then, extension agents and farmers identified, in each zone, plots where at least one of the adaptive managements had been applied for at least 5 years consecutively. Contiguous or close plots with the same crop or type of crop and under conventional management were identified. This enabled the selection of groups of plots with the highest possible physical proximity and contrasting managements, and on the main soil types in each zone, with at least one plot corresponding to the reference adaptive management, and the rest under conventional management. The conventional management implied mineral fertilization in the case of ExO, non-irrigated plots in IRR, annual monoculture for the ROT strategy, and regular mowing and/or no rotation in the case of GSS. In the case of CA, conventional management implied inversion tillage in non-permanent crops, and frequent tillage to keep the soil free of vegetation in the rows of woody crops, where permanent grass cover was considered. The number of groups of plots per zone was determined considering the extension of agricultural land, and the diversity of strategies adopted, in each zone. The number of plots selected, and the management strategies tested in each zone, are listed in Table 1. Overall, the network comprised 157 agricultural plots, grouped in 48 groups. The description of each group, including soil types, number of plots, strategies tested and, in the case of groups considered within the ExO strategy, the source of the organic input applied, is provided as Supplementary Material (Supplementary material 2). The soil types corresponding to each zone (Table 1) and tested group (Supplementary material 2) were defined at the Great Group level in Soil Taxonomy (Soil Survey Staff, 2014), and in some cases attending to special characteristics within each group, such as fluventic traits in Inceptisols and Entisols, or depth limitations.

Soil sampling design and analysis. In the next phase, a sampling strategy was developed to ensure that only areas differing in management, but with homogeneous soil conditions, were compared within groups. That for, in each plot a sampling area was determined so that sampled areas in each group of plots corresponded to the same soil unit for all plots within the group, following the methodology described in Chapter IV (Antón et al. 2019). The delimitation of these homogeneous soil zones was carried out on the basis of the highest available detail (soil series or phase). The regional soil map at 1:25,000 was used in the areas where it was available (~40% of the territory and ~70% of cultivated land). Where this was not the case, the delimitation was made from soil information available at 1:50,000, geological information and photo-interpretation. In all cases, the process was completed with a field visit, and with extra soil profiles description when necessary. Attention was paid to generate zones that were as homogeneous as possible, considering in addition to soil criteria, others such as slope or orientation (Tugel et al., 2008; Wiesmeier et al., 2013).

For each sampling area, a sampling design was adapted following the one described by Stolbovoy et al. (2007) for comparing SOC stocks changes in croplands. A randomized template was used to define at least three representative sampling squares per sampling zone (i.e.

areas with the same type of soil in each plot of the group). The sampling template was suited to the boundaries of each sampling area, so that the size of the squares was always proportional to, and dependent on, the size of the sampling area defined per plot. Based on a 25-point grid defined within each of the squares, a disturbed composite sample of 25 sub-samples was collected at 0-20 cm, the most common tillage depth in the region (Lasco et al., 2006). A 100-cm^3 undisturbed core was collected at the center of each area to determine bulk density at 0-20 cm. This sampling design grants random and representative topsoil sampling. All the processing of cartographic information was performed with ArcGIS 10.6 (Redlands, CA: Environmental Systems Research Institute, Inc., 2018).

Disturbed samples were air-dried, thoroughfully mixed and sieved at 2 mm. Because of the elevated inorganic C content in many samples, organic C was analyzed by wet oxidation (Tiessen and Moir, 1993). The stock of SOC for each group of plots was calculated from SOC concentration, bulk density, coarse fragment content and depth, for an equivalent soil mass to that of the sample point with the lowest bulk density in each group (Ellert and Bettany, 1995; Meurer et al., 2018; Poeplau and Don, 2013; Smith et al., 2019).

Soil organic carbon storage assessment and statistics. Data on SOC stocks were first used to make a comparison at the regional level in the different zones identified, and at a local level in each zone, between different soil typologies. Data are provided as means ± standard deviation, and ANOVA was performed to assess differences between groups based on a probability level of $p < 0.05$.

The study of the effect of each strategy considered on SOC storage was performed for each group of plots according to the natural logarithm of the response ratio (RR), understood as the ratio in SOC between the plots with adaptive management, and those under conventional management within each group:

$$LRR = \ln(\mathrm{RR}) = \ln(\frac{\bar{X}_R}{\bar{X}_C}) \qquad \text{Equation 1}$$

where $\bar{X}_R$ and $\bar{X}_C$ are the mean values in the reference plots with adaptive management, and those under conventional management within each group, respectively. This represents a practical way to quantify and summarize the magnitude and direction of the results, allowing to linearize and normalize the sampling distribution (Hedges et al., 1999). The variance of the LRR for each group was calculated following these authors as:

$$var(LRR) = \frac{(SD_R)^2}{n_R \bar{X}_R^2} + \frac{(SD_C)^2}{n_C \bar{X}_C^2} \qquad \text{Equation 2}$$

where *SD* and *n* indicate the standard deviations and the sample size of the reference and conventional plots within each group of plots.

Following the approach commonly applied in meta-analyses comparing results on the same parameters but from different study areas, the overall effects of each strategy were analyzed with an unweighted fixed effects (FE) model. This was done at two different scales: first, in the zones including more than one group of plots, allowing to estimate an overall effect in those zones, and second, at the regional scale, providing an overall effect in the region. This model assumes that the only source of variability in the analysis is that associated to the sampling process within each group, calculated according to Equation 2 (Hedges et al., 1999). The unweighted analysis assigns the same weight to each group, avoiding the underestimation of the LRR due to differences in sample sizes.

The LRRs for different strategies at group, zone and regional levels were represented in forest graphs, transformed into RR for simplification. The effect was considered significant when the 95% confidence interval (CI) of the RR did not overlap one (α = 0.05) (Hedges et al., 1999). All statistical analyses were carried out with R (R Core Team; 2019). Calculations and model performance for RR analysis were carried out using the *metafor* package (Viechtbauer, 2010).

RESULTS

Soil organic carbon storage per agricultural zone and soil type. Figure 2 shows SOC stocks stratified to bioclimatic zones, for plots under conventional management, which can be considered the baseline for agricultural soils in the region. Average values ranged from less than 15 Mg SOC ha^{-1} at some points in zone 1, to more than 100 Mg SOC ha^{-1} in zone 10, for the studied depth (0-20 cm).

Among the zones selected for this study, SOC stocks in zones 10 and 11 were significantly higher than in zones 1, 3, 5 and 7 (with no differences between them). Zone 4 had an average stock similar to that in zone 11, but the highest variability by far.

SOC stocks for different soil types within each zone showed differences only in zones 1 and 4. In zone 1, Xerolls displayed the highest observed values, while Gypsids and Fluventic Entisols and Inceptisols the lowest ones. In zone 4, plots on Calcixerepts with a petrocalcic horizon at depth (denoted as Xerepts with depth limitations), had much higher mean values and variability than those on other types of Xerepts.

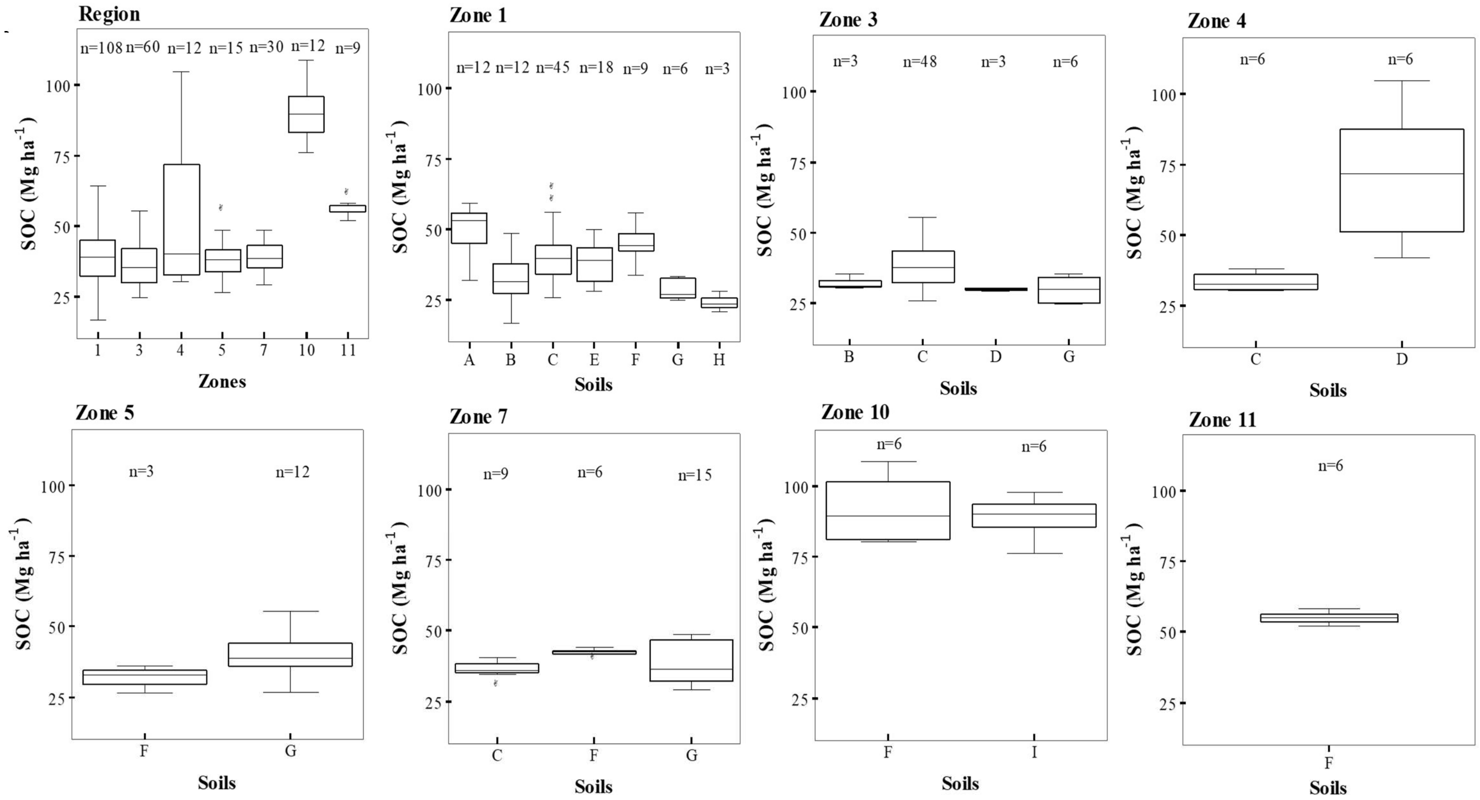

Figure 2. Soil organic carbon (SOC) stocks in conventionally managed topsoils (0-20 cm) in the region and in the zones selected for this study, for the different type of soils in each zone. A: Xerolls, B: Ustolls, C: Xerepts, D: Xerepts with depth limitations, E: Calcids, F: Orthents, G: Fluventic Inceptisols and Entisols; H: Gypsids; I: Udepts (Soil Survey Staff, 2014).

Effect of management on soil organic carbon stocks. The results of the strategies effect on SOC storage are shown in Figure 3 and 4 as RR for each group of plots, together with the overall effect per zone, and in the whole region. Across the region, CA, ExO, IRR and GSS had a net positive effect, and a negative effect was observed for ROT.

The RR for each individual strategy was different among zones and groups of plots. Variability within each group was rather heterogeneous. For CA, 4 out of the 10 groups of plots tested displayed a net positive effect, and only one (in zone 3) had a net negative effect. The effect was overall positive in zone 1, and nill in zones 3 and 7. ExO resulted in net SOC gains in 9 out of 16 groups tested, with only one (in zone 1) displaying net SOC losses. Only zone 4 showed no overall positive zonal values. IRR had a positive effect in 4 out of the 6 groups tested, with a greater response in zone 1 than zone in zone 4. ROT showed a positive effect in one group (in zone 7) of the 9 tested, and no effect on 6 of them. The net effect was negative in zone 3, and nill in zones 1 and 7. Finally, improved grassland management with GSS had a significant positive effect in 4 out of 7 groups of plots, spread across 4 zones (1, 5, 10, and 11).

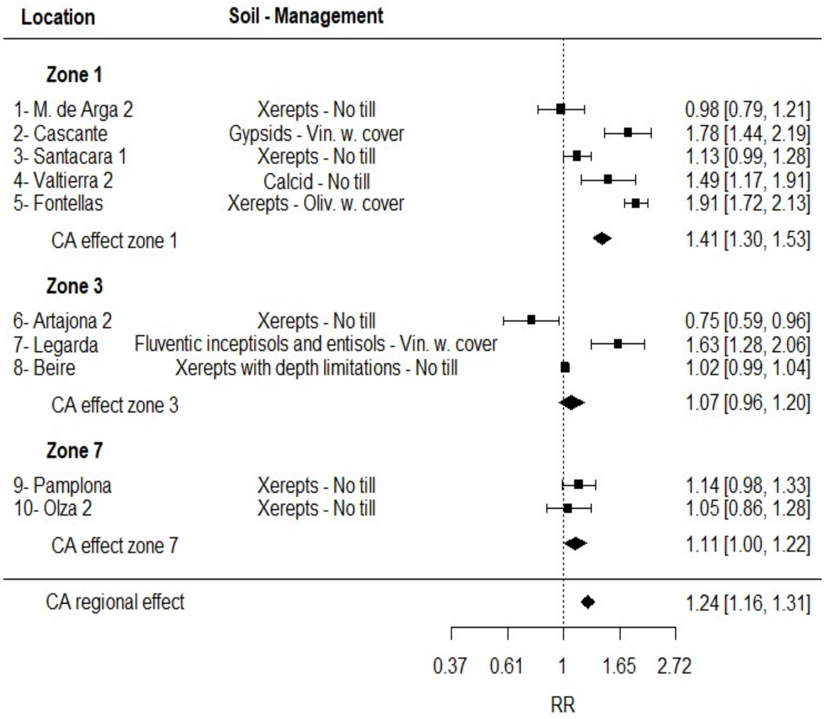

Figure 4. Response ratio (RR) of soil organic carbon (SOC) stocks (0-20 cm) for conservation agriculture (CA). Zones correspond to those in Figure 1. The effect was considered significant when the 95% confidence interval (CI) of the RR did not overlap one (α = 0.05)

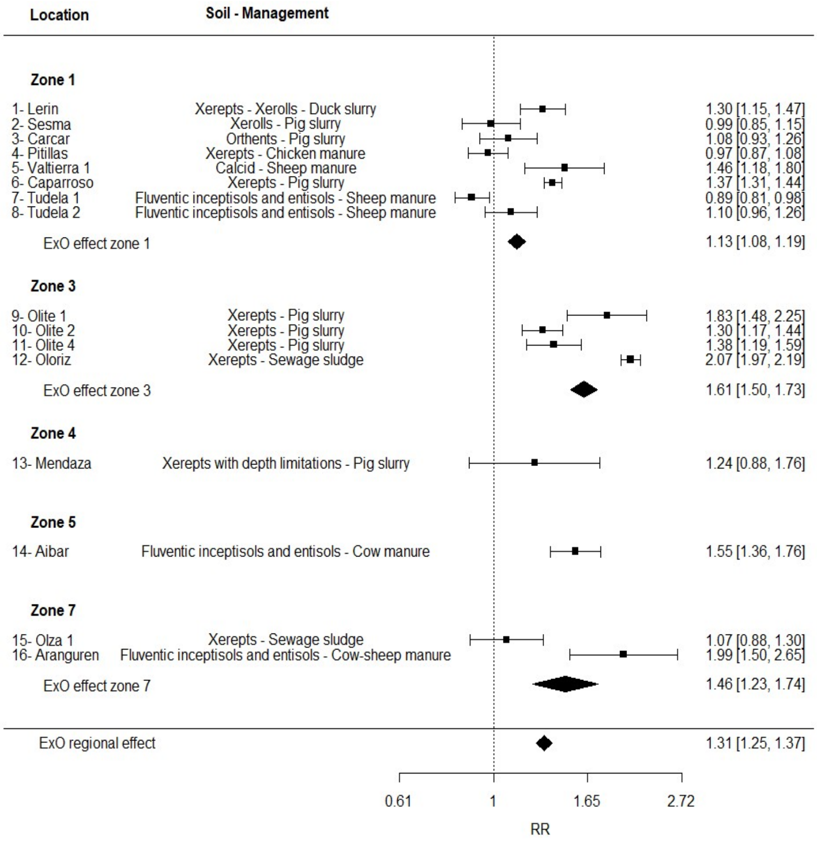

Figure 5. Response ratio (RR) of soil organic carbon (SOC) stocks (0-20 cm) for addition of exogenous sources of organic C (ExO). Zones correspond to those in Figure 1. The effect was considered significant when the 95% confidence interval (CI) of the RR did not overlap one (α = 0.05)

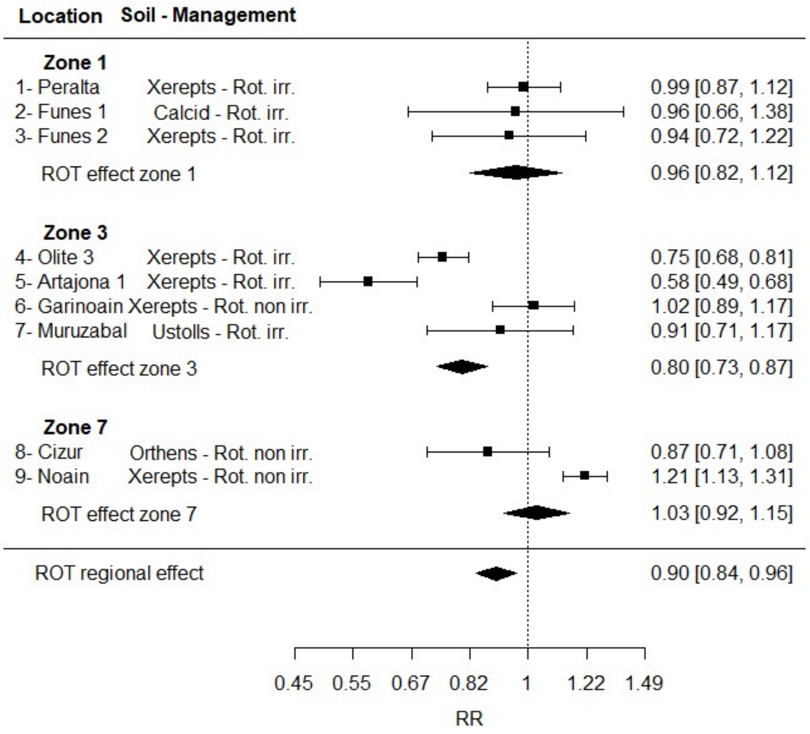

Figure 6. Response ratio (RR) of soil organic carbon (SOC) stocks (0-20 cm) for rotations (ROT). Zones correspond to those in Figure 1. The effect was considered significant when the 95% confidence interval (CI) of the RR did not overlap one (α = 0.05)

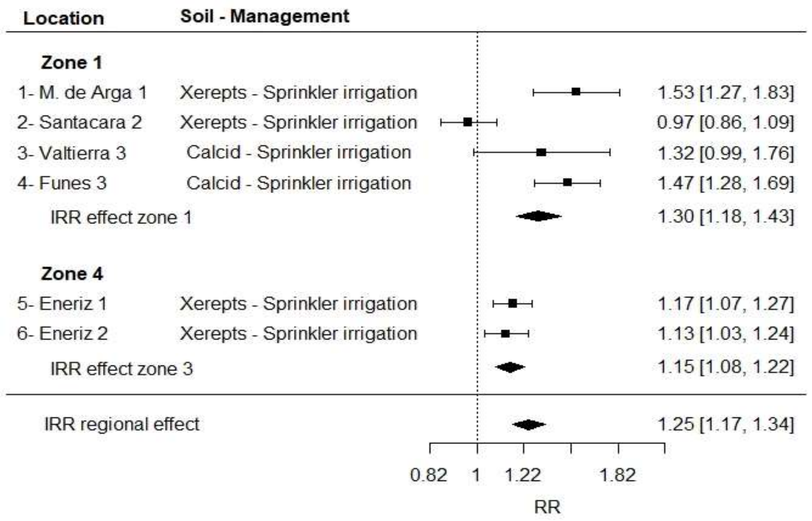

Figure 7. Response ratio (RR) of soil organic carbon (SOC) stocks (0-20 cm) for irrigation (IRR). Zones correspond to those in Figure 1. The effect was considered significant when the 95% confidence interval (CI) of the RR did not overlap one (α = 0.05)

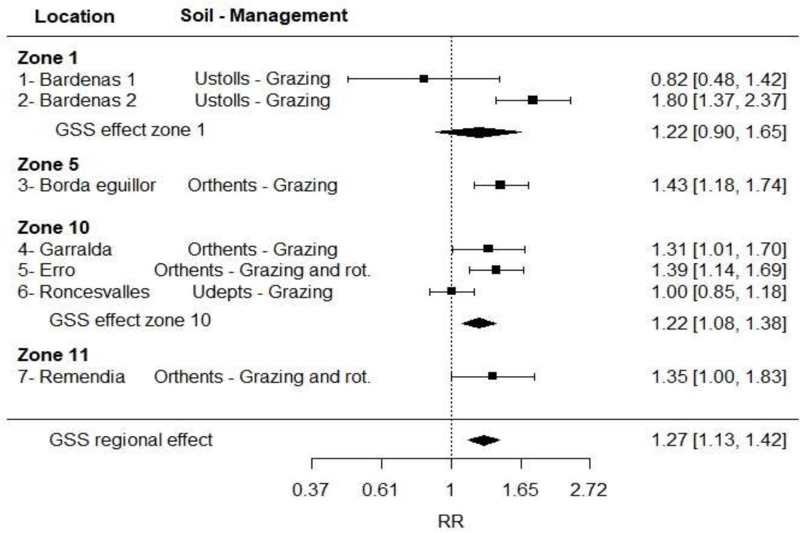

Figure 8. Response ratio (RR) of soil organic carbon (SOC) stocks (0-20 cm) for controlled grazing and/or rotation in grasslands (GSS)). Zones correspond to those in Figure 1. The effect was considered significant when the 95% confidence interval (CI) of the RR did not overlap one (α = 0.05)

DISCUSSION

Regional characteristics and soil organic carbon. The climate and soil characteristics defined for the 12 zones in the study corresponded to the expected ranges considering the regional biophysical traits (Supplementary Material 1). This includes climates from warm maritime in the North-West, to dry temperate Mediterranean and dry Steppe in the South-East (Papadakis, 1952) and soils in the orders of Alfisols, Ultisols, Entisols, Inceptisols, and Aridisols (Soil Survey Staff, 2014). This heterogeneity of pedoclimatic conditions in the region supports the need for a stratified study for accurate assessment of SOC stocks (Lasco et al., 2006; Smith et al., 2019; Tugel et al., 2008). The analysis of SOC storage in conventionally-managed soils (Figure 2) revealed that the more humid zones, situated at the North of the region (zones 10 and 11 in Figure 2), where the most common agricultural use is grasslands, had the highest SOC stocks. This is in agreement with general observations in Europe (de Brogniez et al., 2015) and Spain (Rodríguez Martín et al., 2016, 2019), and usually explained by a more favorable water balance allowing for greater primary productivity, and better SOC preservation in grasslands (usually not tilled and without plant residues removal with harvest) than croplands (Wiesmeier et al., 2013). In this study, such effect cannot be determined overall, as no croplands were present in zones 10 and 11 (Table 1). However, comparing croplands and grasslands present at the South of the region in the most arid zone 1, (Table 1), the former were observed to have significantly higher stocks (40.0 ± 9.5 Mg C ha^{-1}) than the later (31.8 ± 9.4 Mg C ha^{-1}), again supporting the interest of stratified studies at the regional scale.

