Universidad de Córdoba

Escuela Técnica Superior de Ingeniería Agronómica y de Montes

TESIS DOCTORAL

AGRICULTURA DE CONSERVACIÓN Y CAMBIO CLIMÁTICO. PROSPECTIVA CIENTÍFICA Y POTENCIAL DE MITIGACIÓN

CONSERVATION AGRICULTURE AND CLIMATE CHANGE. SCIENTIFIC FORESIGHT AND MITIGATION POTENTIAL

PROGRAMA DE DOCTORADO

INGENIERÍA AGRARIA, ALIMENTARIA, FORESTAL Y DE DESARROLLO RURAL SOSTENIBLE

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Córdoba, Marzo de 2024

TITULO: *Conservation Agriculture and climate change. Scientific foresight and mitigation potential*

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DOCTORANDA/O

ÓSCAR VEROZ GONZÁLEZ

TÍTULO DE LA TESIS:

Agricultura de Conservación y cambio climático. Prospectiva científica y potencial de mitigación

INFORME RAZONADO DE LAS/LOS DIRECTORAS/ES DE LA TESIS (se hará mención a la evolución y desarrollo de la tesis, así como a trabajos y publicaciones derivados de la misma)

Los directores de la tesis el Prof. Dr. Emilio J. González Sánchez y la Dra. Rosa Mª. Carbonell Bojollo, informan que el doctorando ha cubierto los objetivos previstos en la tesis compartiendo su formación con la investigación. Gracias al desarrollo de las investigaciones llevadas a cabo, el doctorando ha avanzado en el conocimiento de los efectos beneficiosos que la Agricultura de Conservación tiene sobre el cambio climático, concretamente en la mitigación de sus efectos a través del incremento del secuestro del carbono y de la reducciones de los gases de efecto invernadero. Además, el doctorando ha realizado una labor prospectiva del campo científico de la Agricultura de Conservación y sus efectos sobre el cambio climático, para así conocer la estructura intelectual, social y conceptual del ámbito en el que se enmarca la investigación realizada.

La tesis realizada se enmarca dentro de las acciones desarrolladas en los proyectos europeos LIFE+ Climagri “Best agricultural practices for Climate Change: Integrating strategies for mitigation and adaptation” (LIFE13 ENV/ES/000541) y LIFE Agromitiga “Development of climate change mitigation strategies through carbon-smart agriuclture” (LIFE17 CCM/ES/000140), ocupando el doctorando en este último el cargo de coordinador general.

Como consecuencia de los trabajos realizados en el macro de la tesis, tres de los capítulos de este trabajo se han plasmado en publicaciones en revistas indexadas en el JCR, siendo éstos los siguientes:

- Gonzalez-Sanchez, E.J., Veroz-Gonzalez, O., Conway, G., Moreno-Garcia, M., Kassam, A., Mkomwa, S., Ordoñez-Fernandez, R., Triviño-Tarradas, P., Carbonell-Bojollo, R. (2019). Meta-analysis on carbon sequestration through Conservation Agriculture in Africa. Soil & Tillage Research 190, pp 22-30. https://doi.org/10.1016/j.still.2019.02.020
- Carbonell-Bojollo, R., Veroz-González, O., Ordóñez-Fernández, R., Moreno-García, M., Basch, G., Kassam, A., Repullo-Ruibérriz De Torres, M.A., González-Sánchez, E.J. (2019). Effect of Conservation Agriculture and environmental factors on CO2 emissions in a rainfed crop rotation. Sustainability, 11, 3955; https://doi.org/10.3390/su11143955
- Carbonell-Bojollo, R., Veroz-González, O., González-Sánchez, E.J., Ordóñez-Fernández, R., Moreno-García, M., Repullo-Ruibérriz De Torres, M.A. (2022). Soil Management, Irrigation, and Fertilisation Strategies for N2O Emissions Mitigation in Mediterranean Agricultural Systems. Agronomy, 12, 1349. https://doi.org/10.3390/agronomy12061349

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

Córdoba, a 4 de marzo de 2024

Las/los directoras/es

Fdo.:Emilio J. González Sánchez
Rosa Mª Carbonell Bojollo

AGRADECIMIENTOS

Dice un proverbio chino que "si caminas solo irás más rápido, si caminas acompañado llegarás más lejos". Nada más adecuado para definir lo que ha sido mi travesía por mi etapa predoctoral, pues aunque me ha tomado más tiempo de lo deseado, he tenido la suerte de tener muchos compañeros de viaje en diferentes ámbitos de mi vida sin cuya ayuda no hubiera sido posible alcanzar el destino final.

Justo es empezar mi agradecimiento por mis directores de tesis, Emilio González y Rosa Carbonell. Nuestra relación trasciende la meramente académica, llegando a ser una amistad forjada a través de muchos años y que comenzó hace más de 25 años cuando compartíamos vivencias en la carrera. Sin vuestras aportaciones, ideas y consejos, esta tesis no habría sido posible. A ello hay que añadir vuestro empuje, generosidad y apoyo cuando lo he necesitado.

No quiero dejar pasar la ocasión de agradecer también su apoyo a Fali Ordóñez y a Jesús Gil, los cuales me acogieron en el seno de la Asociación Española Agricultura de Conservación Suelos Vivos cuando recalé allá por el año 2005. Mucho del conocimiento que ahora poseo y que ha servido de base para el desarrollo de esta tesis se lo debo a ellos. Además, su confianza en mí ha hecho que crezca profesionalmente a lo largo todos estos años.

En esta travesía también he tenido la suerte de estar acompañado de un gran equipo de buenos profesionales y mejores personas. Quién sabe cuántas horas hemos pasado juntos en un ambiente inmejorable, que ha hecho que acudir cada día a la oficina o al campo, fuera un placer. Quiero acordarme en este sentido de mis compañeros de la Asociación y de las personas de otras entidades como la Federación Europea de Agricultura de Conservación, el IFAPA y la Universidad de Córdoba, con las que he trabajado codo con codo. Gracias a Carolina González, Manolo Gómez, Francisco Sánchez, Raúl Gómez, Jesús Rincón, Julio Román, Miguel Repullo, Manolo Moreno, Antonio Conde y Beatriz Agüera.

Me gustaría terminar este apartado de agradecimientos con mi familia, pilar fundamental en este camino y a los que dedico estos últimos párrafos. Ha querido el destino que con esta tesis emule a mi padre, Ricardo, al que recuerdo compaginando la tesis con el trabajo a una edad parecida a la mía. Sin duda alguna, ha sido un ejemplo de superación que me ha servido de estímulo a lo largo de mi desempeño profesional. A mi madre, Eloísa, trabajadora incansable, le debo la cultura del mérito y esfuerzo, que hace que dé lo mejor de mí en cada proyecto que acometo. A mis hermanos, Ricardo, Raúl y Azahara, que sé que siempre estarán para lo que necesite. Por todo ello, muchas gracias, os quiero.

Dejo para el final a mis tres compañeras en mi viaje a través de la vida, mi mujer Nati y mis hijas Victoria y Nati. A mi mujer he de agradecerle su enorme generosidad y comprensión, simplemente tomar su mano en los momentos de mayores desvelos, hace que toda preocupación que ocupa mis pensamientos se desvanezca. Y qué decir de Victoria y Nati, ellas son lo mejor que me ha pasado en la vida. No me imagino una existencia sin mis chicuelas. A las tres os quiero infinito.

CONTENTS

LIST OF FIGURES

Chapter 1

Chapter II

Chapter III

Chapter IV

Chapter V

LIST OF TABLES

Chapter II

Chapter III

Chapter IV

Chapter V

Resumen

El cambio climático es un importante desafío contemporáneo que afecta tanto a las generaciones presentes como a las futuras, ya que las emisiones de gases de efecto invernadero (GEI) representan un grave riesgo, principalmente el dióxido de carbono (CO_2), el óxido nitroso (N_2O) y el metano (CH_4). Existen pruebas científicas que apoyan la hipótesis de que la Agricultura de Conservación puede mitigar eficazmente los efectos del cambio climático, en particular mediante el secuestro de carbono en las plantas y el suelo. En la actualidad, muchos países se han fijado objetivos para reducir las emisiones de gases de efecto invernadero y potenciar el secuestro de carbono. Para reforzar estos objetivos, la Unión Europea ha esbozado retos en la Política Agrícola Común 2020-2027, haciendo hincapié en la necesidad de apoyar y reforzar la protección del medio ambiente, incluida la biodiversidad, y la acción por el clima. Estas iniciativas contribuyen a los objetivos medioambientales y climáticos más amplios de la Unión Europea.