In relation to SOC storage in croplands in zones 1, 3, 4, 5 and 7, the observed values were within the average national range (45.3 ± 28.5 Mg C ha^{-1} in annual crops and 38.09 ± 11.9 Mg C ha^{-1} in permanent woody crops at 0-30 cm, Rodríguez Martín et al., 2016), and in previous studies conducted in these zones (Fernández-Ugalde et al. 2009; Imaz et al. 2010; Antón et al. 2019 (see Chapter IV)). The highest values observed in zone 4, in the West-Central area of the region, corresponded to one particular group of plots on Xerepts with depth limitations (Figure 2), which provides an example of natural heterogeneity and the relevance of considering areas with homogeneous soil characteristics for comparisons among managements.

When assessing the difference between zones and soil types, it has to be noted that SOC storage values shown in Figure 2 corresponded to topsoils of conventionally managed soils. It is known that agricultural management tends to homogenize topsoil properties (Kuzyakov and Zamanian, 2019), blurring natural differences. Despite of this fact, differences observed in zone 1 are an example on the potential natural conditions and limitations imposed by soil type on SOC storage. The soils with the highest SOC content in this zone were those described as Xerolls, i.e., with a Mollic organic-matter rich upper horizon within a *xeric* moisture regime area, corresponding to more or less freely drained Mollisols of regions with Mediterranean climates developed on grasses or oak species (Soil Survey Staff, 2014). On the other hand, the soils containing gypsum (Gypsids, Figure 2), were those with the lowest SOC reference values. The limitations of high gypsum contents for SOC are known (Casby-Horton et al., 2015; Virto et al., 2006).

Adaptive management and topsoil organic carbon. A first observation in terms of the effectiveness of the strategies assessed in this work is that their net effect was uneven, both among them, and within each strategy in different zones. Overall, CA, ExO, and GSS seemed to be efficient at the regional level in promoting SOC storage, in agreement with the general perspective worldwide (Jia and Shevliakova, 2019). However, ROT, did not perform as expected from the general knowledge associated to the effect of crop diversification on SOC. (Autret et al., 2016; Kremen and Miles, 2012; McDaniel et al., 2014).

Conservation agriculture has been widely promoted as an efficient SOC storage technique (Gonzalez-Sanchez et al., 2015; Pittelkow et al., 2014). Its effect seems to be however highly context-specific (Jia and Shevliakova, 2019; Virto et al., 2015). In Spain, for example, no-till has been attributed a potential capacity for fixing atmospheric C of 2 Gg year^{-1}, compared to conventional management, but with different rates in time and space (González-Sánchez et al., 2012). In Mediterranean land, contradictory results have been reported, from net gains (Aguilera et al., 2013) to lower sequestration rates than conventional tillage (Francaviglia et al., 2019). This has been related to local conditions, especially those related to the soil water balance and its interaction with crop yields (Virto et al. 2012; Dimassi et al. 2014; Shekhar and Shapiro 2019). In our study, it was observed that, although the effect at the regional level was positive, it was smaller and with a RR close to 1 in zones 3 and 7 in comparison to zone 1 (Figure 4). These zones differ mostly in their moisture regimes (Table 1), which is drier in zone 1 than in zones 3 and 7. Although no data were recorded for yields in the plots considered in this study, these results agree with the general observation of more frequent yield gains with CA in arid and semi-arid land (Pittelkow et al., 2015). This can be related to the greater effect of improved soil moisture conditions associated to CA (Bescansa et al., 2006). Indeed, CA plots with permanent woody crops and grass cover, where there is no removal of grass biomass with harvest, and organic C inputs from grass are higher than in harvested plots, displayed the most positive RR (Figure 4). In this sense, CA can be an effective technique in the promotion of SOC storage in the topsoil in the South of Navarre. It has to be noted, however, that data in our study refer only to the uppermost soil layer (0-20 cm). It is known that the accumulation of SOC when tillage is reduced can be limited to the upper soil layers (Angers and Eriksen-Hamel, 2008; Meurer et al., 2018). This has to be undoubtedly considered when assessing the role of CA in climate change mitigation *via* soil C sequestration. Nevertheless, from an adaptive perspective, gains in topsoil SOC, which can reduce or control soil erodibility and increase infiltration, can be of high interest in a region subjected to increasing extreme rainfall events and scarce precipitation.

In relation to ExO, our results confirmed the general observation at the scale of the Mediterranean (Aguilera et al., 2013; Francaviglia et al., 2019) that increased C inputs associated to exogenous additions of organic C are the most effective systems for increasing SOC in agricultural soils. The variability of our results (which was high between and within zones, Figure 4) can be related to both soil characteristics and to different types of amendments and doses. The goal of the addition of exogenous organic materials to soil was not to gain SOC *per se*, but to manage soil fertility. As a consequence, the doses and types of amendments varied among plots, depending on crops needs and on the availability of economically viable sources. The relevance of the origin and type of organic amendments for exogenous SOC stabilization has been widely reported (Bhattacharya et al., 2016). No direct relationship was found between one particular type of organic amendment and SOC gains, which suggests that the net effect depended on a combination of factors. In addition to the amount (Francaviglia et al., 2019), the time of application and the fractionation of doses, for instance, has been observed to be determinant in final SOC gains when pig slurry is used in similar climate conditions than those in the South of Navarre (Domingo-Olivé et al., 2016).

The actual benefit of importing organic C to increase SOC storage in agricultural soils is under debate, as it can imply loosing C in other systems, depending on the alternative fate of the C in the materials used (Powlson et al., 2011). In the plots included in the study, which represented real agricultural plots using organic amendments and/or fertilization in the region, the most common sources were of animal origin. In this sense, the regional scale can be an adequate framework to redistribute C from surplus systems such as intensive animal production farms to SOC-depleted agricultural soils. Integrating crop and livestock systems can be a good adaptation option (Jia and Shevliakova, 2019).

Some variability was observed in our results when studying IRR (Figure 3) in zones 1 and 4. The effect of irrigation on SOC storage is not clear. Zhou et al. (2016) observed, in a global meta-analysis, that in all the studied biomes, irrigation induced an increase in SOC of 1.27%, for an increase in C stock in plants of 34.4%. This difference was explained by the fact that irrigation increased both primary production and microbial biomass responsible for mineralization. Trost et al. (2013) found that 8 out of 14 long-term field experiments resulted in SOC gains with irrigation. The effect was observed to be related to climate conditions, with aridity increasing SOC gains. In fact, plots in zone 4 (with a less dry climate than zone 1, Table 1) displayed a smaller effect than those in zone 1. However, unlike in other regional-scale studies (Da Gama et al., 2019; Nunes et al., 2007; Rodríguez Martín et al., 2019), irrigated systems were seen here as able to contribute to SOC storage at a regional scale, when adequate management conditions accompanied irrigation.

Crop diversification cannot be separated from irrigation to understand the net negative impact of ROT in SOC in this study (Figure 3). None of the groups of plots considered in zones 1 and 3 displayed a positive effect of ROT. The only group of plots with a positive effect of ROT was in zone 7, where irrigation is not used. This has a regional explanation, as these zones differ mainly in their humidity regime (Table 1), making irrigation very rarely used in the more humid zone 7, and widely used in the drier zones 1 and 3. In arid and semi-arid areas, fallow and monoculture (or rotations with low diversity) are frequent as a strategy to cope with natural water scarcity (Liu et al., 2016). The advantages of including rotations in cropping systems, and the reduction of fallow periods, have been established for temperate and moist areas (Poeplau and Don, 2015). In semi-arid areas, only when irrigation is introduced, more complex crop rotations can be adopted. When this happens, however, irrigation is associated to an intensification of tillage and increased fertilization, which in turn may increase SOC losses (Meurer et al., 2018; Six et al., 1999). As such, ROT cannot be considered a win-win strategy for increasing SOC in irrigated areas. Even so, the neutral effect observed in zone 1, indicates the possible viability of this measure that, although did not increase SOC, can increase yield through intensification. Thus, considering climate change projections, and the undeniable adaptive potential of irrigation, adequate combinations of ROT and IRR could be explored in context-specific assessments, including both biophysical and socio-economic aspects.

Finally, the variety of practices considered as improved grasslands management (GSS), was wide, as the zones studied comprised the widest climate gradient in the region (Figure 3). However, a general trend was observed towards more SOC under GSS management. In all cases, the conventional management implied the exclusion of animals and biomass exportation from the fields. Including controlled grazing, and/or changing land-use to include crop-lay rotations, which very likely improve the net C balance in the systems, was observed to be efficient in SOC storage. Average and low intensity grazing has been seen to lead to SOC gains in moist and dry temperate areas (Abdalla et al., 2018). This was the case also in most groups of plots in zones 10 and 11, where the baseline was the highest in the region (Fig. 2).

Regional assessment. The objective of this study was to assess, at a regional scale, the effectiveness of different strategies expected to have an adaptive potential. Although most of them had positive effects overall, these were not straightforward nor uniform across the region. The reasons for this variability seem different for the different strategies. While for CA climate seemed to induce differences in net SOC gains, ExO effect seemed more dependent on the combination of management factors, such as the source, doses and frequency of application, as explained above.

One singular observation is that, although some differences were observed in the SOC storage baseline of different soil types under conventional management, this factor was not able to detect differences in all cases within each of the studied zones (see for instance zones 1 and 3 in Fig. 2). A number of reasons can explain this observation. First, although soil types were selected on the basis of their taxonomic characteristics in Soil Taxonomy (Soil Survey Staff, 2014), only the upper 20 cm of the profile were considered for this study. Some profiles differing in their taxonomic classification, may have similar characteristics (such as clay content or mineralogy) in this part of the profile. For instance, all soils in zones 1, 3, 4 and 5 contained more than 20% carbonates in their upper horizon, which is a known factor of SOC stabilization (Rowley et al., 2018). Second, all soils studied here corresponded to agricultural soils, most of which have been managed for decades. As explained above, this implies a homogenization of their surface properties compared to their natural standards, which are managed to progressively approach the most favorable conditions for crops (Kuzyakov and Zamanian, 2019).

In relation to the role of soil type as a factor in the effectiveness of the strategies, none of the soil types considered was systematically observed to result in gains or losses of SOC among the different strategies. Although the scope and extension of this work does not allow for a detailed study of this factor, an example is the case of Xerepts (the most frequently found soil type, Fig. 3 and 4). In addition to the reasons outlined above to explain this lack of correlation, this suggests that the study of the influence of soil type on SOC storage at a regional scale may require criteria other than the soil genetic classification.

Regardless of soil type, the results observed allow for a regional assessment of SOC gains under different systems in relation to established objectives, such as the 4per1000 initiative. Although more an encouraging figure than a target (Rumpel et al., 2020; Soussana et al., 2019), this figure can be contrasted to the observed quantitative changes to provide a perspective for comparison with other studies. Data in this study came from plots with at least five years under the same management. Most ranged between 5 and 20 years of relatively continuous management. Translating an annual gain of 4‰ in this time lapse would correspond to net gains from 2% to 8% (RR of 1.02 to 1.08). Data in Fig. 3 and 4 indicate that this range is well below or below the average gain observed for CA, ExO, IRR and GSS overall, but within the range of some changes observed in some cases, such as CA in zones 3 and 7.

In the European context it has been observed that adaptive strategies can be effective to improve SOC storage in arable lands, although they are modulated at local level by pedoclimatic conditions (Costantini et al., 2020). For instance, a study developed in Bavaria based on C sequestration scenarios including promising management practices revealed that the 4p1000 target is not feasible for this region (Wiesmeier et al., 2020). For Hamidov et al. (2018) adaptation strategies under climate change scenarios reduced SOC losses in 75% of 20 agricultural adaptation case-studies across Europe, and SOC levels were expected to decrease in only two of them (10%). Our study highlights this site-dependence, as different responses to the same strategy were observed depending on local conditions. Zone 1 (with the highest agricultural surface) seems in this sense strategically interesting, as the one with most diverse agricultural systems (Table 1), in addition to a high proportion of groups showed a positive response. Some of the soils in this zone had the lowest observed baseline SOC contents (Fig. 2).

Another important aspect at the regional scale, is that our approach assessed management strategies already in practice in Navarre. This implies that some farmers are already familiar with them, and that they can be used in the region in conventional farms within the average profitability thresholds. This can be a relevant factor in favor of their expansion across the region, in contrast with the problems associated to the introduction of new techniques (White et al., 2018). Although the farmers' reasons for adopting adaptive strategies are diverse (Demenois et al., 2020; Prokopy et al., 2019), the existence of successful pioneer farmers in the local environment is a known factor of effective adoption of alternative managements (Altieri et al., 2015).

Finally, and in relation to climate change adaptability, major climate change threats identified for this region are related to changes in temperatures (average increase and heat waves) and rainfall (scarcity and extreme events). In this context, an increase of SOC stocks may have a positive impact on several soil properties such as water storage and infiltration, soil erosion, biodiversity and soil fertility, crucial for adaptation. However, the relationship between SOC and these properties is not straightforward, and is also known to be soil and climate-dependent (Johannes et al., 2017). Future research is needed to assess the relationship of SOC to soil vulnerability. Also, some of the changes that might have a positive effect in adaptation, might not correspond to increased climate change mitigation, if for instance SOC sequestration rates at depth are not as clear as at the topsoil (CA), their energetic cost overpasses their benefits in SOC (IRR), or they hinder mitigation in other sectors (ExO). Following the criteria established by the 4per1000 initiative (Rumpel et al., 2020), these aspects need to be revised for a general assessment of each strategy. Greenhouse gasses emissions associated to each strategy (such as N_2O) should also be considered to this respect.

In addition, it has to be noted that SOC accumulation related to the agricultural systems studied here is not endless nor irreversible. Soils are a finite carbon sink implying that sequestration rates tend to decline to negligible within decades or years (Chenu et al., 2019). Also, new changes in management, or the mere effects of changes in climate can revert SOC gains in very short time lapses (Álvaro-Fuentes et al., 2012; Jebari et al., 2018).

CONCLUSIONS

The analysis of different bioclimatic zones was useful to identify areas with different climate conditions and soil characteristics, which corresponded to different dominant land uses. The relevance of climate and, to a lesser extent, soil type, on baseline of SOC storage was confirmed in the region of Navarre.

The regional approach allowed to observe relevant differences in SOC associated to the managements tested. These should be taken into account when promoting the expansion of different systems. As expected, management of exogenous sources of organic carbon (ExO) was the most efficient strategy to increase SOC stocks in croplands across the region. Optimized grasslands management strategy (GSS) also resulted in net SOC gains in all the zones tested. This confirms the importance of organic matter management in croplands and livestock farms. The potential benefit of conservation agriculture (CA), the implementation of irrigation (IRR) and crop rotations (ROT) needs to be evaluated with care, as it was observed to be uneven in the region for CA (being less efficient with decreasing aridity), management-dependent for IRR, and overall negative in ROT, likely related to the use of irrigation and the intensification of cropping sequences with it. Therefore, although the final benefits of topsoil SOC gains need to be assessed considering other aspects such as their climate neutrality or economic viability, these results support the inclusion of ExO, GSS and, to some extent, CA in regional adaptation programs, and highlight the need of regional approaches and adequate segmentation for the assessment of the efficiency of commonly adopted agricultural practices. The observed variability in terms of the adoption and effectiveness of the five strategies tested also indicates that site-specific assessment is needed.

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Supplementary material 1. Climate and soil characteristics and vulnerability traits for each zone.

Zone	Climate (Papadakis, 1952)	Soil		
		Major soil types (Soils Survey Staff, 2014)	Characteristics	Vulnerability traits
1. Ribera	Mild Steppe (AvM-Ost) and Dry Temperate Mediterranean (AvMMe)	Aridisols	Aridic soil moisture regime.	Water deficit
			Cambic B horizons	Accumulation of gypsum or carbonates (some petrocalcic horizons) at depth
			Accumulation horizons containing carbonates, and/or gypsum.	Low organic matter content Some salinity issues
		Entisols, some inceptisols	Little profile development.	Limited depth, stoniness
			Aridic or Xeric soil moisture regime.	Low organic matter content
2. Fluvial areas	Dry Temperate Mediterranean (AvMMe)	Entisols (Fluvents)	Little profile development.	Stoniness, poor texture
			Aridic or Xeric soil moisture regime.	
			Stoniness and coarse textures	
		Aridisols	Aridic soil moisture regime.	Stoniness, water deficit

3. South Midlands	Dry Temperate Mediterranean (AvMMe)	Inceptisols, some Entisols	Accumulation horizons at depth with carbonates (and in some, gypsum)	Accumulation of carbonates (or gypsum) at depth. Some petrocalcic, limited depth Low organic matter content
		Mollisols (Xerolls)	Xeric moisture regime SOM accumulation at surface	Water deficit
4. North Midlands	Moist Temperate Mediterranean (AvMMe)	Inceptisols, entisols	Xeric moisture regime Accumulation horizons > 800 m.a.s.l. carbonate-free profiles	Limited depth (low water retention) Carbonates accumulation
		Alfisols (Palexeralf)	On relatively old river terraces Clay accumulation horizon at depth	Stoniness
5. East Midlands	Moist Temperate Mediterranean (AvMMe)	Inceptisols (Calcixerepts, Haploxerepts), Entisols	Xeric moisture regime Calcixerepts: carbonates accumulation.	Carbonates accumulation Limited depth (Entisols) Slope
		Alfisols (Palexeralf)	On relatively old river terraces Clay accumulation horizon at depth	Stoniness

6. East Pre-Pyrenees	Cool Maritime Mediterranean (AvTrME)	Entisols (Udorthent, Xerorthent)	Most within the Lithic group	Reduced effective depth (low water retention capacity) Slope
7. Pamplona Basin	Moist Temperate Mediterranean (AvMMe)	Inceptisols (Haploxerepts, Calcixerepts)	Xeric soil moisture regime Deep, clayey in most cases	Limited drainage
		Some entisols (Xerorthents, Udorthents, Fluvents)		Limited depth, stoniness (low water retention capacity)
8. Urbasa-Andia-Aralar	Cool Maritime Mediterranean (AvTrME)	Inceptisols (Dystrudepts)	Udic soil moisture regime Low pH, low base saturation	High acidity, slope
		Entisols (Lithic Udorthent)	Very limited profile development	High acidity, reduced depth, low water retention capacity
		Spodosols	Acid, coarse texture, B spodic horizon	High acidity, coarse texture, low water retention capacity.
9. Arakil corridor	Cool Maritime Mediterranean (AvTrME)	Inceptisols, Entisols (Fluvents)	Udic soil moisture regime Low profile development	Stoniness

10. Valleys N of Pamplona	Cool Maritime Mediterranean (AvTrME)	Mosaic of Inceptisols (Humudept) and Entisols (Udifluvent)	Udic soil moisture regime Low profile development High organic matter content	Acidity Limited depth Slope Low water retention capacity
		Alfisols, Ultisols (Haploumult)	Clay accumulation at depth (Ultisols low base saturation)	Acidity
11. East Pyrenees	Cool Maritime (AvTrHU)	Inceptisols (Dystrudepts), Entisols (Udorthents)	Udic soil moisture regime Low profile development	Acidity Limited depth Slope
12. Northwest area	Cool Maritime (AvTrHU) and Warm Maritime ((AvMHU-Hu)	Inceptisols, Entisols	Udic soil moisture regime	Acidity Limited profile depth Slope
		Alfisols, Ultisols	Udic soil moisture regime Clay accumulation horizons	Acidity Slope Limited depth (Haplumults)

Supplementary material 2. Main soil type, number of plots, strategy and management tested in each group.