La Agricultura de Conservación promueve la mínima alteración del suelo, el mantenimiento de una cubierta permanente y la diversificación de las especies vegetales. La Agricultura de Conservación es un sistema que apoya la gestión sostenible de la tierra, la protección del medio ambiente y la adaptación al cambio climático y su mitigación. La Agricultura de Conservación es una herramienta importante para mitigar el cambio climático y se ha estudiado en las últimas décadas, inicialmente en América del Norte y del Sur, y después en el resto del mundo, especialmente en Asia y Europa.

Esta tesis aporta nuevos conocimientos sobre la contribución de la Agricultura de Conservación a la mitigación del cambio climático y sobre cómo, a través de una mejor gestión del suelo, se pueden reducir las emisiones de gases de efecto invernadero clave procedentes de la agricultura.

En el Capítulo III se presenta un meta-análisis sobre el secuestro de carbono mediante la Agricultura de Conservación en África. África es el continente que menos contribuye a las emisiones mundiales de gases de efecto invernadero, pero el más vulnerable a los efectos del cambio climático. Los efectos no se limitarán al aumento de la temperatura media y a la modificación de los regímenes de precipitaciones, sino también al aumento de la gravedad y la frecuencia de las sequías, los golpes de calor y las inundaciones.

La agricultura no sólo se ve afectada por el cambio climático, sino que también contribuye al calentamiento global. Sin embargo, no todos los sistemas agrícolas afectan negativamente al cambio climático. La Agricultura de Conservación es un sistema agrícola que promueve la no perturbación o la perturbación mínima del suelo (es decir, la siembra directa), el mantenimiento de una cubierta vegetal permanente y la diversificación de las especies vegetales. Gracias a estos principios, mejora la biodiversidad y los procesos biológicos naturales sobre y dentro del suelo, contribuyendo así a una mayor eficiencia en el uso del agua y los nutrientes y a una mayor productividad, a sistemas de cultivo más resistentes y a una producción de cultivos mejorada y sostenida. La Agricultura de Conservación se basa en la aplicación práctica de tres principios interrelacionados junto con buenas prácticas agrícolas complementarias. Las características de la Agricultura de Conservación la convierten en uno de los sistemas más aptos para contribuir a la mitigación del cambio climático mediante la reducción de la concentración atmosférica de gases de efecto invernadero.

En este capítulo se evalúa el potencial de secuestro de carbono de la Agricultura de Conservación, tanto en cultivos anuales como perennes, en las diferentes regiones agroclimáticas de África. En total, la estimación del potencial de secuestro anual de carbono en los suelos agrícolas africanos a través de la Agricultura de Conservación asciende a 143 Tg de C al año, es decir, 524 Tg de CO_2 al año. Esta cifra representa unas 93 veces la cifra actual de secuestro en África, donde la agricultura basada en el laboreo es el sistema más común.

En el Capítulo IV se estudia el efecto de la Agricultura de Conservación y de los factores ambientales sobre las emisiones de CO_2 en una rotación de cultivos de secano. Son muchos los factores que intervienen en la liberación de emisiones de CO_2 del suelo, tales como el tipo de manejo del suelo, la materia orgánica del suelo, las condiciones de temperatura y humedad del suelo, el estado fenológico del cultivo, las condiciones climáticas, el manejo de residuos, entre otros. El objetivo de este capítulo es analizar la influencia de estos factores y sus interacciones en la determinación de las emisiones, evaluando el coste medioambiental expresado como kg de CO_2 emitido por kg de producción en cada uno de los cultivos y campañas estudiadas. Para ello, se realizó un ensayo de campo en una finca de Sevilla (España). El presente capítulo compara la

Agricultura de Conservación, incluyendo sus tres principios (no laboreo, cubierta permanente del suelo y rotación de cultivos), con el laboreo convencional. Las emisiones de dióxido de carbono medidas a lo largo de las cuatro estaciones del experimento mostraron un incremento fuertemente influenciado por las precipitaciones durante el periodo vegetativo, en ambos sistemas de manejo del suelo. Los resultados de este capítulo confirman que eventos extremos de precipitación alejados de las medias normales, dan lugar a episodios de elevadas emisiones de CO2 a la atmósfera. Esto es muy importante, ya que una de las consecuencias para futuros escenarios de cambio climático es precisamente el aumento de episodios extremos de precipitación y periodos extremadamente secos, dependiendo de la zona considerada. El total de valores de emisión de las diferentes parcelas del estudio muestran como los suelos bajo el sistema convencional (laboreo) han estado emitiendo un 67% más que los suelos bajo el sistema de agricultura convencional durante la campaña 2010/11 y un 25% para la última campaña donde se observan las diferencias más apreciables.

En el Capítulo V se evalúan las estrategias de gestión del suelo, riego y fertilización para mitigar las emisiones de N_2O en los sistemas agrícolas mediterráneos. Alimentar a una población creciente, que alcanzará los 10.000 millones en 2050, es un reto importante. Otro reto importante es aumentar la productividad de los cultivos de forma sostenible, ya que el aumento de los insumos agrícolas puede provocar emisiones de gases de efecto invernadero, incluido el N_2O de los fertilizantes. Varios factores pueden influir en las emisiones de N_2O, como el riego, el sistema de gestión del suelo o el tipo de fertilizante utilizado. El objetivo de esta investigación es estudiar el impacto de cada uno de los factores mencionados sobre las emisiones de N_2O durante tres campañas agrícolas de cultivo en un cultivo de maíz, considerando tres fertilizantes nitrogenados: urea, nitrato amónico, y un fertilizante con el inhibidor de la nitrificación 3,4-dimetilpirazol fosfato; dos estrategias de riego: a demanda (100%) y riego deficitario (75% de la demanda); y una comparación de dos sistemas de manejo del suelo: sistemas de laboreo convencionales y siembra directa. Las interacciones entre los tres factores y sus efectos sobre las emisiones se analizaron mediante un análisis de componentes principales. Se registraron mayores emisiones en las parcelas que recibieron la dosis de riego más alta. El manejo más favorable para reducir las emisiones de N_2O derivadas de

la actividad agrícola para cultivos de maíz bajo clima mediterráneo fue la siembra directa, el uso de un fertilizante con inhibidor de la nitrificación y una dosis de riego del 75% del riego convencional.

Abstract

Climate change is a significant contemporary challenge affecting both present and future generations, and greenhouse gas emissions represent a serious concern, mainly carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4) There is substantial scientific evidence supporting the notion that Conservation Agriculture can effectively mitigate the effects of climate change, particularly through carbon sequestration in plants and soil. Currently, many countries have set goals to reduce greenhouse gas emissions and enhance carbon sequestration. To reinforce these objectives, the European Union has outlined challenges in the Common Agricultural Policy 2020–2027, emphasizing the need to support and fortify environmental protection, including biodiversity, and climate action. These initiatives contribute to the European Union's broader environmental and climate objectives.

Conservation Agriculture promotes minimum soil disturbance, the maintenance of a permanent soil cover, and the diversification of plant species. Conservation Agriculture is a concept in support of sustainable land management, environmental protection and climate change adaptation and mitigation. Conservation Agriculture is an important tool to mitigate climate change and have been studied in the last decades, initially in North and South America, and then in the rest of the world, especially in Asia and Europe.

This thesis has produced new knowledge about the contribution of Conservation Agriculture to the mitigation of climate change and how through better soil management, the emissions of key greenhouse gas from agriculture can be reduced.

In Chapter III a meta-analysis on carbon sequestration through Conservation Agriculture in Africa is presented. Africa is the smallest contributor to global greenhouse gas emissions among the continents, but the most vulnerable to the impacts of climate change. The effects will not be limited to a rising average temperature and changing rainfall patterns, but also to increasing severity and frequency in droughts, heat stress and floods.

Agriculture is not only impacted upon by climate change but also contributes to global warming. However, not all agricultural systems affect negatively climate change. Conservation Agriculture is a farming system that promotes continuous no or minimum soil disturbance (i.e. no tillage), maintenance of a permanent soil mulch cover, and diversification of plant species. Through these principles it enhances biodiversity and natural biological processes above and below the ground surface, so contributing to increased water and nutrient use efficiency and productivity, to more resilient cropping systems, and to improved and sustained crop production. Conservation Agriculture is based on the practical application of three interlinked principles along with complementary good agricultural practice. The characteristics of Conservation Agriculture make it one of the systems best able to contribute to climate change mitigation by reducing atmospheric greenhouse gas concentration.

In this chapter, the carbon sequestration potential of Conservation Agriculture is assessed, both in annual and perennial crops, in the different agro-climatic regions of Africa. In total, the potential estimate of annual carbon sequestration in African agricultural soils through Conservation Agriculture amounts to 143 Tg of C per year, that is 524 Tg of CO_2 per year. This figure represents about 93 times the current sequestration figure for Africa, where tillage-based agriculture is the most common system.

In Chapter IV, the effect of Conservation Agriculture and environmental factors on CO_2 emissions in a rainfed crop rotation are studied. There are many factors involved in the release of CO_2 emissions from the soil, such as the type of soil management, the soil organic matter, the soil temperature and moisture conditions, crop phenological stage, weather conditions, residue management, among others. This chapter analyses the influence of these factors and their interactions to determine the emissions by evaluating the environmental cost expressed as the kg of CO_2 emitted per kg of production in each of the crops and seasons studied. For this purpose, a field trial was conducted on a farm in Seville (Spain). The study compared Conservation Agriculture, including its three principles (no-tillage, permanent soil cover, and crop rotations), with conventional tillage. Carbon dioxide emissions measured across the four seasons of the experiment showed an increase strongly influenced by rainfall during the vegetative period, in both soil management systems. The results of this chapter confirm that extreme events of precipitation away from the normal means, result in episodes of high CO_2 emissions into the atmosphere. This is very important because one of the consequences for future scenarios of climate change is precisely the increase of extreme episodes of precipitation and periods extremely dry, depending on the area considered. The total of emission values of the different plots of the study show how the soils under the conventional system (tillage) have been emitting 67% more than soils under the conventional agriculture system during the 2010/11 season and 25% for the last campaign where the most appreciable differences are observed.

In Chapter V the soil management, irrigation and fertilisation strategies for N_2O emissions mitigation in mediterranean agricultural systems are assessed. Feeding a growing population, which will reach 10 billion in 2050, is a major challenge. Another major challenge is to increase crops' productivity in a sustainable way, as the increase in agricultural inputs may lead to greenhouse gas emissions, including N_2O fertiliser. Several factors can influence N_2O emissions such as irrigation, the soil management system, or the type of fertiliser used. The aim of this chapter was to study the impact of each above-mentioned factor on N_2O emissions during three growing seasons in a maize field, considering three nitrogen fertilisers: urea, ammonium nitrate, and a fertiliser with the nitrification inhibitor 3,4-dimethylpyrazole phosphate; two irrigation strategies: on demand (100%) and deficit irrigation (75% of demand); and a comparison of two soil management systems: conventional tillage systems and no-tillage. The interactions among the three factors and their effects on emissions were analysed through a principal component analysis. Higher emissions were recorded in plots that received the highest irrigation dose. The most favourable management to reduce N_2O emissions derived from agricultural activity for maize crops under a Mediterranean climate was no-tillage, using a fertiliser with nitrification inhibitor and an irrigation dose of 75% of conventional irrigation.

Chapter I

Introduction, hypothesis and objectives, and structure of the thesis

I-1. Introduction

Climate change is one of the greatest challenges facing the world in general and the agricultural sector in particular. This phenomenon is determined by the concentration in the atmosphere of the so-called Greenhouse Gases (GHG), which are mainly carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4) and fluorinated gases (CFCs), as identified in the Kyoto Protocol and the Paris Agreement.

There is scientific evidence that the concentration of GHGs in the atmosphere has increased significantly in recent decades. Thus, atmospheric concentrations of CO_2, N_2O and CH_4 have increased since 1750 by 156%, 47% and 23%, respectively (IPCC, 2023). Scientific evidence shows that these increases are unequivocally caused by human activity (IPCC, 2023). As a consequence of the enhanced greenhouse effect created by the increased presence of these gases in the atmosphere, the Earth's global average temperature has risen by at least 1.1°C since 1880, with most of this increase occurring since 1975, at a rate of approximately 0.15 to 0.20°C per decade (NASA, 2023). This is leading to a global change in temperature and precipitation patterns known as climate change (WMO, 1992).

If there is any productive activity that is closely linked to climate and its variability, it is undoubtedly agriculture, and climate change affects it very directly. Although there are some aspects of climate change that may be beneficial in some regions, such as longer growing seasons and higher temperatures, we must not forget that these changes are being or will be regional in nature and only in low latitudes (Malhi et al., 2021). Thus, the scientific community agrees that most of the impacts of climate change will be negative and adverse. Lack of water availability, increased frequency of extreme weather events, as well as the incidence of pests and diseases associated with the new climatic conditions are some examples of such adverse phenomena.

Thus, globally, not only are droughts expected to increase in most regions of the world, but also the area affected by drought is expected to increase from 15% to 44% by the year 2100 (Malhi et al., 2021). As a consequence, yields of major crops in areas with increased numbers and periods of drought are expected to be reduced by more than 50% by 2050 and by almost 90% by 2100 (Li et al., 2009). Against this background, one might think that the increase in atmospheric CO_2 concentration could benefit agricultural productivity by increasing biomass and crop water use efficiency as a consequence, but these beneficial effects are likely to be offset by rising temperatures and altered precipitation (DaMatta et al., 2010). In this regard, Aydinalp & Cresser (2008) found that many economic projection models showed substantial economic losses in cases where temperature increases were greater than the equivalent of twice the increase in CO_2 concentration.

The increased frequency of extreme precipitation events is another phenomenon occurring as a consequence of climate change with a direct effect on agriculture. Among these effects is soil loss due to water erosion, which means a reduction in the area suitable for crop cultivation. In Europe alone, an estimated 35 million hectares of agricultural soils and grasslands are affected by moderate or severe erosion rates (above 5 t/ha per year), representing more than 80% of all soils in this situation (Eurostat, 2023). In addition, soil degradation processes have a huge economic cost. An impact assessment carried out by the European Commission showed that soil degradation processes in Europe could cost up to 50 billion euros per year (European Commission, 2020).

However, erosion does not only result in the loss of soil and usable agricultural land, but also has a negative impact on crop yields. According to a study by Bakker et al. (2004), yield reductions caused by erosion are around 4% for every 10 cm of soil lost. This means that areas suffering moderate erosion rates (around 10 t/ha/year) will lose on average 0.4% yield per decade, a percentage that can easily be 10 times higher in areas suffering more severe erosion. In general, the reduction in crop yields will become more severe as erosion progresses, as root growth becomes increasingly difficult. In a more recent study, L. Zhang et al. (2021) estimated that crop yields were significantly reduced when erosion rates caused the most fertile soil horizon (A horizon) to be less than 25 cm deep.

Another consequence of climate change on agriculture is the change in pest development and plant pathogen population dynamics (Elad & Pertot, 2014). Pest infestations in various crops are expected to worsen with climate change, as warmer and wetter conditions are more favourable for their proliferation, which may have an adverse impact on agricultural yields and even their viability, as pest populations depend mainly on abiotic factors such as humidity and temperature. This is confirmed by some studies that estimate reductions in crop yields of 10-25% due to increased infestation of insect pests that may occur due to a temperature increase of 1°C (Shrestha, 2019). However, the impact will vary from region to region and depending on the adaptability of pests to climate change (Malhi et al., 2021).