Zone	Location	Plots	Soil	Strategy	Management
1	Lerín	5	Xerolls	ExO	Duck slurry
1	Sesma	5	Xerolls	ExO	Pig slurry
1	Peralta	6	Xerepts	ROT	Crop rotation with irrigation (Rot. irr.)
1	Carcar	4	Orthents	ExO	Pig slurry
1	Pitillas	4	Xerepts	ExO	Chicken manure
1	M. de Arga 1	5	Xerepts	IRR	Sprinkler irrigation
1	M. de Arga 2	4	Xerepts	AC	No till
1	Valtierra 3	4	Calcid	IRR	Sprinkler irrigation
1	Valtierra 1	2	Calcid	ExO	Sheep manure
1	Valtierra 2	2	Calcid	AC	No till
1	Fontellas	2	Xerepts	AC	Olives grove with cover (Oliv. w. cover)
1	Cascante	2	Gypsids	AC	Vineyard with cover (Vin. w. cover)
1	Funes 1	3	Calcid	ROT	Crop rotation with irrigation (Rot. irr.)
1	Funes 3	4	Calcid	IRR	Sprinkler irrigation
1	Funes 2	4	Calcid	ROT	Crop rotation with irrigation (Rot. irr.)
1	Santacara 2	4	Xerepts	IRR	Sprinkler irrigation

1	Santacara 1	2	Xerepts	AC	No till
1	Tudela 1	2	Fluventic inceptisols and entisols	ExO	Sheep manure
1	Tudela 2	2	Fluventic inceptisols and entisols	ExO	Sheep manure
1	Bardenas 1	3	Fluventic inceptisols and entisols	GSS	Managed grazing (Grazing)
1	Bardenas 2	3	Ustolls	GSS	Managed grazing (Grazing)
1	Caparroso	2	Xerepts	ExO	Pig slurry
3	Olite 1	3	Xerepts	ExO	Pig slurry
3	Olite 2	5	Xerepts	ExO	Pig slurry
3	Olite 3	3	Xerepts	ROT	Crop rotation with irrigation (Rot. irr.)
3	Olite 4	3	Xerepts	ExO	Pig slurry
3	Artajona 1	4	Xerepts	ROT	Crop rotation with irrigation (Rot. irr.)
3	Artajona 2	4	Xerepts	AC	No till
3	Garinoain	3	Xerepts	ROT	Crop rotation without irrigation (Rot. non irr.)
3	Oloriz	2	Xerepts	ExO	Sewage Sludge
3	Legarda	3	Fluventic inceptisols and entisols	AC	Vineyard with cover (Vin. w. cover)
3	Beire	2	Xerepts with depth limitations	AC	No till
3	Muruzabal	2	Ustolls	ROT	Crop rotation with irrigation (Rot. irr.)
4	Mendaza	4	Xerepts with depth limitations	ExO	Pig slurry
4	Eneriz 1	2	Xerepts	IRR	Sprinkler irrigation

4	Eneriz 2 Borda	2	Xerepts	IRR	Sprinkler irrigation
5	Eguillor	4	Orthents	GSS	Managed grazing (Grazing)
5	Aibar	5	Fluventic inceptisols and entisols	ExO	Cow manure
7	Pamplona	2	Xerepts	AC	No till
7	Olza 1	4	Fluventic inceptisols and entisols	ExO	Sewage Sludge
7	Olza 2	4	Fluventic inceptisols and entisols	AC	No till
7	Cizur	3	Orthents	ROT	Crop rotation without irrigation (Rot. non irr.)
7	Noain	3	Xerepts	ROT	Crop rotation without irrigation (Rot. non irr.)
7	Aranguren	3	Fluventic inceptisols and entisols	ExO	Cow-sheep manure
10	Garralda	2	Orthents	GSS	Managed grazing (Grazing)
10	Erro	3	Orthents	GSS	Managed grazing and rotation (Grazing and rot.)
10	Roncesvalles	3	Udepts	GSS	Managed grazing and rotation (Grazing and rot.)
11	Remendia	5	Orthents	GSS	Managed grazing and rotation (Grazing and rot.)

Chapter VI

Soil water retention and soil compaction assessment in a regional-scale strategy to improve climate change adaptation of agriculture in Navarre, Spain

“En una tierra laborable

es tan importante o más su estructura física para que sea fértil,

que el caudal de alimentos que contenga.”

Daniel Nagore Nagore
El abono. Resorte vital de la producción agrícola
Diputación Foral y Provincial de Navarra. Dirección de Agricultura y
Ganadería. Editorial Aramburu. Pamplona. 1939

CHAPTER VI

Soil water retention and soil compaction assessment in a regional-scale strategy to improve climate change adaptation of agriculture in Navarre, Spain

ABSTRACT

The aim of this study was to evaluate the effectiveness of the different agricultural management adaptive strategies considered in the framework of a regional climate change adaptation roadmap in Navarre (Spain), from the point of view of soil physical indicators associated to soil compaction and water retention. These indicators were chosen as representative of the potential of these strategies to improve the soil physical condition. That for, the effectiveness of conservation agriculture (CA), crop rotations (ROT), additions of organic matter (ExO), irrigation (IRR) and innovative grassland management (GSS) was assessed by monitoring soil bulk density (BD) and soil available water holding capacity (AWHC) in a network of 159 agricultural fields across homogeneous agro-climatic zones in the region. A sampling protocol designed to compare groups of plots with or without adaptive practices, and with equal soil characteristics within each zone, allowed to determine the effect size of each strategy (measured as response ratios, RR, calculated as the relative value of BD and AWHC in fields with adaptive management vs. without). Both parameters responded to soil and crop management, although the observed effect was highly variable. Only the ExO strategy showed an overall positive effect (RR 95% confidence interval (CI) [0.95-0.99]) on BD. ROT, IRR and GSS displayed no effect and, in the case of CA, the effect was negative (RR CI [1.01-1.06]). In terms of AWHC, although the results within the zones were heterogeneous, the overall effect associated to the strategies ROT, ExO, IRR and GSS was neutral, and only CA resulted in an overall negative effect (RR CI [0.85-0.97]). The observed variability in terms of the effectiveness of the five strategies tested in this region highlights the need to understand the complexity of interrelationships between management and dynamic soil properties at the regional scale.

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INTRODUCTION

Changes in long-term temperature and precipitation patterns associated to climate change can have a major impact on agriculture at global scale, which may determine both the distribution of cropping systems in arable areas and the variation in production over the years (IPCC, 2014; Jia et al., 2019).

Soil may play a key role for assessing and controlling this vulnerability, since changes in soil properties may have profound impacts, both in time and space, on the ability of land to support crops and agricultural management (Rounsevell et al., 1999). Soil represents also a dynamic and regulatory system that generates a multitude of functions, which in turn support the provision of ecosystem services by soil and agriculture (Adhikari and Hartemink, 2016; Blum, 2005; CEC, 2009). These functions can also be negatively impacted by climate change (Bouma, 2014).

In this sense, the main climate drivers to be considered when assessing the vulnerability of agrosystems are those related to temperatures and precipitation patterns, including gradual changes or extreme events, along with others such as rising levels of carbon dioxide and nitrogen in the atmosphere (Allen et al., 2011; French et al., 2009). The effect of these drivers on the soil chemical, physical and biological degradation may be varied (Allen et al., 2011; French et al., 2009). For instance, functions related to biomass production, nutrient supply and cycling, protection against pests and pathogens, biodiversity conservation, water infiltration and availability, as well as the formation of a stable physical structure in the soil and erosion prevention, could be strongly affected by increased duration and intensity of droughts or higher temperatures (Handmer, J., Y. Honda, Z.W. Kundzewicz, N. Arnell, G. Benito, J. Hatfield, I.F. Mohamed, P. Peduzzi, S. Wu, B. Sherstyukov and Yan, 2012; Hatfield et al., 2011; Porter et al., 2015).

At the same time, changes in soil cover and management associated to the intensification of agricultural production, and the increasing demand for natural resources, increase anthropogenic pressure affecting soil properties and leading to soil degradation processes (Horel et al., 2015). Understanding alterations in soil properties over time of cultivation, such as the increase in the soil bulk density (BD), the disruption of soil aggregates, or alterations in pores distribution that may affect soil water dynamics (Kuzyakov and Zamanian, 2019; Li et al., 2021), , have been the object of attention for years by researchers, policymakers and farmers focusing on developing soil degradation control strategies (Panagos et al., 2015; Virto et al., 2015). These strategies should consider not only their potential impact on soil conservation, but also the need for maintaining agricultural yields and, if possible, mitigating the effects of climate change on land degradation (Chenu et al., 2019). Moving towards adaptive soil management strategies that can adjust to the current or projected conditions of climate drivers by improving the soils resilience, may thus allow to moderate or avoid these negative impacts, by promoting soil restoration (del Pozo et al., 2019). The limitations of these strategies are site-specific and determined through the interaction of biochemical and physical factors as well as the social and institutional framework considered (Costantini et al., 2020; IPCC, 2019; Jia et al., 2019). In Europe, an evidence of the current interest in this matter are the European Commission proposal of alignment of the Common Agricultural Policy (CAP) with the European Union’s environmental, climate, and biodiversity protection commitments set in the European Green Deal (European Commission, 2020; European Commission Staff, 2020; Panagos et al., 2020) or the recent European Commission evaluation support study on the impact of CAP on sustainable soil management (Augier et al., 2020).

An adequate assessment of the response of agricultural soils to such strategies requires the use of indicators, which should be as sensitive as possible to changes in soil functions, and to possible alterations in management and/or climate (Andrews et al., 2004; Doran and Parkin, 1996). A number of indicators linked to soil functions have been designed, which are related to soil physical, chemical and biological properties that can be monitored in the context of sustainable land management, soil degradation and climate change adaptation (Allen et al., 2011; Drobnik et al., 2018; Rinot et al., 2019). The most frequently used ones, because of their relevance in soil functioning and climate change mitigation, are those related to soil organic C (SOC) storage and cycling. Many studies have highlighted the potential and limitation of different strategies in improving SOC in agricultural soils (Chenu et al., 2019; Dignac et al., 2017; Paustian et al., 2019).

However, although recent global initiatives to promote SOC storage in agricultural soils highlight that the interest of this increase lays also on its potential to improve soil condition and the functioning of agrosystems, as benefits associated with SOC gains (Rumpel et al., 2020; Soussana et al., 2019), soil physical indicators, which can add useful information on the effectiveness of management strategies to changes in rainfall patterns or water balances, are less often addressed. These indicators can be of great interest in regional contexts. Those related to soil water retention and soil compaction are the most frequently used (Bünemann et al., 2018). Soil water retention is sensitive to management strategies, which implies that these strategies may induce a positive or negative response to changes in climate, especially to variable and high intensity rainfall or drought events. In the same sense, soil compaction, as expressed by BD (Blanco-Canqui et al., 2015), represents an adequate indicator of soil associated with multiple soil functions such as aeration, root development and infiltration (Allen et al., 2011).

As a consequence of the lower attention paid to these indicators, the consequences of most of the adaptive soil management strategies in terms of the restoration of the soils physical condition are not always well known or straightforward. For instance, although manure application generally improves soil water retention and BD (Williams and Hedlund, 2013; Yu et al., 2020), Blanco-Canqui et al. (2015) suggest that changes in these soil properties may be small or not be measurable in the short term under field conditions (< 5 yr). The effect of tillage reduction or suppression has been linked to greater soil water retention in different agro-climatic conditions (Bescansa et al., 2006; Mondal et al., 2019). Their consequences in BD ant total porosity are less clear, with most studies reporting increased BD without tillage (Skaalsveen et al., 2019), but a trend of this effect to decrease with increasing experimental duration (Li et al., 2019) and the variety of crops considered (Alhameid et al., 2019).

The effects of crop rotation on the soil physical properties show also inconsistent results. Factors such as the crops included in the rotation, intensification and soil management system seem to be determinant in this sense (Kazula et al., 2017; Zuber et al., 2015). A similar dependency on local conditions has been observed for the link between controlled grazing and other conservation management strategies for grassland soils, and the soil physical condition (Teague et al., 2011). This implies that the assessment of these soil management strategies aiming to improve soil water conservation and the soil physical status requires careful knowledge of the soil factors affecting them (Al-Rumikhani, 2002; Reynolds et al., 2002). The effect of other adaptive strategies not directly related to soil management, such as the adoption of irrigation, seems more related too to the local soil and crops management techniques than to the use of irrigation by itself (Antón et al., 2019, see Chapter IV).

In this context, the main objective of this work was to carry out a quantitative assessment of the effectiveness of a number of agricultural practices in achieving an improvement in the soil water retention, assessed as its available water holding capacity (AWHC) and in BD, at the scale of the region of Navarre, in Northern Spain. These strategies were those already being implemented by some farmers in the region, with a potential to reduce the vulnerability of agricultural land to the projected regional climate change by improving the soil resilience to agradual increase of temperature, heat waves, changes in rainfall patterns and an increase in the number and frequency of extreme precipitation events (Gobierno de Navarra, 2017). The work was conducted within the framework of the European Strategy for Adaptation to Climate Change (European Commission, 2013), the regional climate change roadmap in the region of Navarre (Spain) (Gobierno de Navarra, 2017) and a regional-scale project (LIFE Nadapta) launched in 2017 in the region, with the goal of advancing towards a comprehensive design of climate change adaptation policies. In this sense, the study aimed to set a regional monitoring network of sites, in line with the challenging need for up-scaling studies on soil quality (FAO, 2013; Paustian et al., 2016).

For this purpose, a first objective was to define the actual baseline of these soil physical indicators under conventional management conditions in the territory, by monitoring a representative number of agricultural fields in different agroclimatic areas. Then, we aimed to study the effect of the most relevant agricultural practices promoted in the regional roadmap for climate change adaptation on AWHC and BD, in a selection of representative agricultural fields across the region.

MATERIALS AND METHODS

Study area. The Autonomous Community of Navarre (10,391 km^2) is located in the North of Spain (Figure 1). The region is characterized by high climatic variability, with a rainfall gradient ranging from >2500 mm in the N to <350 mm in the SE (Pejenaute Goñi, 2017), as the most significant natural division in the territory. Mean annual temperatures vary between 14.5 ºC (in Buñuel, 41º58’47”N; 1º26’38”W) and 9.3 ºC (in Irabia, 42°59'07"N; 1°09'28"W), with a more or less marked seasonal oscillation depending on altitude, proximity to the sea, and latitude (Gobierno de Navarra, 2020). At present, 39% of the total area is used as agricultural land (90.7% cropland and 9.3% grassland).

Selection of soil management strategies. The agricultural managements considered in this study were those selected as adaptive in the regional action plans for climate change adaptation (Gobierno de Navarra, 2017), and most commonly found in the region. They were conservation agriculture (CA), management of exogenous sources of organic C (ExO), and rotations (ROT), as cropping strategies in extensive crops. Other managements of regional interest, i.e. the implementation of irrigation (IRR), and optimized grasslands management (GSS), were also included. CA included no-till in extensive crops and permanent grass cover in permanent woody crops. ExO included the regular addition of different sources of organic matter at agronomic doses (i.e. with the purpose of fertilization), ROT included different crops in the regular sequence of cultivation. IRR was tested in plots with irrigation, and GSS included mostly controlled grazing strategies, and in some cases, in combination with lay or lay/crops rotations. Some of these practices are among those recently identified as those for which a better understanding of the processes and changes in the soil associated with SOC gains or losses is needed (Chenu et al., 2019).

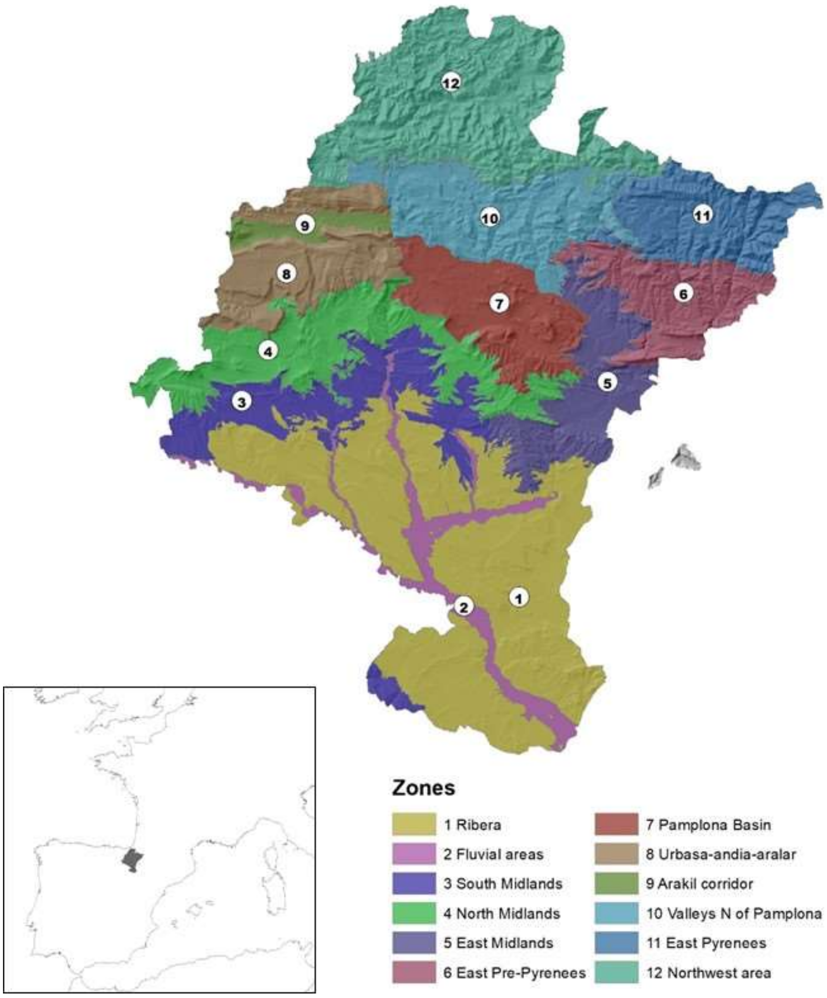


Figure 1. Location of the region of Navarre (bottom left) and homogeneous zones defined for this study.

Table 1. Climate, average SOC stock in reference plots at 0-20 cm, management strategies, number of groups and plots and soil groups. Managements are conservation agriculture (CA), addition of exogenous sources of organic C (ExO), rotations (ROT), irrigation (IRR), and controlled grazing and/or rotation in grasslands (GSS).