Finally, we should not forget how climate change can affect weed populations whose development, like a crop, depends on the weather conditions in each area. It is well known that, depending on the metabolic pathway followed by carbon in the process of photosynthesis, plants can be distinguished between C3 and C4. In general, C3 plants respond better to an increase in CO_2 concentration, increasing the leaf area and their biomass, and can therefore represent a competition problem for a crop, especially if the crop is a C4 plant (Korres et al., 2016). Apart from the growth of weed plants, climate change also significantly influences the efficacy of herbicides for weed control by affecting their mode of action, which in turn depends on the metabolic function of the plant on which the herbicide acts. Consequently, any change in climatic conditions that affects the metabolic pathways of plants has a negative impact on herbicide performance (Varanasi et al., 2016).

In addition to suffering the effects of climate change, agriculture is also a greenhouse gas emitter and, although it is not the main cause of global warming, it does contribute to this phenomenon. Thus, in the European Union countries as a whole, agriculture, with emissions of 424 million tonnes of CO_2 equivalent into the atmosphere, was the second largest emitter in 2020 after the energy sector, although it is true that this value corresponds to 11.4% of total GHG emissions in the EU-27 and that since the base year (1990) the agricultural sector has reduced its emissions by 20% (EEA, 2022). According to the Annual European Union Greenhouse Gas Inventory, most of the GHG emissions from the agricultural sector are CH_4 and N_2O. Methane emissions are associated with the decomposition of organic materials (plant remains and animal waste) under anaerobic conditions (without oxygen), from the digestion of ruminant livestock (enteric fermentation in cows, sheep and goats), stored manure and crops under flooded conditions (such as rice) (Moreau et al., 2012). Nitrous oxide emissions occur when bacteria mineralise nitrogenous substances in soils and manure pits, and when synthetic nitrogen fertilisers applied to fields volatilise into the atmosphere (Moreau et al., 2012). All in all, methane and nitrous oxide emissions account for 49.7% and 76.3% of total CH_4 and N_2O emissions in the European Union (EU) respectively. With regard to CO_2, and according to the above-mentioned inventory, emissions from the agricultural sector accounted for only 0.33% of total EU CO_2 emissions. Such a small amount is due to the fact that only the gaseous exchanges of this gas between agricultural soils and the atmosphere as a result of the microbial decomposition of organic matter are taken into account, not considering the emissions derived from the consumption of fossil fuels produced in agricultural operations or in the processes of synthesis and production of agricultural inputs, which are included in sectors other than agriculture.

Faced with this scenario, the EU has set itself the challenge of drastically reducing GHG emissions, establishing a regulatory framework for this purpose, such as the European Green Deal, which sets very ambitious targets in this respect. Thus, through this document, the challenge is to make Europe climate neutral by 2050. To make this target legally binding, the Commission proposed the European Climate Legislation, which also sets a new, even more ambitious target of a net reduction in greenhouse gas emissions of at least 55% by 2030 compared to 1990 levels.

To achieve these objectives, sustainable soil management will be essential to increase the amount of carbon sequestered and stored in plants and soils. This is all the more important following the finding, based on information gathered through national GHG inventories submitted to the UNFCCC (United Nations Framework Convention on Climate Change), that net removals from terrestrial ecosystems in the EU have been on a declining trend over the last decade, largely driven by the deteriorating condition of forest ecosystems. In addition, these inventories show that land uses such as cropland, grassland, wetlands and settlements have overall annual net emissions. With this in mind, the European Commission proposed to amend Regulation (EU) 2018/8418 concerning the LULUCF (Land Use, Land Use Change and Forestry) sectors by setting a target for annual net removals by these sectors to reach 310 Mt CO_2 eq by 2030. The proposal, which is embodied in Regulation (EU) 2023/839, also includes a target of achieving climate neutrality across this sector by 2035, meaning that carbon uptake in terrestrial ecosystems should balance greenhouse gas emissions from all land use, livestock and fertilisers. To respond to these objectives, in December 2021, the European Commission published the Communication COM (2021) 450 final "Sustainable Carbon Cycles", in which it called for scaling up solutions to reduce CO_2 concentrations in the atmosphere, through capture and long-term storage, proposing among other solutions, the practices included in the so-called carbon farming, which promote the sequestration of atmospheric carbon by storing it in agricultural soils. As a follow-up to this Communication, in November 2022 the European Commission published a proposal for a Regulation COM(2022) 672 final entitled "Establishing a Union certification framework for carbon removals", which lays the foundations for the development of a voluntary EU framework for the certification of carbon credits under quality criteria applicable to carbon sequestration activities, the establishment of rules for the verification and certification of carbon removals and the development of rules for the operation and recognition by the Commission of certification schemes. The Commission, with the support of a group of experts, is currently developing certification methodologies adapted to the different types of carbon removal activities, while the Commission's proposal will be discussed by the European Parliament and the Council, in accordance with the ordinary legislative procedure, with a view to adopting a final Regulation.

With regard to non-CO_2 GHG emissions from agriculture, such as N_2O or CH_4, it is the Effort Sharing Regulation (ESR) that sets binding annual GHG emission targets for Member States from 2021 to 2030. These national targets cover emissions not only from agriculture, but also from domestic transport (excluding aviation), buildings, small industry and waste. The ESR is part of a package of policies and measures to reduce the EU's emissions, which fall under the target of a 55% reduction by 2030 compared to 1990 levels.

In this context, we must not forget the main European policy concerning the agricultural sector, the Common Agricultural Policy (CAP), whose general objectives include the fight against climate change. Specifically, the CAP 2020-2027 calls for supporting and strengthening environmental protection, including biodiversity, and climate action, contributing to achieving the Union's environmental and climate objectives, including the commitments made under the Paris Agreement. This is embodied in one of the specific objectives of the CAP, which states "To contribute to climate change mitigation and adaptation and to sustainable energy". For this objective the Commission produced a report called Brief No 4 "Agriculture and climate mitigation"[1] whose key messages are:

- EU agriculture, including land use, land-use change and forestry, accounts for 12% of GHG emissions.
- European agriculture is more vulnerable to climate change than other economic sectors.
- Potential mitigation from changes in practices involve the use of mitigation technologies, improved soil management to increase sink capacity, biomass production, reduction of fossil fuel use as well as reduction of waste and litter.
- EU agriculture has a key role to play in meeting the commitments of the Paris agreement, the European sustainability and bioeconomy strategies by increasing its ambition on emission reductions in view of the potential risks and the stabilization of agricultural emissions since 2010, while ensuring food security.
- The EU must take into consideration synergies in soil management practices that both sequester and prevent carbon leakage.

For all these reasons, the preparation of the CAP Strategic Plans of each of the Member States, which have been used to design support measures in each of them within the framework of the CAP, have taken these slogans into account in order to promote agricultural practices that mitigate climate change.

In this context, one of the most important challenges facing the agricultural sector is undoubtedly mitigation and adaptation to the effects of climate change, and all of this under an increasingly ambitious regulatory framework in terms of GHG emission reduction targets. The scientific literature, far from being oblivious to society's demand for alternatives that promote a shift towards more climate-smart production systems, has explored various solutions in an attempt to verify and demonstrate their effectiveness and viability. In this sense, and as far as the agricultural sector is concerned, the opportunities for mitigating climate change can be grouped into three broad categories, depending on the mechanism employed:

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[1] https://www.mapa.gob.es/es/pac/pac-2023-2027/brief_oe4_tcm30-520584.pdf

- Emission reductions: As discussed above, agriculture releases significant amounts of CO_2, CH_4 and N_2O into the atmosphere. Fluxes of these gases can be reduced through more efficient management of the carbon and nitrogen cycles in farming practices.

  Reduction of CO_2

  Advances in weed control and farm machinery mean that many crops can be grown under so-called "Conservation Agriculture", the concept of which is discussed below.

  Since soil disturbance tends to stimulate, through increased decomposition and erosion, organic carbon losses and CO_2 emission "trapped" in soil aggregates, Conservation Agriculture (CA) practices, which involve the elimination of soil tillage operations, can reduce quantified emissions by up to 3.8 times for shallower tillage (10 cm) and by up to 10.3 times for deeper tillage (28 cm) (Reicosky & Archer, 2007).

  Reduction of N_2O emissions

  On the other hand, moving towards systems that are less dependent on nitrogen fertilisers or that involve a more rational and efficient use of nitrogen fertilisers would reduce the emission of N_2O. An example of reducing nitrogen inputs is the introduction of legumes in crop rotations, as they fix nitrogen (Dequiedt & Moran, 2015). This reduces emissions from fertiliser manufacture and soil emissions related to fertilisation. Furthermore, soil emissions from legume cultivation are estimated to be lower than, for example, from cereal cultivation (Lötjönen & Ollikainen, 2017).

  The most efficient and rational use of fertilisers involves adjusting application rates based on accurate estimation of crop needs, which could be achieved through precision farming, the use of slow-release fertilisers or nitrification inhibitors, thus avoiding delays between application and uptake of nitrogen (Smith *et al.*, 2008, Moran *et al*. 2008).

  In humid regions, drainage of agricultural land can promote productivity and perhaps suppress N_2O emissions through increased soil aeration, although nitrogen percolation through drainage may instead be lost in gaseous form (Smith et al., 2008).

The use of cover crops or so-called service crops can also be a strategy to reduce N_2O emissions. This involves growing a fast-growing crop at the same time as the main crop or between two sowings of the main crop. This type of crop can utilise the surplus nitrogen remaining after harvesting the main crop and thus reduce N losses from the soil, reducing indirect N_2O emissions from N leaching by up to 50% (Valkama et al., 2015).

Reduction of CH_4

The practice of draining can also serve to reduce CH_4 emissions in rice crops, and is carried out several times during the growing season. Thus, interruption of flooding periods or flooding at a lower elevation in rice crops has been shown to reduce methane emissions.

Another way to reduce emissions in rice cultivation is to use varieties with a low root exudation rate. These exudates are partly responsible for methane being oxidised by anaerobic microorganisms and released into the atmosphere (Smith et al., 2008).

Mitigation options to reduce emissions from livestock farming include improving livestock waste management, and improving digestibility in ruminant livestock feed through improved diets, with a focus on improving the digestibility of food and feed. For example, a 1% increase in fat intake reduces CH_4 emissions by approximately 4% (Macleod et al., 2015).

- Increasing CO_2 sinks: Any agricultural practice that favours the sequestration of carbon in the soil, previously incorporated into the vegetative structure of the crop from CO_2 present in the atmosphere, is a fundamental climate change mitigation strategy. Many studies around the world have shown that significant amounts of atmospheric carbon can be stored in this way in the soil through a range of practices adapted to local conditions, such as CA (Lal, 2004). As an example, in the Andalusian countryside, after 19 years of trials, an increase of 18 tonnes per hectare in organic carbon content was observed in a wheat-sunflower-legume rotation planted under this management system, while no increase was observed under conventional tillage (Ordóñez Fernández et al., 2007).

Plant carbon can also be significantly stored in agroforestry systems, perennial plantations on agricultural land or by deep-rooted crops that contribute to fixing carbon deeper and thus making it more difficult to release into the atmosphere (Albrecht & Kandji, 2003).

Furthermore, increasing soil carbon content offers additional benefits for soil fertility, biodiversity, productivity and improved water storage capacity. These efforts help stabilise and increase production and optimise input use and reverse soil degradation, restoring soil ecological health.

- <u>Increasing energy efficiency</u>: Any process involving energy and/or fuel consumption inherently involves CO_2 emissions into the atmosphere. In this sense, the establishment of agricultural management systems based on a reduction of energy and fossil fuel consumption, or involving the use of renewable energies, represents an opportunity to mitigate climate change. Reducing energy and fuel consumption can be approached from various perspectives:

  In crop management systems, a large part of the energy and fuel consumption is attributable to soil tillage operations. On the one hand, management systems such as CA, which eliminate soil tillage, reduce the number of total tillage operations. There are examples of GHG emission reductions through reduced fuel consumption of up to 44% (Alhajj Ali et al., 2017).

  Another option for reducing energy consumption is based on optimising the doses applied and the correct execution of cultivation operations. In this sense, the use of variable application systems in fertilisation and treatment operations, as well as the use of automatic GPS guidance and guidance assistance systems, typical of precision technologies, are a great advantage, allowing additional fuel savings of over 6% (Bora et al., 2012).

As mentioned above, one of the agricultural systems that encompasses several climate change mitigation mechanisms is CA. CA is defined as an integrated system of agricultural production and land use that is applicable to rainfed and irrigated farming systems, both in annual crops (no-tillage) and perennial crops (cover crops). According to FAO (FAO, 2023), CA is described as an ecosystem approach to sustainable regenerative agriculture and land management based on the practical application of three interrelated context-specific and locally adapted principles, which are minimal or no mechanical soil disturbance, maintenance of permanent vegetation cover on the soil surface and species diversification/crop rotation (Figure I-1).

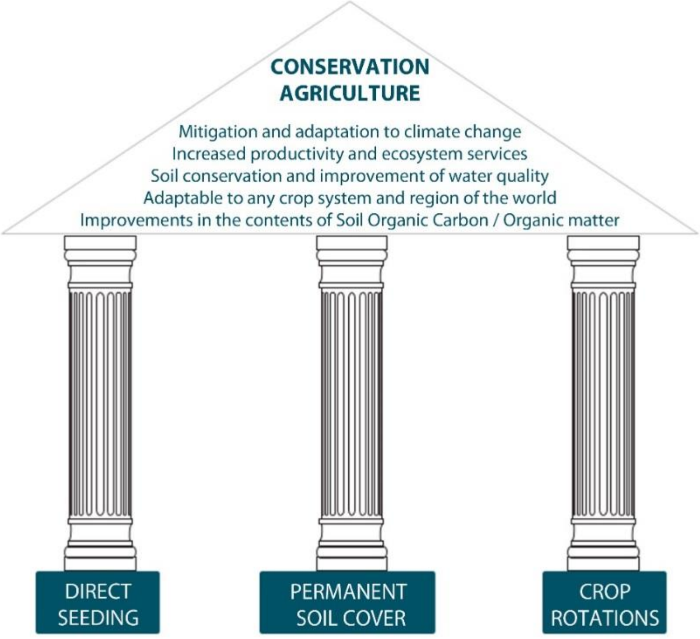

Figure I-1. Principles and benefits of CA.

As discussed above, and due to its environmental benefits in agricultural ecosystems, CA represents a comprehensive solution to all the issues raised above, contributing to climate change mitigation by being a dual action measure against the increase of GHG concentration in the atmosphere. On the one hand, the changes introduced by CA in soil carbon dynamics directly result in an increase in soil carbon, making CA a carbon sink activity (Thapa et al., 2023). On the other hand, the drastic reduction in the number of tillage operations, together with the lack of mechanical soil disturbance, leads to a reduction in CO_2 emissions due to energy savings (Alhajj Ali et al., 2017) and a reduction in organic matter mineralisation processes (Salamanca-Fresno et al., 2022) (Figure I-2).