	Climate	SOC stock	Management strategies and plots			
Zone	Papadakis	0-20 cm (Mg ha^{-1})	Strategies	Groups	Plots	Soil groups
1. Ribera	Mild Steppe (AvM-Ost) and Dry Temperate Mediterranean (AvMMe)	38.2 ± 9.7	CA	5	12	Fluventic Inceptisols and Entisols, Orthents, Xerepts, Xerolls, Ustolls, Calcids, Gypsids
			ExO	8	26	
			ROT	3	13	
			IRR	4	16	
			GSS	2	6	
3. South Midlands	Dry Temperate Mediterranean (AvMMe)	34.7 ± 7.4	CA	3	9	Fluventic inceptisols and entisols, Other Xerepts, Xerepts with depth limitations, Ustolls
			ExO	4	13	
			ROT	4	12	
4. North Midlands	Moist Temperate Mediterranean (AvMMe)	49.0 ± 20.1	ExO	1	4	Xerepts with depth limitations, Other Xerepts
			IRR	2	4	
5. East Midlands	Moist Temperate Mediterranean (AvMMe)	38.2 ± 7.8	ExO	1	4	Orthents, Xerepts with depth limitations
			GSS	1	5	
7. Pamplona Basin	Moist Temperate Mediterranean (AvMMe)	38.9 ± 6.0	CA	2	6	Xerepts, Orthents, Fluventic inceptisols and entisols
			ExO	2	7	
			ROT	2	6	
10. Valleys N of Pamplona	Cool Maritime Mediterranean (AvTrME)	92.4 ± 9.8	GSS	3	8	Orthents, Udepts
11. East Pyrenees	Cool Maritime (AvTrHU)	55.0 ± 2.1	GSS	1	5	Orthent, Fluventic Udepts
12. Northwest area	Cool Maritime (AvTrHU) and Warm Maritime (AvMHU-Hu)	142 ± 17.1	GSS	1	3	Alfisols, Ultisols

Homogeneous areas and network of agricultural plots. In the framework of the project LIFE Nadapta, twelve homogeneous zones were defined by combining biogeographical and vegetation series information (Figure 1) so that each zone had homogeneous conditions for plant growth (Peralta et al., 2013; Rivas-Martinez, 2005).

Within those zones representing the highest proportion of agricultural land in the region (zones 1, 3, 4, 5, 7, 10 and 11), the most common land uses were identified and a network of agricultural plots were identified in order to evaluate the different strategies considered. Plots included in this network were organized in groups on the main soil types in each of the 7 zones. Within each of these groups, reference plots (where one of the adaptive managements had been applied for at least 5 years consecutively) were identified, with the assistance of famers, farmers' unions and extension agents. At the same time, contiguous or nearly plots with the same crop or type of crop, and under conventional management were also identified and included in the group. Each group of plots included therefore the reference fields and several plots under conventional management. The definition of conventional management was done according to the most extended managements in the region, for each of the systems evaluated. That implied mineral fertilization in the case of ExO, non-irrigated plots in the case of IRR, annual monoculture for the ROT strategy, and regular mowing and/or no rotation in the case of GSS. In the case of CA, conventional management implied inversion tillage in non-permanent crops, and frequent tillage to keep the soil free of vegetation between and under the rows of woody crops where permanent grass cover was considered as CA.

Considering the diversity of agricultural land uses existing in the region, the information related to plots within each group was classified firstly by principal soils groups and, secondly, by management, irrigation regime and crop intensity, when necessary. In this sense, in plots under CA and ROT strategies, the irrigation regime of the groups considered was specified. For the plots within the ExO strategy, both the origin of the organic source applied and the irrigation regime were defined, and, in the case of IRR, the cropping intensity was divided into annual crops (usually corn) and intensive-irrigation (with more than one crop per year). The irrigation system in all the irrigated plots was sprinkler irrigation. In this sense, rainfed regimes normally corresponded to extensive cereal crops.

The number of groups of plots per zone was determined considering the extension of agricultural land, and the diversity of strategies adopted, in each zone. The selection of plots within each group was done keeping the highest possible physical proximity between them in order to guarantee soil homogeneity within each group (see sampling strategy below). Climate and soils characteristics, including average SOC stocks measured in the conventionally-managed plots at 0-20 cm, as well as management strategies within each zone and the number of groups and plots, are compiled in Table 1.

Soil sampling design and analysis. A sampling strategy was developed to ensure that, within each group, areas with homogeneous soil characteristics and differing only in management were compared. That for, in each plot of the group, a sampling area was determined so that sampled areas in each group of plots corresponded to the same soil unit for all plots within the group, following the methodology described in Antón et al. (2019) (see Chapter IV). Attention was paid to generate zones that were as homogeneous as possible, considering in addition to the soil type criterion, others such as slope or orientation (Tugel et al., 2008; Wiesmeier et al., 2013). That for, the delimitation of these homogeneous areas within each group of plots was carried out on the basis of the highest available detail (soil series or phase). The regional soil map at 1: 25,000 (IDENA, 2020) was used in the areas where it was available. In this map, soil units are delimited, among other parameters, by slope and position in the landscape. Where this was not the case, the delimitation was made from soil information available at 1:50,000, geological information and photo-interpretation. In all cases, the process was completed with a field visit to verify the final result, and with extra soil profiles description when necessary.

Then, for the sampling area of each plot within each group, a sampling design was adapted following the one described by Stolbovoy et al. (2007) for comparing SOC stocks changes in croplands. In this protocol, a randomized grid template is adapted to the size of the sampling area, and used to define at least three representative sampling squares per sampling zone (i.e. areas with the same type of soil in each plot of the group). This sampling design allowed for selecting the sampling areas considering also the particular conditions of slope and orientation in the sampling area, and therefore granted random and representative topsoil sampling. As such, it was considered valid to ensure that comparison units were as homogeneous as possible in relation to the invariant soil properties, and could reflect the variability of the indicators sensitive to management, as recommended by (FAO, 2013).

All the processing of cartographic information was performed with ArcGIS 10.6 (Redlands, CA: Environmental Systems Research Institute, Inc., 2018).

Sampling was conducted at the end of the growing season of each crop, or as far as possible from the last soil alteration with management in permanent crops to avoid possible seasonal variations in BD (Franzluebbers et al., 1995; Logsdon and Karlen, 2004). Within each of the square sampling areas, 25 sub-samples evenly distributed were carefully collected with a shovel at 0-30 cm, to compile a composite sample. One 100 cm^3 undisturbed soil core was taken at the center of the 0-30-cm depth interval. Disturbed samples were gently mixed and broken apart in large clods, and air-dried. Part of each sample was then sieved at 2 mm. The stone content was determined while sieving.

Intact large clods and sieved samples 0-30 cm) were used to measure soil water retention (SWR) at -33 and -1500 kPa, respectively, considered as the soil moisture content at field capacity and wilting point (Richards and Weaver, 1944). SWR was determined for each sample in 5 and 15 bar pressure plate extractors (Soil Moisture Equipment Corp., Santa Barbara, CA), as described by Dirksen (1999). Volumetric values for the SWR were calculated from the gravimetric measures using BD, determined from the oven-dry (105 ºC) mass of the undisturbed 100-cm^3 cores. Soil AWHC was calculated from the difference in soil moisture content at field capacity (-33 kPa) and wilting point (-1500 kPa), BD data and depth. Stoniness was used for correction when needed.

Bulk density and soil water retention assessment and statistics. Data on BD and volumetric soil AWHC were first used to make a comparison at the regional level between the different zones identified, and at a local level in each zone, between different soil typologies. This first approximation was made in plots under conventional management, aiming to capture the reference level or baseline of the region's agricultural soils, considering that physical and hydraulic degradation processes in these soils had reach at relatively steady state after decades of cultivation time (Targulian and Krasilnikov, 2007). Data are provided as means ± standard deviation and the homogeneity of variances was verified by the Levene test. A univariate analysis of variance (ANOVA) was used to assess differences between groups, and post hoc analysis was performed by the Duncan’s test. Significant results were based on a probability level of $p < 0.05$.

The second approximation involved the study of the effect of each strategy considered on BD and volumetric soil AWHC. This effect was measured for each group of plots according to the natural logarithm of the response ratio (LRR):

$$LRR = \ln(\mathrm{RR}) = \ln(\frac{\bar{X}_R}{\bar{X}_C}) \qquad \text{Equation 1}$$

where $\bar{X}_R$ and $\bar{X}_C$ are the mean values in the reference plot or plots with adaptive management, and those under conventional management within each group, respectively. This represents a practical way to quantify and summarize the magnitude and direction of the results, allowing to linearize and normalize the sampling distribution (Hedges et al., 1999). The variance of the LRR for each group was calculated following these authors as:

$$var(LRR) = \frac{(SD_R)^2}{n_R \bar{X}_R^2} + \frac{(SD_C)^2}{n_C \bar{X}_C^2} \qquad \text{Equation 2}$$

where SD and n indicate the standard deviations and the sample size of the reference and conventional plots within each group of plots, respectively.

Following the approach commonly applied in meta-analyses comparing results on the same parameters from different study areas, the overall effects of each strategy in the zones with more than one group of plots, and at the regional scale, were analyzed with an unweighted fixed effects (FE) model. This model assumes that all groups share a common value of LRR (Hedges et al., 1999), considering that the only source of variability in the analysis is that associated to the sampling process within each group, calculated according to Equation 2. The unweighted analysis assigns the same weight to each group, avoiding the underestimation of the LRR due to differences in sample sizes.

The LRRs for different strategies at group, zone and regional levels were represented in forest graphs, transformed into RR for simplification. The effect was considered significant when the 95% confidence interval (CI) of the RR did not overlap one ($\alpha = 0.05$). All statistical analyses were carried out with R (R Core Team; 2019). Calculations and model performance for RR analysis were carried out using the *metafor* package (Viechtbauer, 2010).

In order to complete the discussion, data on SOC from a previous analysis were taken into account, both in terms of SOC stocks at reference plots (Table 1) and in terms of the overall regional effect of each strategy on this parameter (Table 2) (see Chapter V).

Table 2. Overall regional RR effect and 95% confidence interval on SOC for each strategy. Managements are conservation agriculture (CA), addition of exogenous sources of organic C (ExO), rotations (ROT), irrigation (IRR), and controlled grazing and/or rotation in grasslands (GSS).

Strategy	Overall RR effect (%)	95% confidence interval
ROT	0.9	0.84 – 0.96
GSS	1.27	1.13 – 1.42
IRR	1.25	1.17 – 1.34
ExO	1.31	1.25 – 1.37
CA	1.24	1.16 – 1.31

RESULTS

Baseline by agricultural zones and soil type: Bulk density. Figure 2 shows the results of BD (0-30 cm) corresponding to the plots under conventional management in each of the areas evaluated. These results showed a very large variability, with values ranging from below 0.9 g cm^{-3} at some points in zone 10, to values close to 1.9 g cm^{-3} in zone 4, for the depth studied.

Zones 10 and 12, with 1.15 ± 0.14 g cm^{-3} and 1.21 ± 0.13 g cm^{-3} respectively, had lower average BD values than the rest. Zone 4 displayed values significantly above the others, with an average BD of 1.74 ± 0.14 g cm^{-3}. The rest of zones were grouped with an average value of 1.54 ± 0.11 g cm^{-3}, with zones 5 and 11 outstanding above and below, with BD values of 1.62 ± 0.10 g cm^{-3} and 1.48 ± 0.04 g cm^{-3}, respectively.

Figure 3 shows the BD results corresponding to the top layer (0-30 cm) in the different soil types within each zone. These results showed differences in zones 1, 3, 4 and 7. In zone 1, all soils were fairly homogeneous, although the Xerepts BD (C, 1.61 ± 0.13 g cm^{-3}) was significantly higher than the Orthens BD (F, 1.42 ± 0.05 g cm^{-3}). Soils grouped as Ustolls (B) showed a higher BD value than Xerepts with depth limitations soils (D) in zone 3, with 1.69 ± 0.00 g cm^{-3} and 1.47 ± 0.00 g cm^{-3} respectively.

The two types of soils included in Zone 4, Xerepts (C) and Xerepts with depth limitations (D) showed significant differences between them with BD values of 1.61 ± 0.0 g cm^{-3} and 1.87 ± 0.01 g cm^{-3}, respectively. In zone 7, the BD of soils grouped as Orthens (F, 1.65 ± 0.07 g cm^{-3}) was significantly higher than that of Xerepts (C), and of those grouped as Fluventic inceptisols and Entisols (G), 1.51 ± 0.06 g cm^{-3} and 1.48 ± 0.09 g cm^{-3}.

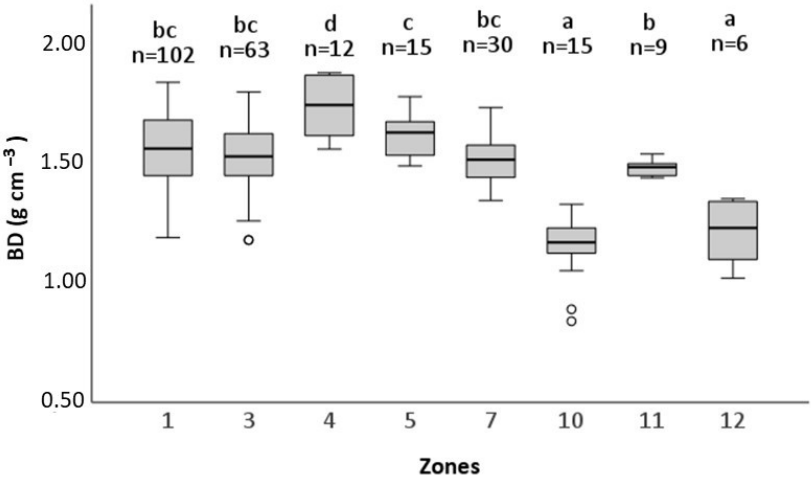


Figure 2. Bulk density (BD) in conventionally managed topsoils (0-30 cm) in each of the zones selected for this study. Center lines show the medians, box limits indicate the 25th and 75th percentiles, whiskers extend 1.5 times the interquartile range from the 25th and 75th percentiles, outliers are represented by dots. Values marked with different letters are significantly different ($p < 0.05$) according to ANOVA. Values showing the same letter belong to the same homogeneous group according to Duncan’s test.

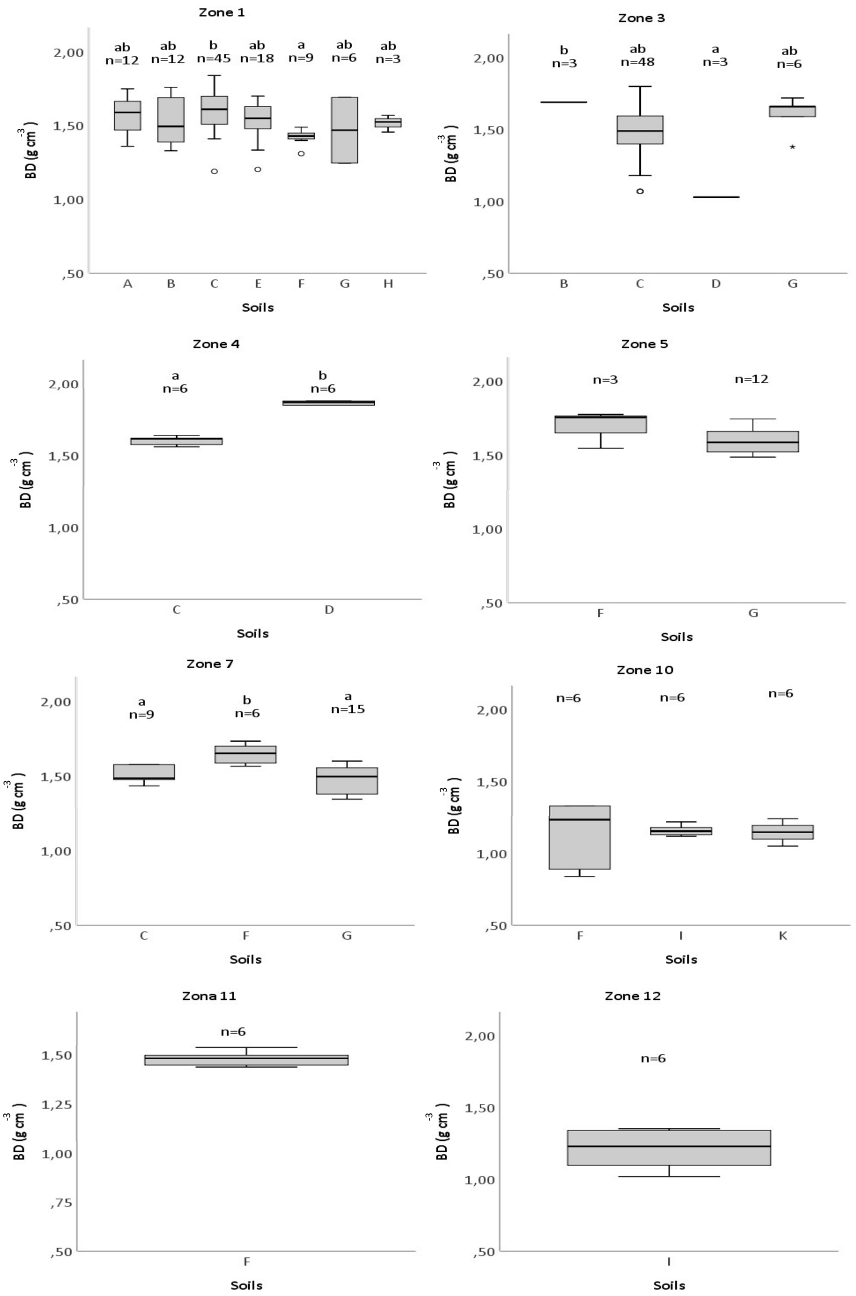


Figure 3. Bulk density (BD) in conventionally managed topsoils (0-30 cm) for the different types of soils in each zone selected for this study. Values showing the same letter belong to the same homogeneous group according to Duncan's test ($p < 0.05$). A: Xerolls, B: Ustolls, C: Xerepts, D: Xerepts with depth limitations, E: Calcids, F: Orthents, G: Fluventic Inceptisols and Entisols; H: Gypsids; I: Udepts; J: Fluventic Udepts, K: Humults (Soil Survey Staff, 2014).

Baseline by agricultural zones and soil type: AWHC. Regarding the results of volumetric soil AWHC in the first 30 cm, represented in Figure 4, an important variability was observed at regional level. However, the same trend observed in the BD analysis was confirmed, since average soil AWHC in zones 10 and 11, with 61.17 ± 11.8 mm and 70.31 ± 7.99 mm respectively, was significantly higher than the others. The rest of the zones showed fairly homogeneous values, although zones 3 and 12 showed values significantly higher than zone 4.

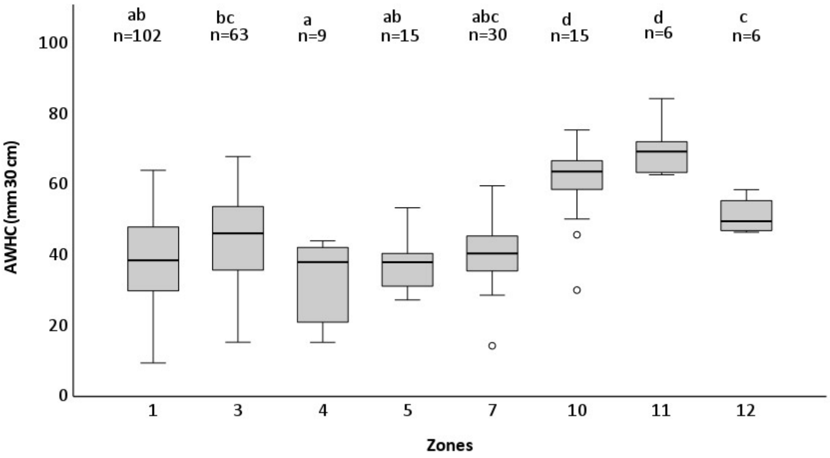


Figure 4. Volumetric soil AWHC (0-30 cm) in each of the zones selected for this study. Center lines show the medians, box limits indicate the 25th and 75th percentiles, whiskers extend 1.5 times the interquartile range from the 25th and 75th percentiles, outliers are represented by dots. Values marked with different letters are significantly different ($p < 0.05$) according to ANOVA. Values showing the same letter belong to the same homogeneous group according to Duncan's test.