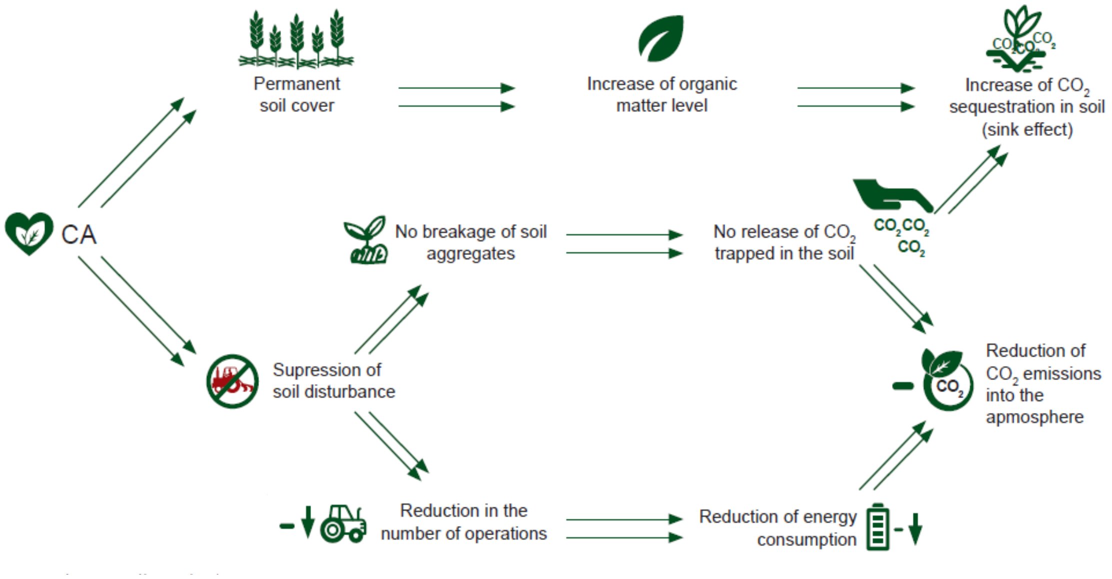

Figure I-2. Climate change mitigation mechanisms of the CA.
Source: AEACSV.

Regarding the action of CA in reducing N_2O emissions to the atmosphere, there is no consensus in the scientific community on its effectiveness. One of the parameters that can affect such emissions is organic carbon, as it is the most important factor in the abundance of denitrifying micro-organisms. In principle, the tillage system chosen that leads to differences in the content of this parameter (in this case CA) will affect microbial density and N_2O emissions, so higher denitrification losses could be expected (Spargo et al., 2008). Conversely, when soil is tilled, organic C and N forms are released from the aggregates and provide substrate for soil organic matter mineralisation, nitrification and denitrification (Pinto et al., 2004), which would affect the nitrogen gas generation potential. Furthermore, according to several authors (Spargo et al., 2008) long-term tillage reduces the soil's capacity to retain N, stimulates nitrate production (NO_3-) through nitrification and decreases the capacity to immobilise N due to decreased availability of C. Thus, some studies have concluded that emissions are higher in conservation tillage systems (Baggs et al., 2003; Kong et al., 2009; Lugato et al., 2018; Rochette, 2008; Sainju, 2015; Z. S. Zhang et al., 2016); others that they are higher in conventional tillage systems (Chatskikh & Olesen, 2007; Pandey et al., 2012; Robertson et al., 2000; K. Smith et al., 2012); and others that the tillage system did not influence emissions (Choudhary et al., 2002; Glenn et al., 2012; Pelster et al., 2011) hence the enormous importance of further studying the relationship of the soil management system among other factors with N_2O emissions in Mediterranean agroecosystems such as in our case.

It is therefore necessary to offer solutions to climate change from agriculture, through agricultural practices such as CA, which have sufficient scientific and technical solvency to be considered as effective mitigation measures in the regulatory framework designed to address climate-related environmental challenges. In this thesis, the mitigation character of JI is approached from a dual perspective. On the one hand, as an activity that reduces GHG emissions, and on the other hand, as a management system that enhances soil carbon sequestration.

I-2. Hypotheses and objectives

The hypothesis put forward in the thesis is that CA is a soil management system that reduces GHG concentrations in the atmosphere thanks to a double effect, carbon sequestration and reduction of GHG emissions.

The main objective of the thesis is to evaluate, at different scales and in different agro-climatic environments, the potential of CA to reduce GHG concentration by increasing soil carbon sequestration and reducing CO_2 and N_2O emissions to the atmosphere. To this end, three specific objectives have been set, namely:

- Assess the large-scale carbon sequestration capacity of CA practices (O1).
- Quantify the short- and long-term effects of different tillage systems on soil CO_2 (O2) fluxes.
- Assess the influence of JI on N_2O (O3) emissions.

These objectives have been achieved and justified in the three peer-reviewed articles, as outlined below:

- O1 in the article: Gonzalez-Sanchez, E.J., Veroz-Gonzalez, O., Conway, G., Moreno-Garcia, M., Kassam, A., Mkomwa, S., Ordoñez-Fernandez, R., Triviño-Tarradas, P., Carbonell-Bojollo, R. (2019). Meta-analysis on carbon sequestration through Conservation Agriculture in Africa. *Soil & Tillage Research* 190, pp 22-30. https://doi.org/10.1016/j.still.2019.02.020

- O2 in the article: Carbonell-Bojollo, R., Veroz-González, O., Ordóñez-Fernández, R., Moreno-García, M., Basch, G., Kassam, A., Repullo-Ruibérriz De Torres, M.A., González-Sánchez, E.J. (2019). Effect of Conservation Agriculture and environmental factors on CO_2 emissions in a rainfed crop rotation. *Sustainability,* 11, 3955; https://doi.org/10.3390/su11143955
- O3 in the article: Carbonell-Bojollo, R., Veroz-González, O., González-Sánchez, E.J., Ordóñez-Fernández, R., Moreno-García, M., Repullo-Ruibérriz De Torres, M.A. (2022). Soil Management, Irrigation, and Fertilisation Strategies for N_2O Emissions Mitigation in Mediterranean Agricultural Systems. *Agronomy*, 12, 1349. https://doi.org/10.3390/agronomy12061349

I-3. Structure

This thesis is divided into five chapters. Three of them comprise published papers in indexed journals. Soil & Tillage Research -Chapter III, Sustainability -Chapter IV- and Agronomy -Chapter V.

- Chapter I: Introduction, hypothesis and objectives, and structure of the thesis.
- Chapter II: Prospective of the scientific field of Conservation Agriculture and climate change: Bibliometric analysis.
- Chapter III: Meta-analysis on carbon sequestration through Conservation Agriculture in Africa.
- Chapter IV: Effect of Conservation Agriculture and environmental factors on CO_2 emissions in a rainfed crop rotation.
- Chapter V: Soil Management, Irrigation, and Fertilisation Strategies for N_2O Emissions Mitigation in Mediterranean Agricultural Systems.
- Chapter VI: General conclusions.

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Zhang, L., Huang, Y., Rong, L., Duan, X., Zhang, R., Li, Y., & Guan, J. (2021). Effect of soil erosion depth on crop yield based on topsoil removal method: a meta-analysis. In *Agronomy for Sustainable Development* (Vol. 41, Issue 5). https://doi.org/10.1007/s13593-021-00718-8

Zhang, Z. S., Chen, J., Liu, T. Q., Cao, C. G., & Li, C. F. (2016). Effects of nitrogen fertilizer sources and tillage practices on greenhouse gas emissions in paddy fields of central China. *Atmospheric Environment*, *144*. https://doi.org/10.1016/j.atmosenv.2016.09.003

Chapter II

Prospective of the scientific field of Conservation Agriculture and climate change: A bibliometric analysis

Chapter II: Prospective of the scientific field of Conservation Agriculture and climate change: A bibliometric analysis.

To put into context the articles that have served as a basis for the elaboration of this thesis, a bibliometric analysis of the scientific production related to the study of no-tillage and its implications on climate change mitigation is presented below. The sources collected for this analysis were articles published in scientific journals with a higher impact index (Q1 and Q2 quartiles) in the *Scopus* and *Web of Knowledge databases*. Bibliometrics is a discipline that uses quantitative and statistical methods to analyse the production, dissemination, and use of information contained in documents such as books, journals, scientific articles, or any other type of bibliographic material. The aim of bibliometrics is to study and define the conceptual, intellectual, and social structure of the field of research in question. Thus, the conceptual structure is established based on the co-occurrence relationships of research topics and/or keywords (Callon et al., 1983). If bibliographical references and citations are used as the unit of analysis, intellectual structure is defined (Small, 1973). Finally, the establishment of relationships between authors and/or their affiliations allows us to understand the social structure of a scientific field (Glänzel, 2001; Peters & Van Raan, 1991). To better understand the evolution of topics over time, we divided the analysis into three distinct periods. The initial period ran from the publication of the first article until 2002. We then divided the following years into two 10-year intervals: the second period ran from 2003 to 2012, and the third from 2013 to 2022. It should be noted that these sub-periods were exclusively used to study thematic development.

II-1. General Analysis

The bibliometric analysis shows that interest in the capacity of Conservation Agriculture (CA) to mitigate climate change is not recent, although in recent years, it has experienced a notable boom. Although the first scientific articles date back to 1995, the number of publications in journals with the highest impact index (Q1 and Q2 quartiles), in which no-tillage as a practice to mitigate climate change was studied in the Scopus and Web of Knowledge databases, did not consistently exceed ten per year until 2007, from which point onwards, scientific production has increased notably until the present day (Figure II-1).

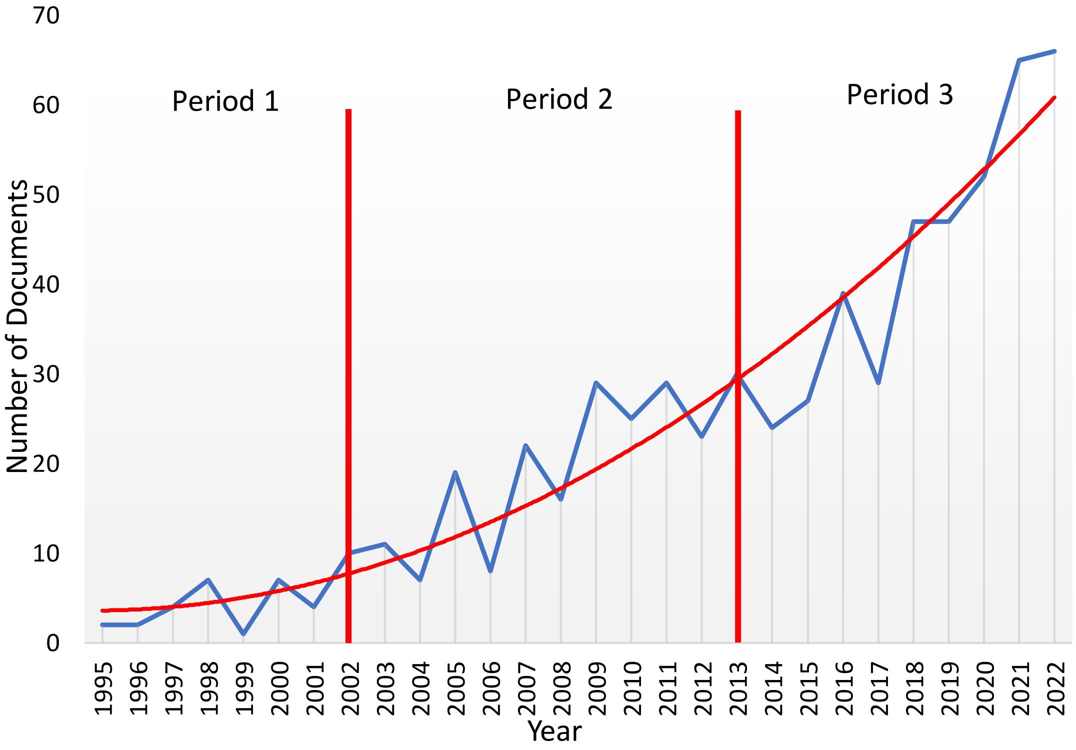

Figure II-1. Evolution of annual scientific production on no-tillage and climate change mitigation in journals included in the Q1 and Q2 quartiles.

Source: Own elaboration based on the Bibliometrix tool (Aria & Cuccurullo, 2017).

The exponential growth in the number of articles published can be attributed to the growing importance of this topic, given the increasingly evident consequences of climate change on ecosystems and our way of life. As awareness of environmental challenges has grown, there is an urgent need to address them, leading to an increase in the research output on CA and related topics. Commitments such as those made in the Kyoto Protocol in 1997 or, more recently, the emergence of the International 4 × 1000 Initiative under the Paris Agreement in 2015, which calls for increasing the sink effect of agricultural soils through the implementation of agricultural practices that promote carbon sequestration, have contributed to increasing the interest of the scientific community in the study of these practices and their relationship with the mitigation mechanisms that they promote. It is also important to note that scientific research in this field requires considerable time and investment due to the nature of the experiments involved. Long-term field experiments on no-tillage have been conducted since the 1980s (Franzluebbers et al., 1995; McConkey et al., 2003; Potter et al., 1998). In addition to the exponential growth in the number of articles, there has also been a corresponding increase in the number of sources publishing research in this area. The number of authors involved in CA research also increased significantly, almost tripling from the second to the third period (Table II-1).

Table II-1. Main bibliometric information of the articles analysed.
Source: Own elaboration based on the Bibliometrix tool (Aria & Cuccurullo, 2017).

Description	**Period 1 (1995-2002)**	**Period 2 (2003-2012)**	**Period 3 (2013-2022)**	**Total (1995-2022)**
Main information about data				
Sources (Journals, Books, etc)	8	35	58	**69**
Documents	37	188	425	**650**
Annual Growth Rate % Annual Growth Rate % Annual Growth Rate % Annual Growth Rate % Annual Growth Rate % Annual Growth Rate % Annual Growth Rate	25.85	8.54	9.16	**13.83**
Document Average Age	24.6	15.6	5.59	**9.56**
Average citations per doc	157.9	84.74	32.89	**55.01**
References	1064	5993	16513	**21598**
Publications/year	4.62	18.8	42.5	**23.2**
Document contents				
Keywords Plus (ID)	198	765	1351	**1757**
Author's Keywords (DE)	125	503	1118	**1468**
Authors				
Authors	126	666	1876	**2493**
Authors of single-authored docs	0	3	0	**3**
Authors collaboration				
Single-authored docs	0	3	0	**3**
Co-Authors per Doc	3.84	4.71	6.44	**5.79**
International co-authorships % International co-authorships % International co-authorships % International co-authorships	8.11	28.19	37.65	**33.23**

With regard to the sources in which publications related to the subject studied have been made throughout this period, Table II-2 shows the most productive scientific journals accompanied by some bibliometric indices. Based on the information shown, it can be seen that in the second period, the number of sources increased by 77% with respect to the first period, and in the third period the increase with respect to the second period was 65%. To determine the ranking shown in this table, a production level of more than five articles per source in at least one period was used. As a result, ten positions were analysed and ordered according to the value of the H index (Hirsch, 2005)which corresponds to the number of articles published by a journal (h), each of which has been cited at least "h" times in other articles. In this case, we see how the most relevant journals in this scientific field coincide in the three periods (Soil & Tillage and Agriculture Ecosystems & Environment), not only in terms of the H index, but also in terms of the number of articles published.

Table II-2. Scientific Production by Source (H=H index, TC=Total Citations of the articles belonging to a source, P=production of articles).
Source: Own elaboration based on the Bibliometrix tool (Aria & Cuccurullo, 2017).