Figures 5 shows the results of volumetric soil AWHC of the upper soil layer (0-30 cm) in the different types of soil within each zone considered. Significative differences between soil types were found in zones 1, 3, 4, 5, 7 and 10. In zone 1, all soils were fairly homogeneous in terms of AWHC, although the groups categorized as Calcid (E, 51.30 ± 10.01 mm), Orthents (F, 41.37 ± 6.43 mm) and Fluventic inceptisols and Entisols (G, 47.52 ± 16.88 mm) appeared significantly higher than Xerolls (A, 27.95 ± 11.05 mm). In zone 3, the group of Xerepts with

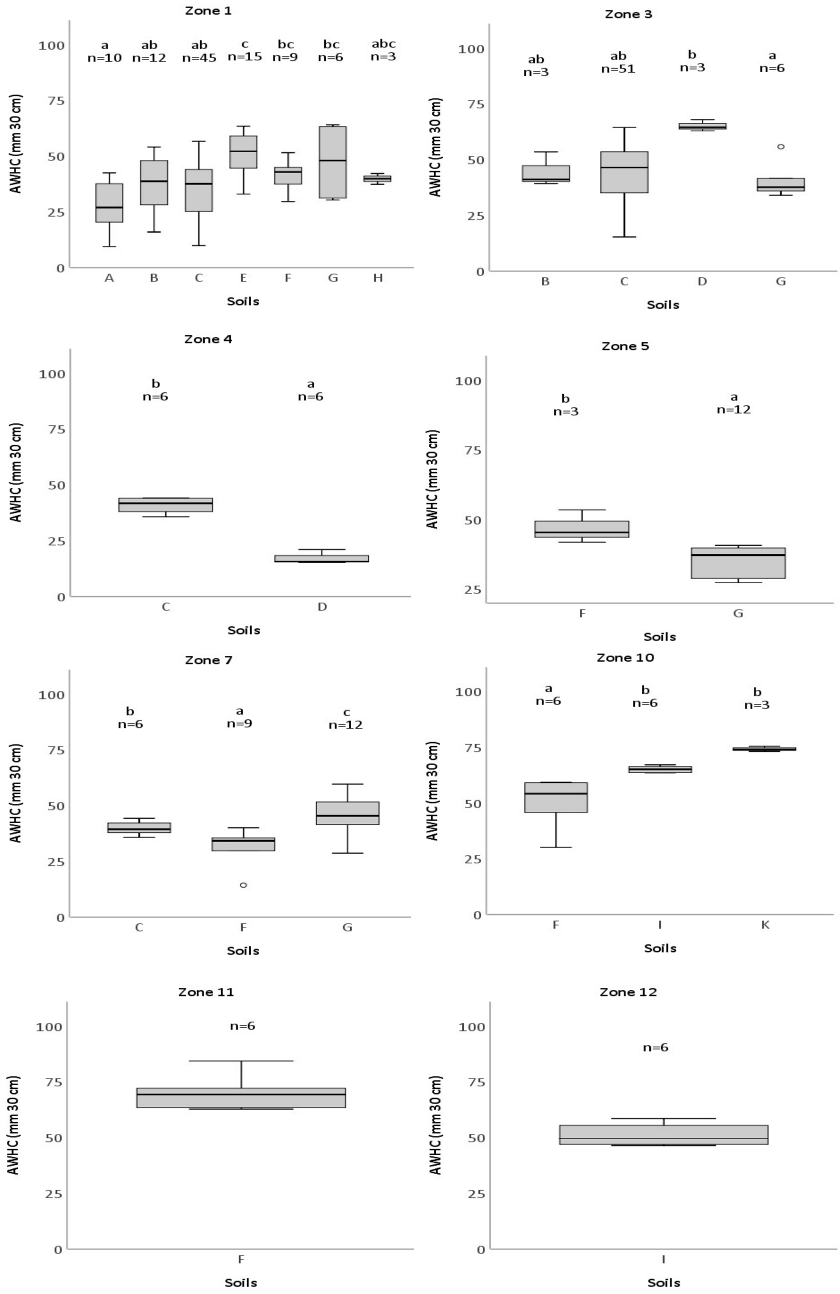
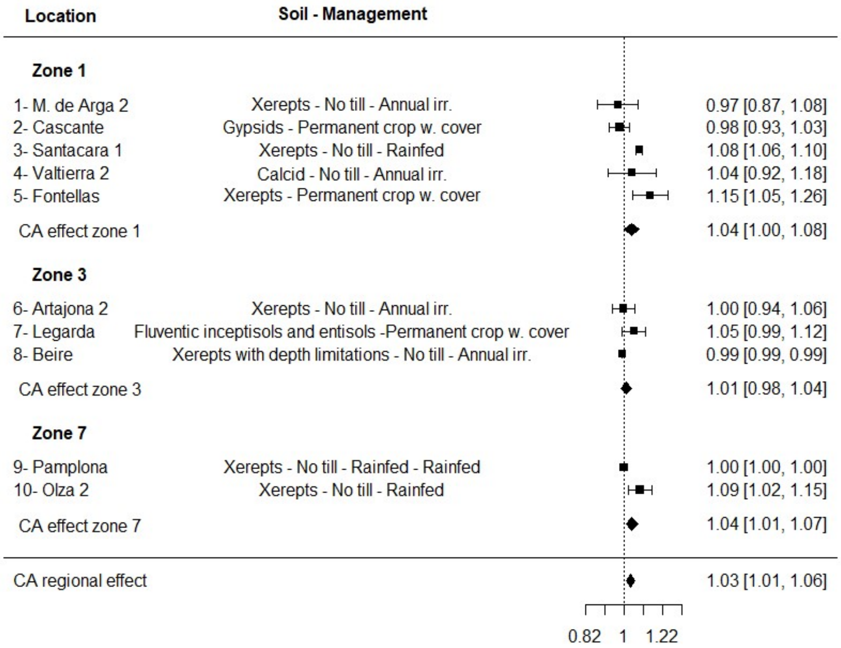


Figure 5. Volumetric soil AWHC in conventionally managed topsoil (0-30 cm) for the different types of soils in each zone selected for this study. Values showing the same letter belong to the same homogeneous group according to Duncan's test ($p < 0.05$). A: Xerolls, B: Ustolls, C: Xerepts, D: Xerepts with depth limitations, E: Calcids, F: Orthents, G: Fluventic Inceptisols and Entisols; H: Gypsids; I: Udepts, J: Fluventic Udepts, K: Humults (Soil Survey Staff, 2014).

depth limitations (D, 59.49 ± 1.38 mm) showed a significantly higher value than soils grouped as Fluventic Inceptisols and Entisols (G, 40.47 ± 7.97 mm). In zone 4, the group of Xerepts (C) showed a significantly higher value than soils categorized as Xerepts with depth limitations (D), with 40.93 ± 3.36 mm and 17.37 ± 3.21 mm respectively. In zone 5, the Orthents soil group (F, 46.93 ± 5.95 mm) showed a significantly higher AWHC value than soils categorized as Fluventic Inceptisols and Entisols (G, 35.04 ± 5.30 mm). The three soils included in zone 7 showed significant differences between them. The Orthents soil group (F) showed the highest value (46.93 ± 5.95 mm) followed by Xerepts (C, 40.07 ± 7.78 mm) and Fluventic inceptisols and entisols group (G), with 31.41 ± 8.98 mm. Finally, soils categorized as Orthents (F) showed a significantly lower AWHC value (50.51 ± 11.39 mm) than the rest of groups within zone 10, with an average AWHC value of 69.79 ± 1.35 mm.

Effect of management on bulk density. Figures 6, 7, 8, 9 and 10 show the results of the effect of the 5 strategies considered on BD, expressed as RR for each group of plots, together with the effect per zone and the overall effect associated to the whole region. It should be noted that, in the case of the BD analysis, the values of the RR above one represent an increase in BD with respect to non-adaptive management (Batey, 2009), so that the positive effect in this case is represented by RR intervals below 1.

The strategy of CA was evaluated in 10 groups through the region. The effect of permanent grass cover in permanent crops was evaluated in 3 groups, where 2 of them showed a neutral effect and one a negative (Figure 6). In the rest of groups, where no till was evaluated, 4 groups was under annual irrigation regime and 3 under rainfed conditions. Within the groups under annual irrigation regime, the trend was neutral, with only one group with a slightly positive effect. In the case of rainfed groups, 2 of 3 of the groups showed a negative effect on BD. At zone level, 2 zones showed a neutral effect, and one zone a negative effect. In the case of the ROT strategy (Figure 7), 9 groups were considered, 6 under irrigated conditions and 3 without irrigation. One of the groups under irrigated condition showed a positive effect (lower BD), in one of them under rainfed conditions the effect was negative (higher BD) and the rest of groups showed a neutral effect. In terms of overall zones evaluation, the 3 zones evaluated in this strategy offered a neutral effect. The strategy ExO (Figure 8) showed a greater variability in the effect than the rest of strategies, so that in 7 of the 16 groups evaluated, a positive effect was observed (lower BD), in 4 groups the effect was negative (higher BD), and in the rest (5 groups) the effect was neutral. Five of the 16 groups within this strategy were under irrigated conditions, where 3 of them showed a positive effect on BD and 2 of them neutral. Groups under rainfed conditions showed a more hetereogeneous effect (4 positive effect, 3 neutral and 4 negative effect). In the evaluation of zones in which more than one group were included, zone 3 showed a positive effect (lower BD), and in zones 1 and 7, the effect observed was neutral. IRR strategy (Figure 9) included 6 groups, 3 of them under intensive irrigation regime and 3 under annual irrigation regime. None of groups under annual irrigation regime showed a negative negative effect. At zones level, zone 1 showed a neutral effect and zone 4 slightly negative effect (higher BD). At zones level, zone 1 showed a neutral effect and zone 4 slightly negative effect (higher BD). Finally, the strategy GSS (Figure 10), showed a negative effect (higher BD) in 2 of the 9 groups evaluated. In 6 groups the effect was neutral and in 1 of them the effect was positive (lower BD). Considering the zones evaluation in which more than one group were included, zone 1 showed a negative effect and in zone 10 a neutral effect was observed. At the regional level, CA showed a negative overall effect (higher BD), the strategies ROT, IRR and GSS showed a neutral effect, and only in the case of plots associated to ExO, a slightly positive effect (lower BD) was observed on the RR. Finally, a general observation was that no relationship was observed between the effect of the strategies considered on BD and the effect on SOC (Supplementary Figure S1).



Location	Soil - Management	
Zone 1		
1- M. de Arga 2	Xerepts - No till - Annual irr.	0.97 [0.87, 1.08]
2- Cascante	Gypsids - Permanent crop w. cover	0.98 [0.93, 1.03]
3- Santacara 1	Xerepts - No till - Rainfed	1.08 [1.06, 1.10]
4- Valtierra 2	Calcid - No till - Annual irr.	1.04 [0.92, 1.18]
5- Fontellas	Xerepts - Permanent crop w. cover	1.15 [1.05, 1.26]
CA effect zone 1		1.04 [1.00, 1.08]
Zone 3		
6- Artajona 2	Xerepts - No till - Annual irr.	1.00 [0.94, 1.06]
7- Legarda	Fluventic inceptisols and entisols -Permanent crop w. cover	1.05 [0.99, 1.12]
8- Beire	Xerepts with depth limitations - No till - Annual irr.	0.99 [0.99, 0.99]
CA effect zone 3		1.01 [0.98, 1.04]
Zone 7		
9- Pamplona	Xerepts - No till - Rainfed - Rainfed	1.00 [1.00, 1.00]
10- Olza 2	Xerepts - No till - Rainfed	1.09 [1.02, 1.15]
CA effect zone 7		1.04 [1.01, 1.07]
CA regional effect		1.03 [1.01, 1.06]

Figure 6. Response ratio (RR) of BD (0-30 cm) for the adaptive management strategy of conservation agriculture (CA). Zones correspond to those in Figure 1. The effect was considered significant when the 95% confidence interval (CI) of the RR did not overlap one (α = 0.05). Soil and management column includes information about principal soil group, strategic management considered and irrigation regime in each group.

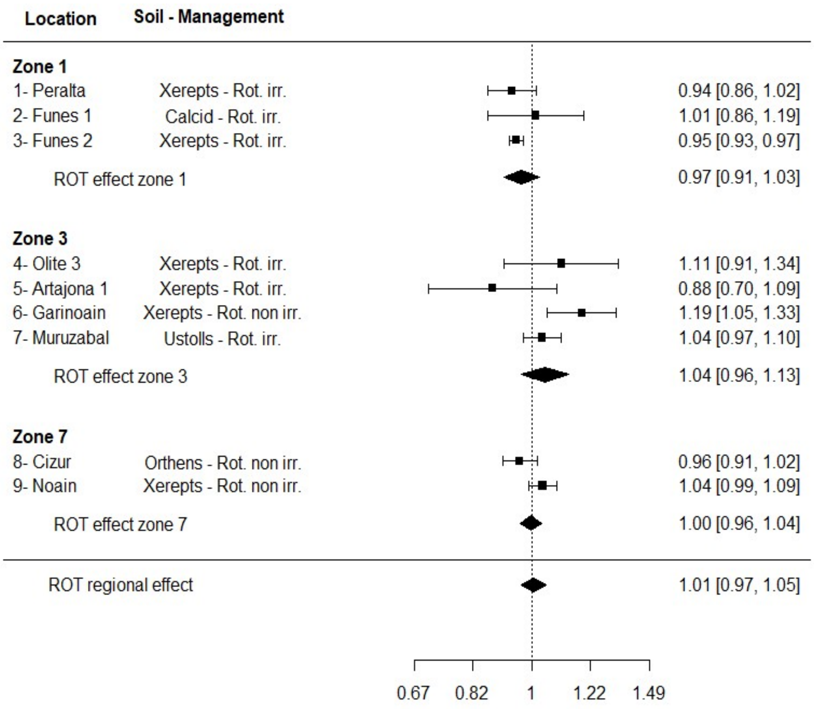


Figure 7. Response ratio (RR) of BD (0-30 cm) for the adaptive management strategy of crop rotations (ROT). Zones correspond to those in Figure 1. The effect was considered significant when the 95% confidence interval (CI) of the RR did not overlap one (α = 0.05). Soil and management column includes information about principal soil group and irrigation regime in each group.

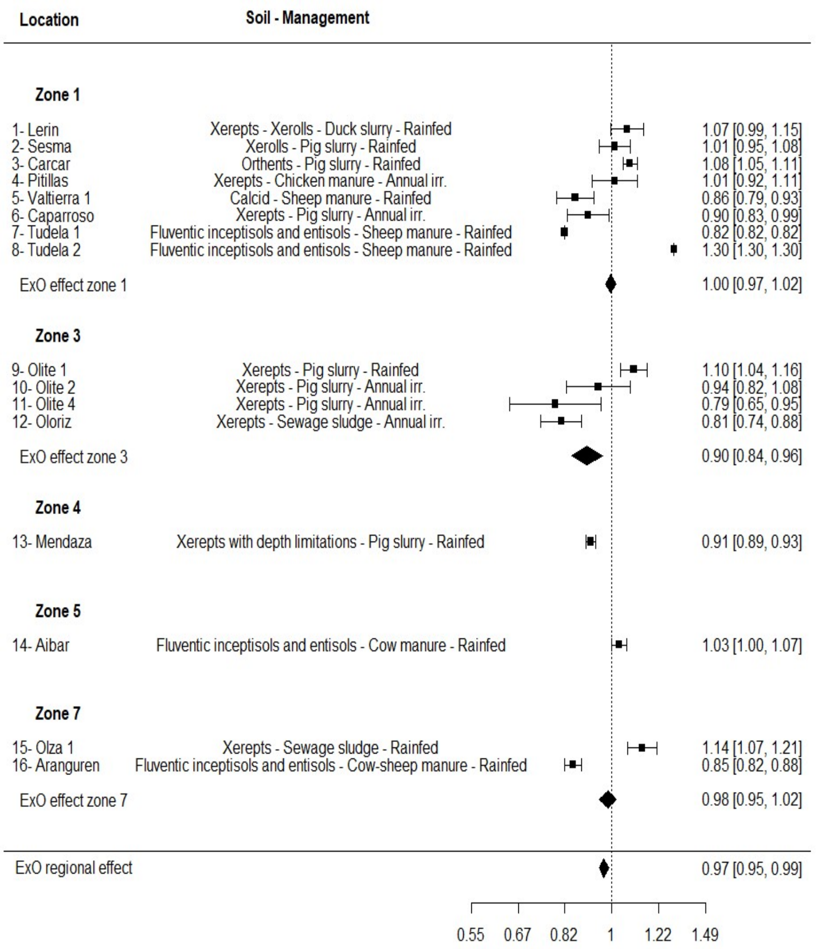


Figure 8. Response ratio (RR) of BD (0-30 cm) for the adaptive management strategy of exogenous sources of organic C addition (ExO). Zones correspond to those in Figure 1. The effect was considered significant when the 95% confidence interval (CI) of the RR did not overlap one (α = 0.05). Soil and management column includes information about principal soil group, organic source applied and irrigation regime in each group.

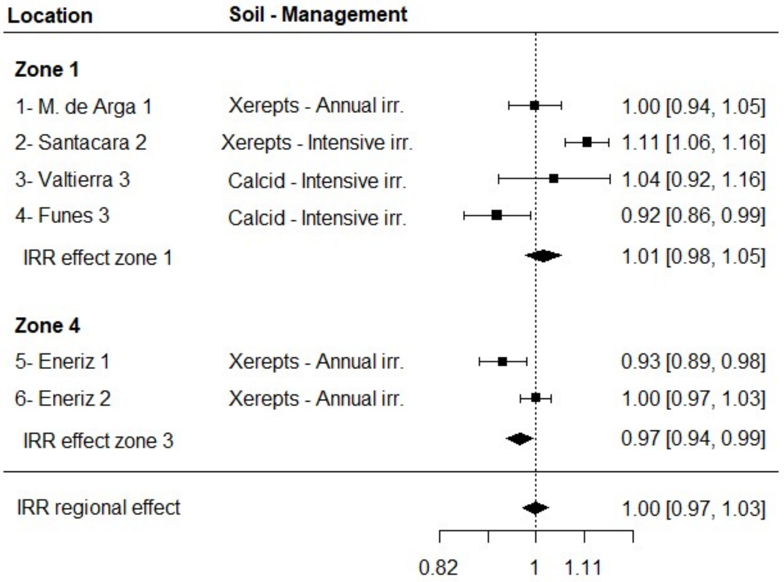


Figure 9. Response ratio (RR) of BD (0-30 cm) for the adaptive management strategy of irrigation (IRR). Zones correspond to those in Figure 1. The effect was considered significant when the 95% confidence interval (CI) of the RR did not overlap one (α = 0.05). Soil and management column includes information about principal soil group and irrigation regime considered in each group.

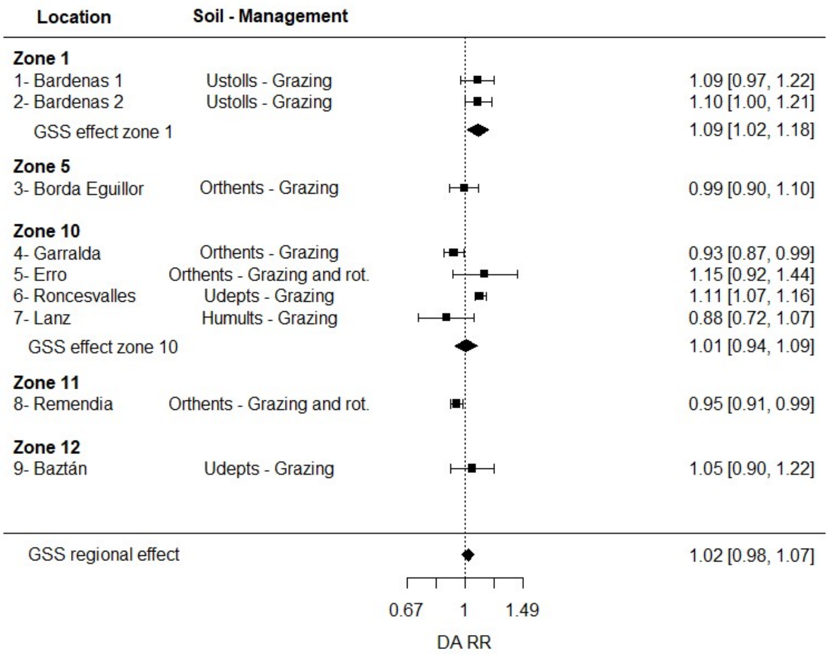


Figure 10. Response ratio (RR) of BD (0-30 cm) for the adaptive management strategy of controlled grazing and/or rotation in grasslands (GSS). Zones correspond to those in Figure 1. The effect was considered significant when the 95% confidence interval (CI) of the RR did not overlap one (α = 0.05). Soil and management column includes information about principal soil group and management considered in each group.

Effect of management on the soil water-holding capacity. Figures 11, 12, 13, 14 and 15 show the results of the RR effect of the strategies considered on the soil AWHC for each group of plots, together with the overall effect by zone and throughout the region. In this case, an increase in the water retention capacity was considered positive.

In the case of practices linked to CA (Figure 11) where 9 groups were considered, no positive effect was observed in any of them. One of the 3 groups where the permanent grass cover in permanent crops was evaluated showed a negative effect on AWHC. In the rest of groups, where no till was evaluated only one group, under rainfed conditions, showed a negative effect on AWHC. At the zone level, zone 1 showed more variability in the response, with an overall negative effect. Zones 3 and 7 showed a neutral effect.

The results associated with ROT (Figure 12) showed great variability within groups. Within the groups under irrigation conditions, one of them showed a positive effect and the rest the effect was neutral. In the case of rainfed groups, the effect was heterogeneous. Considering the evaluation by zones, the 3 zones considered showed a neutral effect. The effect associated to ExO in groups under irrigation conditions showed a positive effect observed in one group in zone 3 whereas the effect was neutral in the other 4 (Figure 13). The results within the ExO groups under rainfed conditions showed a great variability in the region, although the effect observed was negative in 6 of the 11 groups (Figure 13). In the zones evaluation in which more than one group were included, in the 3 zones considered the effect observed was neutral (zones 1, 3 and 7). The IRR strategy (Figure 14), in the case of groups with annual irrigation regimen, the results showed 2 groups with a neutral effect on soil AWHC and one with a positive effect. In the case of the 3 groups under intensive irrigation regime, the results showed negative effect in 2 of them and positive in the third. In terms of zones, zone 1 showed a neutral effect and in the case of zone 4, the effect was positive on this parameter. Finally, the results associated to GSS (Figure 15) showed a neutral effect in 6 out of the 9 groups evaluated. Three groups showed a negative effect on soil AWHC. At the level of zones in which more than one group were included, both zone 1 and 10 showed a neutral effect on this parameter.

As for BD, no relationship was observed between the effect of the strategies considered on AWHC and the effect on SOC (Supplementary Figure S1).

In terms of the regional evaluation, the observed overall effect associated to the strategies ROT, ExO, IRR and GSS was neutral on soil AWHC, whereas the strategy associated to CA was the only one that showed a slightly overall negative effect.

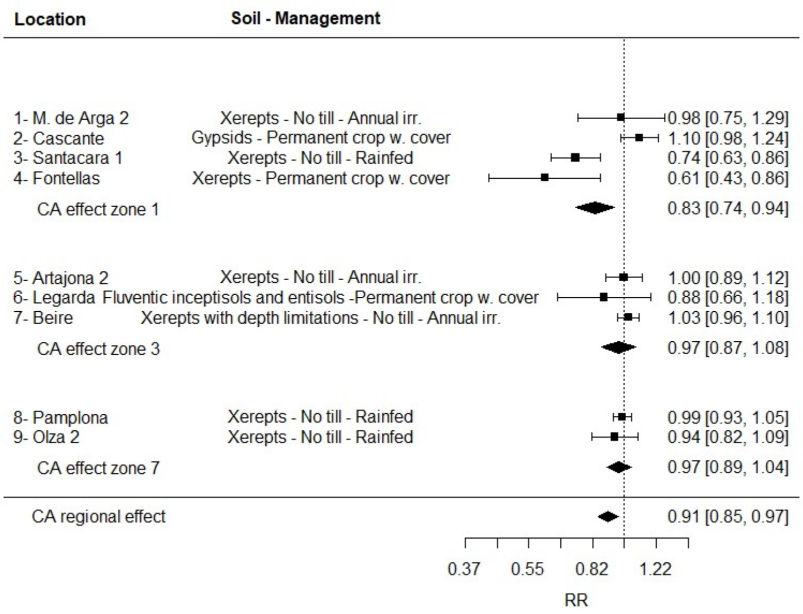


Figure 11. Response ratio (RR) of AWHC (0-30 cm) for the adaptive management strategy of conservation agriculture (CA). Zones correspond to those in Figure 1. The effect was considered significant when the 95% confidence interval (CI) of the RR did not overlap one (α = 0.05). Soil and management column includes information about principal soil group, strategic management considered and irrigation regime in each group.

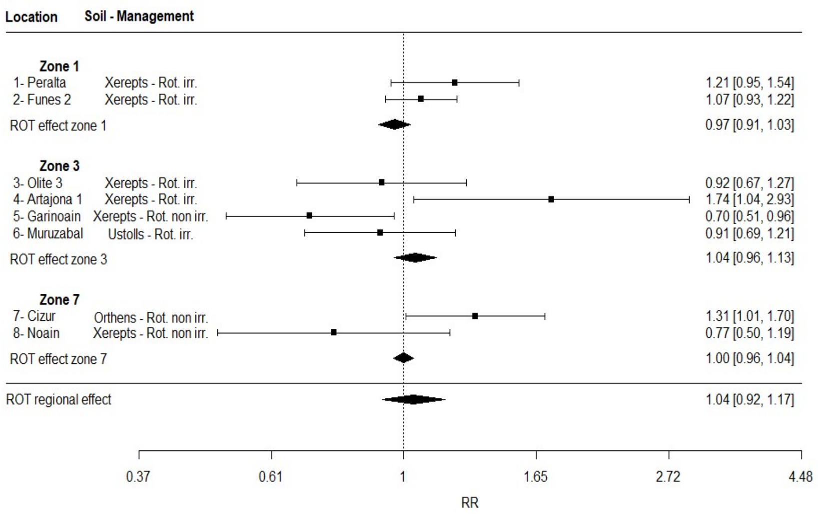


Figure 12. Response ratio (RR) of AWHC (0-30 cm) for the adaptive management strategy of crop rotations (ROT). Zones correspond to those in Figure 1. The effect was considered significant when the 95% confidence interval (CI) of the RR did not overlap one (α = 0.05). Soil and management column includes information about principal soil group and irrigation regime in each group.

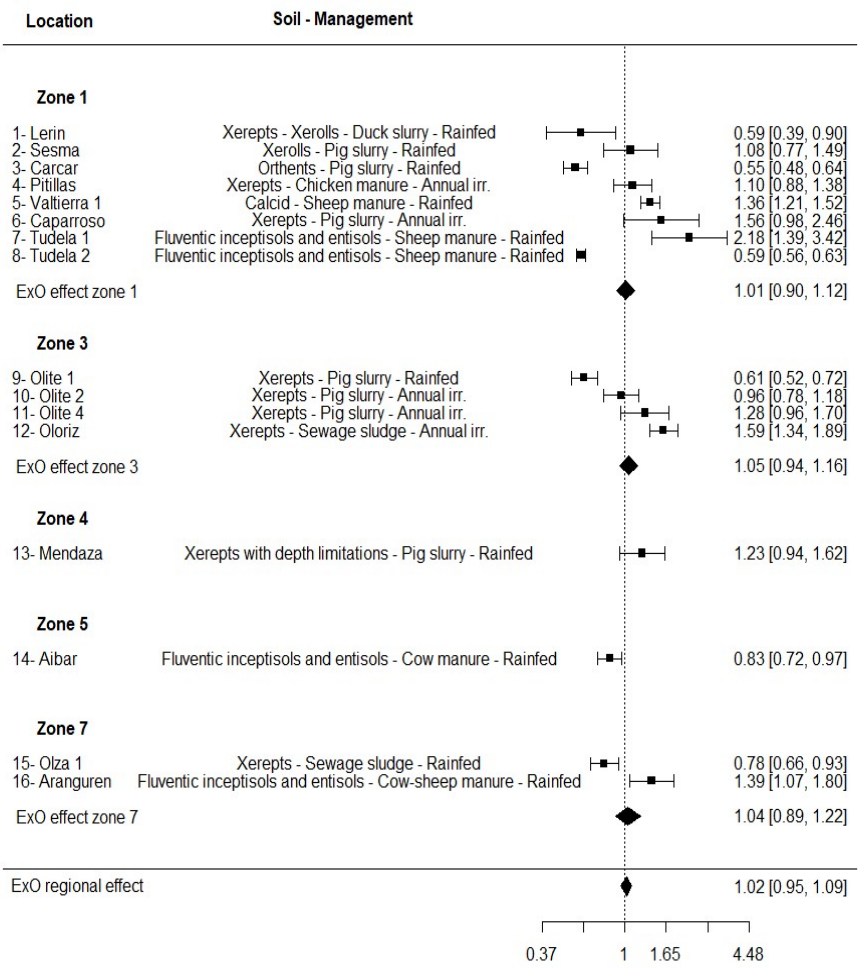


Figure 13. Response ratio (RR) of AWHC (0-30 cm) for the adaptive management strategy of exogenous sources of organic C addition (ExO). Zones correspond to those in Figure 1. The effect was considered significant when the 95% confidence interval (CI) of the RR did not overlap one (α = 0.05). Soil and management column includes information about principal soil group, organic source applied and irrigation regime in each group.

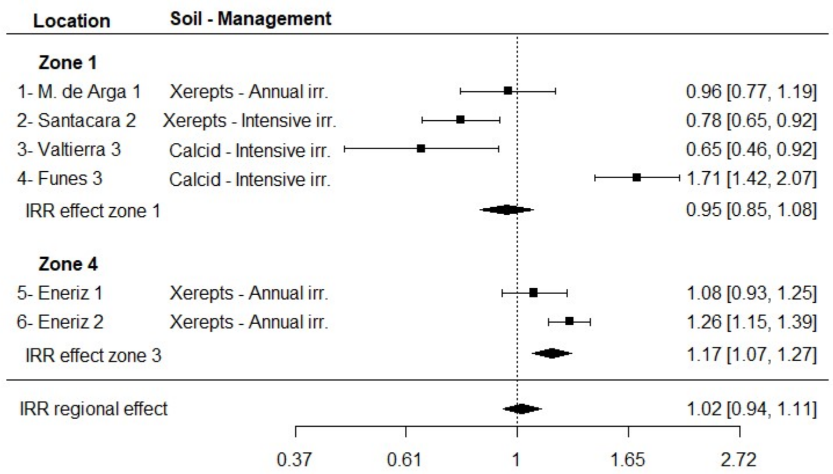


Figure 14. Response ratio (RR) of AWHC (0-30 cm) for the adaptive management strategy of irrigation (IRR). Zones correspond to those in Figure 1. The effect was considered significant when the 95% confidence interval (CI) of the RR did not overlap one (α = 0.05). Soil and management column includes information about principal soil group and irrigation regime considered in each group.

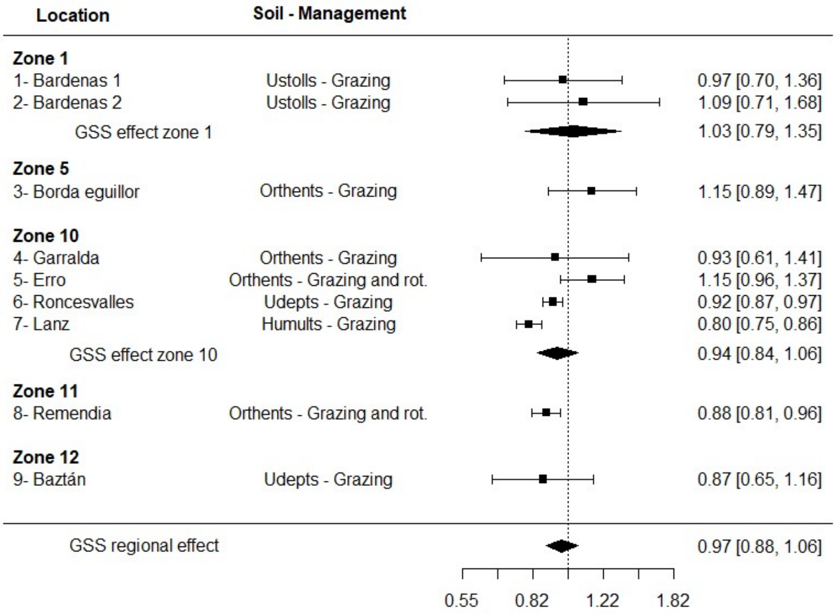


Figure 15. Response ratio (RR) of AWHC (0-30 cm) for the adaptive management strategy of controlled grazing and/or rotation in grasslands (GSS). Zones correspond to those in Figure 1. The effect was considered significant when the 95% confidence interval (CI) of the RR did not overlap one (α = 0.05). Soil and management column includes information about principal soil group and management considered in each group.

DISCUSSION

Regional characteristics. A first general observation can be made in relation to the great variability found both in BD and AWHC in the conventionally-managed fields used as a reference to determine the regional baseline. The source of this variability can be partly explained by the diversity of soils included in the study, belonging to different soil units, and with different SOC stocks (Table 1, see Chapter V), in addition to the wide variety of cultivation systems included within the plots under conventional management in this study, from permanent crops such as olive trees, vineyards or pastures, to plots with arable crops with different management intensities.

The relevance of the amount of SOC stored in the topsoil and the soil physical condition at the regional scale became apparent both for

BD and AWHC. The areas with managements linked to pastures and grasslands, which had the highest SOC contents in average (Table 2, see Chapter V), tended to have the lowest BD values in the region, especially in areas 10 and 12. The highest values of AWHC were also observed in zones 10 and 11, associated with grasslands, and were within the range of those observed in similar pasture zones (Girona-García et al., 2018). This has been repeatedly reported in other regions and national-scale studies (Ammann et al., 2009; Lasanta et al., 2020; Peco et al., 2017; Rodríguez Martín et al., 2016; Tang et al., 2019), and can be explained by the role of SOC in compensating the possible compaction due to intensive grazing and/or cropping (which were the conventional managements tested in these systems) (Johannes et al., 2017; Schäffer et al., 2008). This relationship was reflected in the results of the group associated with pastures in zone 1 (semi-arid), that showed much lower SOC contents (see Chapter V), and displayed AWHC values in line with those observed in cultivated plots in the same zone, and far from the values observed in zones 10 and 11. Greater SOC stocks observed in these zones can be explained by a higher primary productivity because of a moister climate (Table 1), and to the absence of a regular alteration of soil structure by tillage (Bescansa et al., 2006). As for BD, this can be linked to the higher SOC contents observed in these areas associated

BD and AWHC values observed in the other zones, mostly associated to cultivation of different crops, were within those observed in agricultural soils in previous studies conducted in the region (Antón et al., 2019; Bescansa et al., 2006; Fernández-Ugalde et al., 2009; Imaz et al., 2010). Intensive tillage, lower SOC contents than grasslands, and differences in the basic physical-chemical characteristics of the soil as a result of intensive agricultural management may explain the differences observed within the areas and soil types present in each zone (Tang et al., 2019). Seasonal variations of BD as described by some authors (Franzluebbers et al., 1995; Logsdon and Karlen, 2004) can be considered less relevant, as the sampling routine was performed at similar crop stages, corresponding to the end of the growing season or close to harvest.

Adaptive management and bulk density. In relation to the overall effect of the agricultural managements tested in the region on BD, the different strategies evaluated showed a heterogeneous response. Only the strategy ExO showed an overall positive effect on this parameter. ROT, IRR and GSS displayed no clear effect and, in the case of CA, the effect was slightly negative overall.

Greater values of BD than under conventional management, and overall soil compaction, have frequently been associated to the reduction or suppression of tillage with CA (Powlson et al., 2012). However, such an increment seems not clear, or at least not systematic. For instance, Blanco-Canqui & Ruis (2018) suggested that CA can have mixed effects on soil bulk density. Nunes et al. (2020), in a meta-analysis carried out from 295 studies located in the USA, did in fact not find differences in BD between different tillage intensities within the topsoil layers. This variability in the response, together with an overall slightly negative effect observed in this study, support these observations of a heterogeneous response. Even so, the negative trend was more evident in the rainfed groups, in line with previous studies developed in experimental plots in the region, which showed increased BD associated with no tillage throughout the profile (Fernández-Ugalde et al., 2009; Virto et al., 2007). As well as CA is usually associated to a better storage of SOC in the topsoil (González-Sánchez et al., 2012), many authors have emphasized the negative correlation between increases in SOC and soil compaction under CA (Mary et al., 2020; Nunes et al., 2020; Powlson et al., 2014). In this case, although CA showed an overall positive regional effect on SOC of around 24% (Table 2, Chapter V), this increment did not seem to be materialized in an improvement in BD conditions (Figure 6), as it has been observed after the suppression of tillage or the implementation of cover crops, and associated with an increase in SOC and/or root development (Gómez et al., 2011; Priori et al., 2020). This highlights the need for a better understanding between SOC dynamics and soil physics at the local scale. For instance, CA has been seen to have contrasted effects on soil quality in semi-arid land, depending on the crops rotation strategy accompanying it (Schmidt et al., 2018).

The strategy ExO was the only one that resulted in a positive effect on BD in the network of plots considered in this study, reducing it at least partially, since the results displayed also a high variability. This variability can be related to soil characteristics, management and to the different types of amendments and doses used, as ExO amendments were applied according to crops needs and availability of economically viable organic matter sources. Although this strategy only included 5 groups under irrigation, none of this groups showed a negative effect, and it was positive in 3 of them, whereas the response on the rainfed groups was clearly more heterogeneous. The positive effect of ExO in SOC storage has been observed by several authors as responsible for soil (de)compaction (Anderson et al., 1990; Powlson et al., 2012). This coincides with the observed positive regional effect of ExO on topsoil SOC storage in the studied plots (around 31%, Table 2, Chapter V). On the other hand, no consistent trend was identified between the types of amendments applied or the different zones evaluated, with an unequal effect throughout the region (Figure 8). The fact that these plots are under conventional soil management including tillage, should also be considered, because of the homogenizing effect of tillage on this parameter. For instance, the sensitivity of BD and other physical indicators to manure addition was seen to be relatively small compared with that of tillage after 7 years of combined treatment (Bottinelli et al., 2013).

Considering the ROT strategy assessment, the overall effect observed was neutral throughout the region, although the variability in the response was higher than in CA and ExO (Figure 7). The decrease in BD normally associated with crop rotations is usually related to an increase in SOC, so that crop rotations driving SOC gains can result in improved BD (Zuber et al., 2015). In this case, this strategy showed a slightly negative overall regional effect on SOC around -10% (Table 2, Chapter V). For Zuber et al. (2015), the factors that may determine the direction of the effect include soil texture, previous SOC content, crop and tillage intensity, and the climatic region where the system is located. In this respect, most of the groups considered in this strategy included irrigation, which usually can be associated to increased cropping and tillage intensity compared to rainfed systems. Also, plots in all groups considered in this strategy were under conventional soil management including annual tillage.

The latter observation can also explain the overall neutral effect observed in the IRR strategy. Although in this case, the intensity of tillage and the soil homogenization may be counteracting the positive effect on SOC observed associated with this strategy of around 25% (Table 2, Chapter V). It is also important to note that different irrigation regimes were considered under this strategy: while irrigation of annual crops showed no negative effect on BD within the groups analyzed, in contrast with the intensive irrigation regimes.

Finally, for the management of pastures and grasslands (GSS), our results indicated that this strategy did not significantly change the BD at the depth considered. In general, it has been observed that the trampling action of grazing animals when impacting the soil can increase BD, as well as its mechanical resistance (Byrnes et al., 2018; Evans et al., 2012). These authors agree that the intensity of grazing and the time of the year when it happens are determining factors in this case. Byrnes et al. (2018) also included the local environmental conditions associated to the geographical location of grasslands as relevant in their effect on soil condition. In this sense, a slight response to the climatic gradient in our region may be appreciated in the results (Figure 10). The two groups of plots located in zone 1 (the most arid one in the study, Table 1), were those with a negative effect on BD, compared to those groups in more humid areas, which displayed no or positive effects of GSS. It has to be noted too that GSS plots located in zone 1 showed no differences in BD with the cultivated plots in the same area (Figures 10), which highlights the dependence of the response of BD on the scale and location where the soils response to management is studied.

Adaptive management and available water-holding capacity. The first general observation when assessing the response of the different strategies on AWHC is that this parameter seemed to respond to soil and crop management, although the effect was highly variable. Four of the strategies considered (ROT, ExO, IRR and GSS) showed an overall neutral effect, although the results within the zones were heterogeneous. CA was the only one strategy that showed a negative overall effect, although the effect observed within zones associated to that strategy tends to be neutral.

In this sense, both components of AWHC, namely soil moisture retention at field capacity and permanent wilting point, are often related to SOC content (Lal, 2020). In general, soil moisture at field capacity shows a clearer response to SOC, while the response of the soils moisture at wilting point usually is more variable and may depend, in part, on texture (Minasny and McBratney, 2018; Wall and Heiskanen, 2003; Yost and Hartemink, 2019). Hence, the strategies that favor the increase of SOC should also improve the soil AWHC in those soils where an increment of SOC results in a more favorable effect on soil moisture content at field capacity than at wilting point.

Conservation agriculture is often associated with improved soil physical properties which facilitate water absorption and retention, and therefore, its availability for crops (Nunes et al., 2020; Powlson et al., 2014). However, Blanco-Canqui & Ruis (2018), in a review of 14 studies on the effect of CA on AWHC, observed mixed results. According to these authors, the increase in AWHC observed in some cases can be mainly attributed to the gains in SOC generally observed with CA (González-Sánchez et al., 2012). Previous studies conducted in experimental plots in the region showed an improvement in AWHC associated to no-till, which was attributed not only to higher SOC contents, but also to changes in the size and distribution of the network of pores at the topsoil promoted by crop residue management (Bescansa et al., 2006; Fernández-Ugalde et al., 2009). In this study, however, the effect associated to CA on AWHC within the groups was heterogeneous but globally neutral (Figure 11), and the effect on SOC, although also showed some heterogeneity on the same groups evaluated, was negative and close to 0 in zones 3 and 7 in comparison to zone 1, with neutral-positive effect (data not shown). These zones differ mostly in their moisture regime, which is drier in zone 1 than in zones 3 and 7. Crop residues left over the soil in CA provide protection from raindrop impact, reduce flow of surface runoff and may prevent pore sealing and crust formation, increasing the available water to be infiltrate and reducing evapotranspiration (Li et al., 2011). In this line, although some authors suggest that CA may allow for saving irrigation water by improving soil water retention properties (and reducing evapotranspiration) (Ali et al., 2017; Fonteyne et al., 2019), no differences on AWHC were observed within groups where this strategy was applied in irrigated conditions (Figure 11).

The results also indicated that the effect of CA seemed more related to the use of permanent soil cover in permanent crops in comparison to no-till in annual crops than to the fact that the agrosystems were rainfed or irrigated (Figure 11). Permanent soil cover showed a higher variability in the response than no-till, although in this case there was a significant improvement in SOC associated to this practice (data not shown). As already discussed in the BD section, cover crops management can affect in a variable sense the physical conditions of these soils, including those related to water retention (Priori et al., 2020; Virto et al., 2012). This highlights the need of on-site evaluation of the effect of CA on soil water retention in the region, contrasting in detail the results of the agricultural fields considered in each case, before making extrapolations at the regional level.

The results associated to ROT strategy on AWHC in this study showed a neutral effect, with a great variability within groups (Figure 12), and a negative effect on SOC of around -10% (Table 2, Chapter V). For Indoria et al. (2017), the appropriate application of crop rotations can favor the development of micro and macro pores or channels that facilitate the movement and retention of soil water. However, these authors indicated that these positive effects can be modulated by the cropping system and its intensification, and their consequences in the improvement of soil structure, porosity, and SOC content. This is in line with the results found in other studies, in which cross effects were observed both by the type of crops included in the rotation and by the intensity of management (Kazula et al., 2017; Mtyobile et al., 2020). The variety and intensity of the systems included in this study, which, as mentioned above, were mostly associated with irrigation systems, may be influencing the ROT effect.

In this sense, although IRR showed a neutral effect overall (Figure 14), this strategy showed a diverse response throughout the region. The assessment of this strategy can be directly related in this case to the ROT strategy, since as mentioned, the direction of the effect is determined by the type of crop used, intensity of management and tillage system. As observed on BD assessment, annual irrigation regime showed no negative effect on AWHC within the groups analyzed, contrasting with the results associated to intensive irrigation.

Exogenous applications of organic C in the soil are also commonly associated to an improvement on soil physical properties, which implies, among other things, an improvement in the retention of available water for crops (Anderson et al., 1990; Blanco-Canqui et al., 2015; Powlson et al., 2012). This strategy offered indeed the best results in both soil BD and SOC (Figure 8 and Table 2, see Chapter V) in this regional study. In terms of AWHC, despite the overall neutral effect observed, the results showed a great variability both within groups, and in terms of the effect direction (Figure 13). The different types and doses of organic amendments applied could explain this heterogeneity, as least partially, but other interfering factors, such as cultivation or tillage, should be considered when evaluating this strategy at a regional level. In this sense, in line to that observed in the BD assessment, none of 5 groups considered under irrigation conditions showed negative effects on AWHC. In any case, these contrasting results at regional scale showed that there was not a direct relationship between SOC gains and improvements of the soil AWHC in the fields considered in this study (Supplementary Figure S1).

Finally, considering the last strategy, GSS, the results observed in this study showed a neutral effect on AWHC (Figure 15). In this regard, it is known that the effect of trampling by grazing animals can cause soil compaction, decreasing the soil pore space and causing a reduction in infiltration and soil water retention (Hao and He, 2019; Milchunas and Lauenroth, 1993; Pulido et al., 2018). For many authors, the effect of this strategy on soil AWHC depends on the intensity of grazing (Dong et al., 2015; Teague et al., 2011), and the geographical location (Mcsherry and Ritchie, 2013).

Regional assessment. The first remarkable observation at the regional scale was that soil type, as considered in this study, revealed not to be a relevant factor in the evaluation of the impact of the strategies assessed. This could be explained because, although soil types were selected based on their taxonomic characteristics in Soil Taxonomy (Soil Survey Staff, 2014), at the depth considered in this study (0-30 cm) profiles that differ in their taxonomic classification may have similar characteristics in this profile. In addition, in the same line, since all the soils included in this study were agricultural soils mostly managed for decades to improve their conditions for crop development, this may imply a homogenization of their properties in the upper profile (Kuzyakov and Zamanian, 2019).

In relation to the assessment of the soil indicators considered at the regional level, it can be understood that most of the strategies considered here did not show negative effects, and in some cases, some positive effects were observed. It is important to remind that these strategies were assessed because they are already in use in different areas of the region. This suggests that, as observed previously, if they are interesting from the point of view of their profitability, and could have some other positive effects, for instance in SOC storage or controlling or reversing the physical and hydraulic degradation processes, they can be at least considered as able to preserve soil properties and, therefore, soil functions. It should be noted that, this effect, however, is modulated by other factors and should be evaluated in each context.

As observed in other regions (Blanco-Canqui and Ruis, 2018; Nunes et al., 2020), one of the major concerns of producers in the region regarding the reduction of tillage is the risk of increased soil compaction that may affect seedling emergence, root growth or crop yields. In our study, it was observed that, although the effect at the regional level was negative, it was neutral in most of the groups where CA was evaluated. These considerations, together with the fact that CA can be an effective technique in the promotion of SOC in the upper soil layer (Table 2, see chapter V) and the beneficial effects of crop residues management in CA discussed above, mean that CA may represent a strategy to be considered when assessing climate change adaptation in the region. The latter seems to have a climate- or site-dependent effect, with zone 1, with the largest agricultural area, showing the best results. This zone also presents some of the worst soils in terms of physical and hydrological degradation, so that, a case-by-case context should be considered in order to improve this soils condition. In relation to permanent crops, although the use of cover crops showed a wide range of response on the physical indicators considered, their contribution in order to control water erosion, reducing both the first impact of rain drops on the soil and water runoff, is also widely accepted (Priori et al., 2020). Therefore, their application should be considered a promising one to preserve soil degradation and within climate change adaptation strategies in the region.

An adequate combination of ROT and IRR should be explored in context-specific assessments, considering that, on the one hand, the major climate change threats identified for this region are related to changes in temperatures (average increase and heat waves) and rainfall (scarcity and extreme events), and, on the other hand, they represent very widespread practices in the region. In this sense, a detailed study of the soil water movement and retention, and possible measures to improve them, are essential for developing an efficient irrigation system in the semi-arid part of this region, as in many other regions with limited water resources projections (Al-Rumikhani, 2002). However, it should be kept in mind that the results in terms of AWHC underline the fact that the possible differences in this parameter induced by the different managements tested here can be ephemeral in conventional cultivation practices (Chan and Heenan, 1996).

The variability of results associated to the ExO strategy on BD and AWHC suggest that factors as soil characteristics and types of amendments and doses, together with the soil management system, should be taken into account when evaluating this strategy at the regional level. Even so, it represents a strategy to be considered when evaluating both soil degradation control strategies and regional adaptation to climate change, considering, additionally, that presents the best results in terms of SOC promotion. It should also be noted that it allows for the redistribution of surpluses from intensive animal farms or water treatment plants. In this respect, other factors such as the geographical location of the source, their availability and their economic viability should be also considered. Last observation is that most of the groups considered within this strategy were on rainfed conditions, also within zone 1 where irrigation is more extended. This is especially interesting considering that the groups under irrigation conditions reported interesting results, at least in terms of BD.

The results associated with the GSS strategy in relation to BD and AWHC showed a variable effect across the region, where the climate gradient seemed to be a factor, at least in BD. The site-specific factors related to each geographical location appear to be relevant to assess the potential for adaptation to climate change in the region associated with this strategy (Byrnes et al., 2018). In this sense, the zones where this management was more extended, in the North of the region, showed the best results (above average) in terms of physical and hydrological soil degradation.

The observed variability in terms of the adoption and effectiveness of the five strategies tested in this region also suggests that one strategy alone might be not enough to globally improve the soil physical condition. In this sense, some authors have proposed the combination of measures such as irrigation (Fonteyne et al., 2019; Trost et al., 2013) with cover crops and/or animal manure application (Blanco-Canqui and Ruis, 2018), as more effective for instance to improve the potential of no-till in order to enhance the physical properties of the soil and guarantee profitable yields (Pittelkow et al., 2014). Priori et al. (2020) also proposed a combination of cover crops with the use of proper organic amendments, subsoiling techniques as well as use of biological inoculants in degraded areas of tree crops, in order to couple their positive effect. For these authors, the best strategy must be not only site-specific, but also adapted to the ecosystem functions to be improved.

CONCLUSIONS

The aim of this study was to evaluate the effectiveness of different agricultural adaptive strategies considered in the framework of the regional climate change roadmap in the region of Navarre (Spain) (Gobierno de Navarra, 2017) and Nadapta LIFE project in order to control and reverse soil physical degradation and agrosystems vulnerability to climate change. For that purpose, soil indicators associated to soil compaction and water retention were monitored through a network of plot within the region. Both physical parameters considered, BD and AWHC seemed to respond to soil and crop management, although the effect was highly variable.

Although the effect on the physical parameters considered were heterogeneous, the potential benefits associated with CA, both in cultivated plots and in permanent crops, make it interesting in terms of controlling soil degradation processes. The combination of ROT and IRR strategies seems also promising for improving the adaptability of agrosystems in the semi-arid part of this region. ExO should be also considered as a strategy within a framework of climate change regional adaptation, considering that it may allow for the redistribution of surpluses from intensive animal farms or water treatment plants in line with the Circular Economy Action Plan from the European Green Deal (European Commission, 2019). Site-specific environmental factors appeared to be relevant to assess the potential of the GSS strategy.

The observed variability in terms of the adoption and effectiveness of the five strategies tested in this region seemed to be modulated by geographical and management factors, which should therefore be evaluated in each context. This highlights the need to understand the complexity of interrelationships between different aspects of soil management and soil properties at a regional scale, and indicates that more detailed research is needed to assess soil vulnerability and the possible adaptability potential of agricultural management. Moving towards a diagnosis and advice at farm level seems necessary in this sense.

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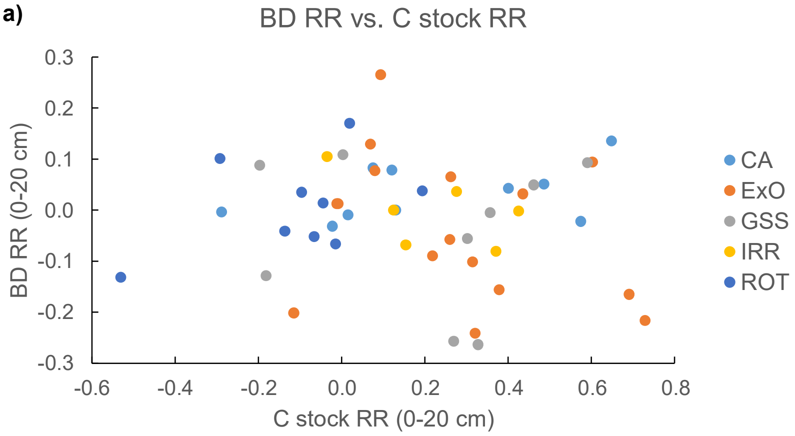
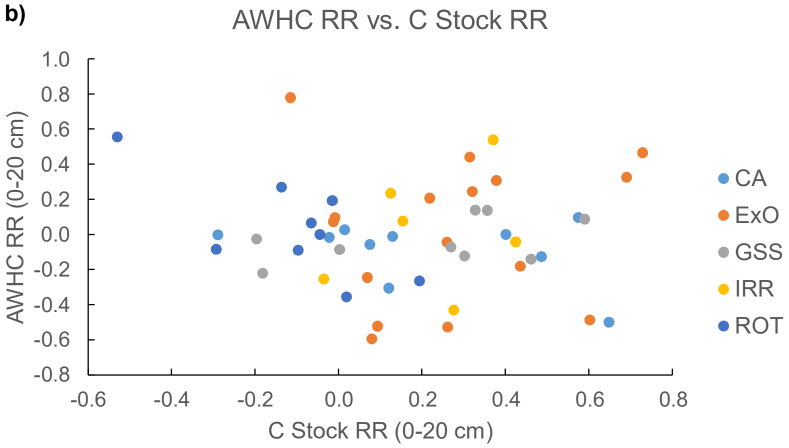
Supplementary figure S1. Response ratios of BD (a) and AWHC (b) vs. those observed for soil organic C stock. 5 different strategies represented by colour: conservation agriculture (CA), management of exogenous sources of organic C (ExO), crop rotations (ROT), irrigation (IRR) and optimized grasslands management (GSS).

a)



b)



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Chapter VII

General discussion
Conclusions

En Agricultura, como en el Comercio, es necesario muchas veces saber perder, para ganar.

Daniel Nagore Nagore
Plegarias del árbol. Enseñanza ambulante.
Diputación Foral y Provincial de Navarra. Dirección de Agricultura y Ganadería. Editorial Aramburu. Pamplona, 1939

CHAPTER VII

General discussion and conclusions

CONTENTS

GENERAL DISCUSSION

Global change and land use

The EU's *Green Deal* establishes an ambitious goal of a climate-neutral Europe by 2050, driving the transition to a green and circular economy, the reduction of pollution and emissions, and the protection of biodiversity (European Commission, 2019). It represents a major challenge for society, as well as for policymakers, industry, and certainly, for science.

In this journey, the agriculture sector clearly appears at the spot light for many reasons. On the one hand, the sector was responsible for 12.5 % of greenhouse gases (GHG) emissions in the EU-27 in 2018 (15.3 % in the case of Spain) (EEA, 2018). A regional analysis shows that the largest contribution to these emissions comes from regions where agriculture is most widespread, with five countries (France, Germany, Spain, Poland and Italy), representing more than 60% of agriculture GHG emissions in Europe. On the other hand, the role of the sector as a C sink agent is widely accepted, by the potential of agriculture to sequester CO_2 and promote C storage in agricultural soils (Chenu et al., 2019; Lal, 2020a; Rumpel et al., 2020). The C storage potential of agricultural soils has been explained associated to historical land degradation issuing from the conversion of natural ecosystems into managed ecosystems, inducing the depletion of soil organic carbon stocks (Lal 2020a). Therefore, for this author, the soil C storage potential will be determined by this historical C loss and the severity and type of degradation, estimating the world soil C storage potential at around 178 Pg in soil (84 ppm of atmospheric CO_2 drawdown).

It is known that an adequate agricultural management strategy involving both tillage control and fertilization can minimize net GHG emissions from agricultural systems, and redirect the net balance toward agrosystems that perform as C sinks (Adviento-Borbe et al., 2007; Ghimire et al., 2017; Mosier et al., 2006, 2005; Sainju et al., 2014). From the mitigation perspective it is however mandatory that the scientific community coordinates and collaborates with policy makers, externalist agents, farmers and other stakeholders to explore and capitalize this potential in order to explore the adequate climate change mitigation options and to enhance the agrosystems resilience (adaptability to changes in climate and other hazards such as pest or diseases). This progressive change seems the most promising, if not the only, way to facilitate a transition towards a primary production system that achieves the ambitious objectives set out in the EU *Green Deal*, and the sustainability standards that society demands (Augier et al., 2020; European Commission Staff, 2020).

Green Deal transition monitoring

An additional major challenge that science must undoubtedly address is the development of instruments and tools to control and monitor this process of transition (European Commission Staff, 2020). This includes the development both of indicators and of sampling methodologies and strategies that enable to monitor the agrosystem as a whole. In particular, following the growing interest in better managing soils to increase soil organic carbon (SOC) contents, the need for credible and reliable measurement/monitoring methodologies for measuring SOC changes directly in soils is emerging, both for national reporting and for emissions trading (Smith et al., 2019). Evidence of this interest is the Joint Research Centre of the European Commission initiative of the LUCAS project (Tóth et al., 2013), the 4per1000 initiative (Rumpel et al., 2020), the incorporation of changes in C stocks in the IPCC's Guidelines for National Greenhouse Gas Inventories associated to the Agriculture, Forestry and Other Land Use (AFOLU) sector (Ogle et al., 2019) or the recent publication of a protocol for measurement, monitoring, reporting and verification of soil organic carbon in agricultural landscapes by FAO (FAO, 2020).

In this sense, the methodology developed throughout this thesis for monitoring changes in soil organic C stock may represent an interesting contribution to the scientific community. This work was carried out with the challenge of developing an effective sampling strategy to determine changes in C stocks, taking into account the scale change from the field to the region, in order to represent a characterization as close as possible to the reality of the territory.

The evolution of the methodology used is evident throughout the thesis. First, the regional study associated to the LIFE Regadiox project (Chapter IV), involving an important component of soil study, focused on the characterization of irrigated agriculture in the region. This project involved the development of a small network of actual agricultural productive plots to characterize different irrigation managements in 3 different irrigated districts in the region. Soil was a determining factor in the definition of this network of plots, where 21 plots were included in total (although for the study presented in this thesis only 8 of these plots were considered). This study also involved the development of an effective sampling protocol for the determination of stock changes in paired plots based on that proposed by Stolbovoy et al. (2007) for the European Commission (see Chapter IV).

This strategy was expanded and improved in the course of the development of the Nadapa LIFE project. In this case, the challenge was the need to characterize the region. From the zoning elaborated to guarantee a regional characterization according to the potential use of the soil for agricultural purposes, to the definition of a network of agricultural productive plots with more than 150 plots in it (and more than 200 considered), ensuring the characterization of the strategies specified in the project. The soil type was again a key factor in this work, in order to provide the best representativeness of the results in the comparisons made within the groups of plots. The development of the sampling strategy to comply with the schedule and, at the same time, ensure the maximum effectiveness of the results represented a real challenge, in addition to data processing and evaluation of the results obtained in order to deal with the spatial variability of the territory. Indeed, in this case the study was not only focused on changes in SOC, but also included other soil indicators as available water holding capacity and bulk density (see Chapters V and VI).

The methodological development carried out in this thesis constitutes one of the most important transversal results of this work. Furthermore, it may represent an interesting contribution to the scientific community, with easy reproducibility in other territories and scales, and applicable to the evaluation of other land uses. As stated in the *Analysis of links between the common* agricultural *policy (CAP) reform and Green Deal* by the EU Commission (European Commission Staff, 2020) "*identifying better methods for measuring carbon removals in agriculture is the first step to enable payments to farmers for the carbon sequestration they provide*."

Climate-change resilient agriculture in Navarre

Agricultural soil degradation in Europe affects more than 56% of the arable area (Prăvălie et al., 2021), involving a multi-pathways process that includes aridity, soil erosion, vegetation decline, soil salinization and SOC decline. Most of these degradation problems are located in Southern Europe, the most arid region (Peel et al., 2007), presenting the lowest values in SOC stocks (de Brogniez et al., 2014), and the highest estimated soil erosion rates (Panagos et al., 2020).

The territorial study carried out in this thesis confirms that the same pattern is repeated in Navarre, with the poorest soils in SOC content located in the Southern area of the region (see Chapter V), which also shows the lowest results in the physical properties considered (see Chapter VI). From this work it can be extracted that agricultural soil vulnerability presents a geographic component, where climate, and to a lesser extent, soil type, seem to play an important role. Similarly, the south of the region concentrates the largest area and diversity of agricultural uses, as well as the highest proportion of positive responses, at least in SOC storage, to the strategies analyzed in this work. This reveals another territorial pattern to consider when evaluating the potential of the territory to reduce its vulnerability, improve the resilience of the region's agricultural soils, and reverse this degradation (Amelung et al., 2020).

The response associated to the adoption of the five adaptive and resilient strategies tested in this region showed uneven results on the proposed vulnerability indicators, SOC (Chapter V), BC and AWHC (Chapter VI). All this highlights the complexity of the interrelationships between different aspects of soil management and soil properties at the regional scale. Although uniform across the region, most of the strategies presented positive effects, in general, on SOC. Note that while conservation agriculture seemed to show a tendency to be less effective as aridity decreases, the effectiveness of rotations and irrigation seems to be strongly influenced by the type and intensity of management. The response of the physical parameters to the adoption of the strategies was more irregular, with no clear relationship between the effect of the strategies considered on the physical indicators and their effect on SOC. This can be explained by the intensity of management associated with most of the strategies, which, except in cases where conservation agriculture is applied, involves conventional tillage. Further studies are needed to understand the effects of SOM content on AWHC under different site-specific situations (Lal, 2020b). In this sense, the combination of measures is revealed as an interesting strategy to explore in order to increase SOC contents and, at the same time, improve the soil physical condition, as suggested by several authors (Fonteyne et al., 2019; Trost et al., 2013; Blanco-Canqui & Ruis, 2018; Priori, Pellegrini, Vignozzi, & Costantini, 2020).

The need to limit the extension of this work in time and space, has put aside the exploration of the possible correlation between SOC contents and the physical indicators.

In this sense, the final response of agrosystems to changes in climate could be also assessed in terms of yields resilence and quality (Lal, 2020c). For instance, in terms of climate change adaptation, Iizumi & Wagai (2019) based on a revision of agricultural economic output in drought years, stated that relatively small enhancements in topsoil SOM content could increase drought tolerance of the food production systems in these terms, in over 70% of the global harvested area. Yields and economic outputs were not considered in this study, and constitute a promising line of study in the future.

The regional assessment carried out in this thesis represents a first stage in the evaluation of an adaptation strategy for the agricultural sector of the region to the effects of climate change, as described in the regional climate change roadmap of Navarre (Gobierno de Navarra, 2017). It also represents an important contribution in the process of transition towards the goals set in the EU *Green Deal*, and is also in line with the recent *Evaluation support study on the impact of the CAP on sustainable management of the soil* by the EU commission (Augier et al., 2020), which already identifies the need to consider soil properties and climatic conditions in order to identify management practices that are best suited to local conditions. If the information obtained on SOC storage is of major interest, the physical indicators considered provided additional relevant information for a complete overview of the potential effect of the measures considered in this roadmap. The relevance of the study seems especially strategic because the management strategies considered are common practices that are more or less spread in the territory. A database on surface areas dedicated to each of these strategies in the region is unfortunately still missing, and would be necessary to assess their real impact on the territory.

Irrigation cross-sectional analysis

FAO considers agriculture both a major cause and casualty of water scarcity (FAO, 2018). Indeed, agriculture is the world's largest water-consuming sector, accounting for 70% of water use on average, although it is estimated that the consumption of freshwater for agricultural irrigation accounts for 60%–90% of all water use, depending on the level of economic development and the climate of the area (Adeyemi et al., 2017).

Face to this, the increasing environmental concern of modern societies, their growing demand for public involvement on the management of natural resources, and the number of stakeholders involved in water management, generate an inevitable discussion on the governance and competition of water use in many territories (Ricart and Clarimont, 2016).

Additionally, a possible increase in water demands for irrigation is predicted associated to changes in temperatures (average increase and heat waves) and precipitation (scarcity and extreme phenomena) associated with climate change. For example, Savé et al. (2012) estimated that irrigation requirements would increase between 40 and

250% by the end of the 21st century in the Fluvià watershed (Catalonia). On the other hand, FAO estimates that by 2050 it will be necessary to produce an additional 70% more food due to population growth (FAO, 2011). All this together raises the conversion of drylands to irrigation to a current delicate issue, socially, environmentally and economically speaking (Ricart and Clarimont, 2016). According to these authors, addressing this situation requires the development of agricultural systems that ensure a maximum efficiency of water use in agriculture, by minimizing losses. These systems are to be part of a transition to sustainable agriculture supported by policies encouraging good governance regarding the management of water, land and the environment, and recognizing the territory as an integrating matrix of common goods with different uses and demands

In this framework, irrigated agriculture, both due to its fundamental role in the food and raw material supply chain globally (23% of cultivated land representing 45% of total food production), as well as for its potential as a climate-smart soil management strategy, has received worldwide scientific interest in recent decades (Velasco-Muñoz et al., 2019). The potential of irrigated agriculture to sequester C in the soil is widely documented in the literature (Lal, 2020c; Pareja-Sánchez et al., 2020). Disparity in results is however observed, with some showing positive effects and others negative or nil (Da Gama et al., 2019; Mudge et al., 2017; Nunes et al., 2007; Trost et al., 2013; Zhou et al., 2016), where differences in climate and soil characteristics seem to play a key role (Costantini et al., 2020). In the same way, it is also known that irrigation can also increase GHG emissions compared to dryland management, especially of those GHG associated with soil (Erb et al., 2017; Sanz-Cobena et al., 2017).

In this context, Amelung et al. (2020) indicate that science and technology must address the development of SOC storage strategies, adapted to local edaphoclimatic conditions and local management opportunities, where site-specific trade-offs are considered, and these must be rapidly scaled up and implemented in order to contribute to climate change mitigation, in line with Costantini et al. (2020). Throughout this thesis, some of the key aspects of this issue were addressed. First, the effect of the introduction of irrigation on C dynamics incorporation in a calcareous cultivated Mediterranean soil was analyzed in detail at a field scale in Chapters II and III. Secondly, the potential of irrigation as a climate change mitigation and adaptation strategy was explored at the regional scale in chapters IV, V and VI.

Chapters II and III, allowed the exploration of the mechanisms and controls involved in SOC dynamics and incorporation in a calcareous cultivated Mediterranean soil (38% carbonates content in the 0-30 cm), and their interaction with the transition from rainfed to irrigated cultivation of extensive crops. It is based on 7-years dataset of a C3-C4 natural isotopic labeling study.

The presence of carbonates has a special relevance in this study, specifically as a factor of organic matter stabilization, since it is considered to play an important role in soil functioning under our edaphoclimatic conditions (Rowley et al., 2018). In this sense, soil carbonates can promote the rapid incorporation and stabilization of crop residues into stable aggregates of different sizes (Fernández-Ugalde et al., 2011). This explains why the mechanistic parallel model, in which the C inputs are directed to the two pools directly, with no exchange of C between them, was the best approximation to the real SOC dynamics in the studied soil. This contrasts with the general understanding of SOC stabilization process (Lehmann & Kleber, 2015; Six et al., 2000, 2004) represented in this case by the sequential model option, and reveals that further investigations about the processes responsible for such a response in calcareous soils are needed. The elevated content of alkaline carbonates in the studied soil could also explain, in part, the relatively long MRTs of the fraction $POC_{50-2000}$ observed in this study (close to 40 years).

The first part of the study, Chapter II, confirmed that the adoption of irrigation induced changes in the two fractions of SOC considered: total organic C (TOC) and particulate organic C ($POC_{50-2000}$), over the 7-year study period in the study soil, where the overall increases showed a trend to be greater in irrigated areas. The greater evolution observed over time in the $POC_{50-2000}$ fraction than in TOC, confirmed their behavior as an early indicator of SOC changes under the conditions of this study, as pointed out in other general and local studies (Apesteguía et al., 2017; Cotrufo et al., 2019; Poeplau et al., 2018). In addition, it was remarked the importance of determine the HI in this type of studies where the determination the C residues potentially incorporable to the soil are made from crop yield (Unkovich et al., 2010).

The second part of this study, Chapter III, based on a modeling approach supported by the natural C3-C4 isotopic labeling study, revealed that these changes were most likely due to an increase in C inputs from crop residues associated to irrigation, not only because of increased yields, but also because of a more efficient incorporation of these residues into SOC, in the case of irrigated system (19% higher irrigated vs. rainfed), in the 30 cm soil depth considered.

Derrien & Amelung (2011) already explained the importance of the correct determination of organic C inputs in this type of models, especially in cases where steady-state conditions are not preserved, causing errors in the estimation of mean turn-over rates. This importance was indeed clear in our model design, as a new parameter had to be included in the model in order to adjust the proportion of the potential C in crops residues that are actually incorporated into the soil. This was done after a quick field study determined a mismatch between aboveground crop biomass left in the field after harvest and the amount actually found before incorporation with tillage. The unexpected outcome was the difference in this parameter associated with irrigation, which can be explained, in part, by the difference in the root distribution in the studied 0-30 cm soil layer, as irrigation tends to increase roots density in the topsoil (Mahgoub et al., 2017). This is an example of how, as explained by Blankinship et al. (2018), the gap between conceptual understanding, measurement and modeling represents the real challenge to understand SOC dynamics and improving biogeochemical field projections. Finally, the modelling results did not support however the hypothesis of an accelerated SOC mineralization with irrigation, which opens new research questions.

The interest of this type of studies is not only as a fundamental part of climate change mitigation strategies, as already mentioned, but also with a focus on improving soil quality, supporting the ecosystem services provided by agricultural soils and reducing their vulnerability to the impacts of climate change, increasing their resilience and favoring the adaptation of the sector.

Many authors agree that when addressing this issues at a regional scale, the real challenge is represented by the change of scale (*up-scaling*) from the experimental field to the region (Chenu et al., 2019; Dignac et al., 2017; FAO, 2013; Paustian et al., 2019). In this regard, for Wiesmeier et al. (2019) and Karlen et al. (2014) it is of particular importance to consider regional approaches to properly estimate organic C storage potential for specific climate and land use conditions, management and vegetation characteristics.

The effect of the introduction of irrigation at a regional scale in Navarre in relation to SOC storage is addressed in both Chapter IV and V of this thesis, with the latter constituting a more complete analysis.

The observed effect associated to irrigation was overall positive, with an average effect of 25% of increase in SOC, although it presented a considerable variability. This effect may be related to climatic conditions, with a slight trend in which aridity increases SOC gains, where the average values ranged from 15% to 30% from the most arid zone to the least arid one. This is in line with the previous discussion, where the geographical pattern in SOC storage potential was remarked, where the Southern areas, with a higher degree of aridity, presented more opportunities in terms of C storage (Amelung et al., 2020). For Paustian et al. (2019) the main challenges for C quantification at the territory scale are the high spatial variability and relatively small observable changes relative to the background stock (baseline).

In contrast, the potential to improve other physical properties of the soil seemed not to be so evident, as observed in Chapter VI of this thesis. As discussed above, this can be explained by the intensity of management associated with this type of agriculture, which, except in cases where CA is applied, involves conventional tillage, and in some cases, intensive rotations.

The analysis conducted in Chapter IV highlights the potential of irrigation to provide key ecosystem services to society, such as erosion control and climate regulation, as well as to ensure an increase in both crop yields and net gains to the farmer. The results observed in this chapter, indicate that depending on the agricultural management, it is possible to compensate the increase in GHG emissions associated to irrigation by SOC storage, at least in the first years after irrigation adoption. In this case, the system would be consider to perform as a C sink, acting as a climate change mitigation agent during this time. This has been observed in other studies (Adviento-Borbe et al., 2007; Ghimire et al., 2017; Mosier et al., 2006, 2005; Sainju et al., 2014). However, it has to be stressed that this will be the rule only until the SOC stock converges to a new steady state in the newly irrigated systems, thus approaching their maximum storage potential (Chenu et al., 2019; Follett, 2001), when the rates C accumulation rates may decrease over time or become nil. If emissions are not reduced in the meanwhile, the system would be reverted to a net GHG source

In addition to that, when considering the possible mitigating effect of irrigated agriculture (or other agricultural practice), based on the C storage potential of agricultural soils, it should be noted that in addition to limited in time, the storage process is reversible, so that the C accumulated over the years in the soil can be re-emitted when the management (or climate) changes (Chenu et al., 2019; Follett, 2001). All this draws a (temporal) limit on the agricultural soils capacity to compensate for GHG emissions. With the target of zero-emission agriculture in 2050 in mind, efforts should be clearly focused not only on increasing the C sink ability of agricultural systems, but also (and especially), on reducing the emission factors associated with agricultural management.

For Trost et al. (2013), although the irrigation type or intensities may influence N_2O emissions, the intensive fertilizations strategies normally associated to irrigation seem to be more relevant for the release of N_2O due to the more reactive nitrogen compounds (and water) availability within the soil. For Sanz-Cobena et al. (2017), optimizing N fertilization, not only in terms of dosage but also in timing of application, as well as the type of fertilizer used, are crucial to reduce N_2O emissions. As in Mediterranean agroecosystems irrigation is usually applied during the summer period, leading to optimal moisture and temperature conditions for N_2O production, water management must be also considered an emission factor (Aguilera et al., 2013). There are many efforts focused on the development of strategies to control and reduce GHG emissions, such as crop residues management (Maris et al., 2018), the use of organic fertilizers (Aguilera et al., 2013) or those focused on efficient water management such as regulated deficit irrigation (Zornoza et al., 2016), or related to irrigation timing and frequency (Franco-Luesma et al., 2019).

In this framework, it is noteworthy to mention that in the study described in chapter IV, GHG emissions were estimated from survey data associated to different inputs and to soil management, and not directly measured. As such, the intensity of the rotation fertilization and irrigation were shown to be the key factors for GHG emissions. As such, irrigated plots with annual crops showed a considerable increase in emissions compared to dryland conditions, where those from soil stand out from the rest. They corresponded to 4.50 Mg $eqCO_2$ ha^{-1} y^{-1} for 1.24 without irrigation in Miranda, 7.44 Mg $eqCO_2$ ha^{-1} y^{-1} for 0.67 in Funes, and 5.36 Mg $eqCO_2$ ha^{-1} y^{-1} for 0.67 in Valtierra, increasing emissions, therefore, between 3.6 and 11 times compared to the rainfed system. At the same time, gross monetary gains multiplied by 3.5 in Miranda, by 4.2 in Funes and by 1.9 in Valtierra. Fodder irrigation, on the other hand, with a less intensive management, showed equivalent or lower emissions than the rainfed system in Miranda, multiplying by 2 times the gross profits. Similarly, it was observed that managements associated with a greater increase in gross monetary gains did not correspond to those that promoted greater SOC storage. For instance, in Miranda, annual irrigated management represented a 28% increase in SOC compared to the rainfed baseline and a 350% increase in gross gains, while irrigated fodder increased SOC by 43% with a 200% increase in monetary gains. All this raises the importance for policies to consider the need for financial compensation if SOC storage is the major driver for decision makers in relation to management of agricultural soils.

Several important messages can be extracted from this transversal analysis of irrigation at the regional scale. First, it is necessary to further understand the effect of irrigation adoption on SOC dynamics in the medium to long term, highlighting the importance of long-term studieson this issue (Augier et al., 2020; Chenu et al., 2019; Lal, 2020c). Second, appropriate segmentation of the territory is needed for the evaluation of its potential to provide key ecosystem services to society at the regional level. Finally, the interest of exploring the potential of the combination of irrigation with other management strategies that can lead to positive externalities is to be explored in detail.

A global vision and final considerations

This thesis provides a functional assessment of the agricultural use of the territory of the region of Navarre. Agricultural soils provide important services that society should valorize, not only those related to the supply of food and other materials, but also to other key functions such as climate regulation, or the control of land degradation and vulnerability.

The consideration and valorization of these services must be included in the agenda in order to guide a transition towards a sustainable agriculture that will allow to face global change. In this sense, recent initiatives are driving this agenda, such as the EU *Green Deal*, the new CAP and its proposals for sustainable soil use, the 4per1000 initiative or the Millennium Development Goals. To this end, it is imperative that the scientific community coordinates and collaborates with policy makers, extension agents, farmers and other stakeholders to explore and capitalize the potential of agriculture to achieve this target.

Within the framework of this thesis, a series of studies and works have been carried out in order to contribute to this issue.

Part of the work allowed to advance in the knowledge of the organic matter cycle in a carbonate soil in a semi-arid Mediterranean climate and its relationship with the introduction of irrigation. This knowledge has allowed the collection of data on the potential of irrigation for the stabilization of organic C in agricultural soils of the region. In addition, it represents a contribution to the application of models in the particular conditions of the soils of the region, characterized by the presence of carbonates.

Although data indicated a significant potential of these soils for SOC storage, it is important to highlight the large number of edaphoclimatic and agricultural management factors that are involved and, therefore, on which this potential will depend. The methodology developed to characterize and monitoring the impact of these strategies in the region also represents an output (transversal) to be highlighted.

Irrigated agriculture, has a special role in this thesis due to its relevance in the region. From this work we can extract not only the potential of irrigation within climate-smart managements, but also the trade-offs and risks associated to it, and importance of integrating this type of studies in the development of policies and decision making in relation to agricultural land management. The journey towards sustainable agriculture must be driven by the development of agricultural systems that ensure the maximum efficiency in the use of water, and by appropriate governance in the management of water resources.

Finally, the work carried out during this thesis has also raised new questions to be addressed and that may provide interesting lines of action for the future. The study of organic matter dynamics at the field scale has demonstrated its effectiveness in assessing changes in the short-medium term resulting from the introduction of irrigation. Further work in this line of work would allow a more detailed study, and long-term monitoring of these changes through a longer time series of data. In addition, the interaction between irrigation and deep SOC storage, as well as studying in detail the relationship between irrigation, SOC and soil carbonates are promising lines of study in the future.

In relation to the regional study, this work provides some tools, and opens a path, to continue progressing in the assessment of the transition towards the challenge of zero-emissions agriculture as set by the European Union. Both the territorial database generated and the methodological approach may be of interest in achieving this objective. Correlation between SOC content and physical indicators in the region, cause-effect relationship between SOM content and yields and economic outputs, and the definition of database on surface areas dedicated to different strategies in the region represent possible lines of research in this sense.

CONCLUSIONS

Conclusions obtained from the studies that are part of the present thesis are the following:

1. The adoption of irrigation in the calcareous soil of this study induced changes in SOC and $POC_{50\text{-}2000}$ stocks over the 7-year study period, with a trend towards overall greater increments in the irrigated areas. Crop types and agricultural management were key drivers on this process in the soil and climate conditions of the studied area.

2. Changes in SOC and $POC_{50\text{-}2000}$ stocks over the 7-year study period were most likely due to an increase in C inputs from crop residues associated to irrigation, not only because of the increased productivity, but also because of a more efficient incorporation of these residues into SOC, in the studied topsoil layer.

3. The parallel two-pool model option used to represent SOC dynamics in this soil seemed to be a closer representation of the agrosystem evaluated than a classical sequential two-pool model. The interaction of the mineral phase of this soil, with 38% carbonates in the studied depth, could explain at least partially this observation, due to the protection of fresh organic matter in the soil favorized by carbonates.

4. The analysis of different bioclimatic zones was useful to identify areas with different climate conditions and soil characteristics, which corresponded to different dominant land uses.

5. The relevance of climate and, to a lesser extent, soil type, on the baseline of SOC storage, and other key indicators such as bulk density and available water-holding capacity was confirmed in the region of Navarre.

6. As expected, management of exogenous sources of organic carbon (ExO) was the most efficient strategy to increase SOC stocks in croplands across the region. Optimized grasslands management strategy (GSS) also resulted in net SOC gains in all the zones tested. The potential benefit of conservation agriculture (CA), irrigation (IRR) and crop rotations (ROT) in terms of SOC storage, needs to be evaluated with care, as it was observed to be uneven in the region. Less efficient with decreasing aridity in the case of CA, management-dependent for IRR, and overall negative in ROT, likely related to the use of irrigation and the intensification of cropping sequences with it.

7. Bulk density and the available water-holding capacity seemed to respond to soil and crop management, although the effect was highly variable. Only the strategy associated to management of exogenous sources of organic carbon (ExO) showed an overall positive effect on bulk density. Crop rotations (ROT), irrigation (IRR) and optimized grasslands management strategy (GSS) displayed no clear effect and, in the case of conservation agriculture (CA), the effect was slightly negative overall. In relation to available water-holding capacity, four of the strategies considered (ROT, ExO, IRR and GSS) showed an overall neutral effect, although the results within the zones were heterogeneous. CA was the only one strategy that showed a negative overall effect, although the effect observed within zones associated to that strategy tends to be neutral.

8. The neutral trend observed on physical properties and the effectiveness in promoting SOC in the topsoil mean that CA may represent an interesting strategy when evaluating adaptation to climate change in the region. Considering the observed variability, an adequate combination of ROT and IRR should be explored in context-specific,

although a combination of both strategies seems to be promising for improving the adaptability of agrosystems in the semi-arid part of this region. Site-specific environmental factors appeared to be relevant to assess the interest of the GSS strategy in terms of adaptability of agrosystems (e.g. high baseline values in the northern zone, where it is more widespread). ExO should be also considered as a strategy within a climate change regional adaptation due to the generally positive effect of on physical properties a clear effectiveness in increasing SOC in agricultural soils.

9. The observed variability in terms of the adoption and effectiveness of the five adaptive strategies tested in this region seemed to be modulated by geographical and management factors, which should therefore be evaluated in each context. This highlights the need to understand the complexity of interrelationships between different aspects of soil management and soil properties at a regional scale, and indicates that more detailed research is needed to assess soil vulnerability and the possible adaptability potential of agricultural management to changes in climate.

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