Period 1: 1995-2002	**N sources: 8**			**Period 2: 2003-2012**	**N sources: 35**			**Period 3: 2013-2022**	**N sources: 58**			**Total**	**N sources: 58**		
Source	**H**	**TC**	**P**	**Source**	**H**	**TC**	**P**	**Source**	**H**	**TC**	**P**	**Source**	**H**	**TC**	**P**
Soil & Tillage Research	24	2853	24	Soil & Tillage Research	56	7143	73	Soil & Tillage Research	34	3339	95	Soil & Tillage Research	70	13335	192
Agriculture Ecosystems & Environment	5	1186	5	Agriculture Ecosystems & Environment	28	2821	32	Agriculture Ecosystems & Environment	26	2315	46	Agriculture Ecosystems & Environment	44	6322	83
Environmental Pollution	2	216	2	Plant And Soil	12	665	12	Science of The Total Environment	19	1000	36	Geoderma	20	991	35
Global Change Biology	2	273	2	Geoderma	8	346	8	Journal of Cleaner Production	18	875	21	Science Of The Total Environment	20	1083	38
Applied Soil Ecology	1	136	1	Climatic Change	7	294	7	Geoderma	16	645	27	Journal of Cleaner Production	18	875	21
Ecosystems	1	130	1	Global Change Biology	7	1636	7	Catena	10	535	14	Global Change Biology	14	2355	14
Science	1	971	1	Australian Journal Of Soil Research	6	215	7	European Journal Of Agronomy	8	362	8	Plant And Soil	13	695	14
Soil Biology & Biochemistry	1	78	1	Soil Biology & Biochemistry	5	497	5	Journal Of Environmental Management	8	194	15	Soil Biology & Biochemistry	12	759	13
				Biology And Fertility Of Soils	4	203	4	Land Degradation & Development	8	439	11	Catena	10	535	14
				Applied Soil Ecology	3	300	3	Agricultural And Forest Meteorology	7	156	8	Land Degradation & Development	10	581	13

With regard to the evolution over time of the sources with the highest number of publications (Figure II-2), it can be seen that, since its beginning, the journal Soil & Tillage Research has been the most productive in the scientific field studied, followed by the journal Agriculture, Ecosystems & Environment. To date, the other sources do not reach 50 publications per year, which means that they are far from the first two sources cited.

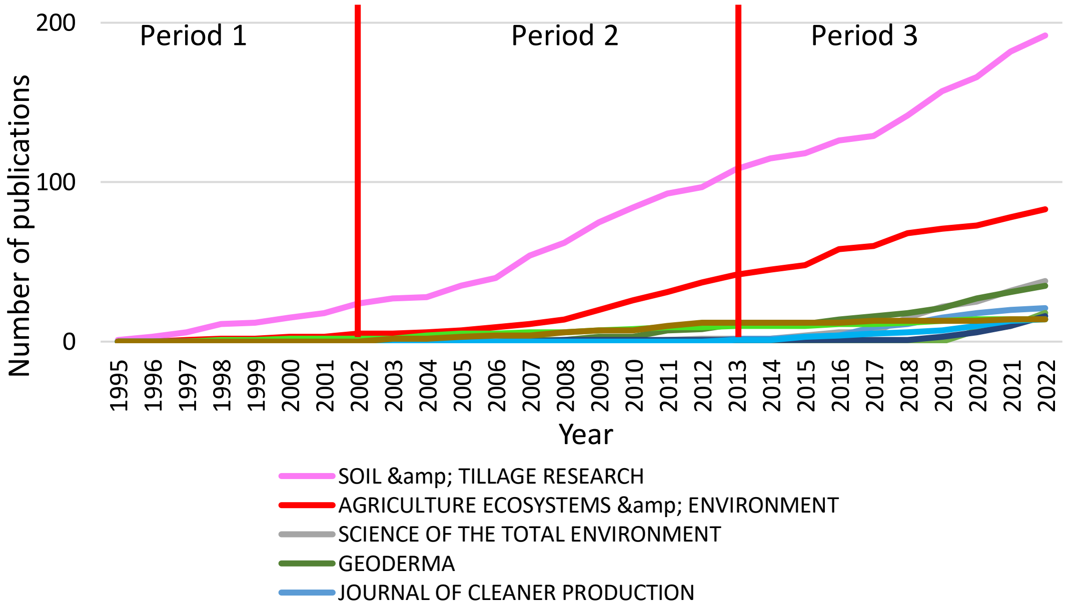

Figure II-2. Time evolution of publications by source type.
Source: Own elaboration based on the Bibliometrix tool (Aria & Cuccurullo, 2017).

II-2. Author Analysis

The analysis of the authors in the scientific field under study offers the possibility of studying the social and intellectual structures of the field. Thus, with regard to social structure, bibliometric analysis makes it possible to establish networks of collaboration between authors and the relationships between the countries to which the authors' institutions of affiliation belong. For its part, data such as productivity per author and the co-citation ratio in each document provide us with information about the intellectual structure

As shown in Figure II-3, our analysis of the author collaboration network revealed 14 clusters, with four of these interconnected clusters identified and listed as 1, 2, 3 and 4. Cluster 1 is the largest cluster, with connections to five smaller clusters.

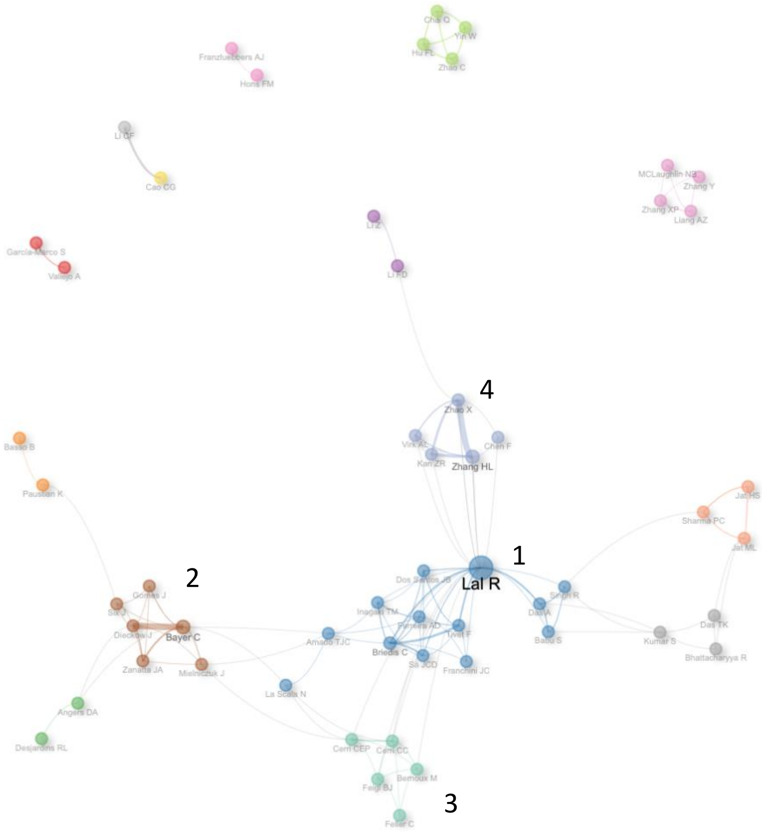

Figure II-3. Author Collaboration Network.
Source: Own elaboration based on the Bibliometrix tool (Aria & Cuccurullo, 2017).

In terms of the content of each of the clusters of the collaborative network, cluster 1, the most relevant of all and to which the most productive author belongs, focuses on the effect of the transformation of natural ecosystems on soil carbon dynamics in tropical and subtropical climates. Among the transformations identified is the transition to agricultural ecosystems managed under CA. Some of the conclusions reached in the work of this collaborative network indicate that one way to recover the natural capital lost in agricultural systems, mainly due to the loss of soil organic carbon, is through no-tillage systems (de Moraes Sá et al., 2022). Tropical and subtropical climates are also the subject of study by the authors of cluster 2, with carbon sequestration in tropical and subtropical climates (Bayer et al., 2006; Boddey et al., 2010; Rodrigues et al., 2022; Veloso et al., 2018) and the mitigation of GHG emissions, such as CO_2 (Pes et al., 2011), N_2O (Bayer et al., 2015), and CH_4 (Bayer et al., 2012) as key topics.

Cluster 3 authors conducted studies in Brazil, which is one of the countries with the largest area devoted to CA, and also appears to be one of the most scientifically productive countries. Cluster 4 corresponds to the group of collaborating authors conducting their work in China and encompasses a broader relationship between CA practices and their ability to mitigate climate change, as it not only focuses on the increase in carbon sequestration due to this management system (Liu et al., 2022), but also addresses its effects on the reduction of CO_2, N_2O and CH_4 (Virk et al., 2022). Authors located in border clusters show less connectivity with other clusters and, consequently, have a less extensive collaboration network.

Figure II-4 shows the production of the most relevant authors during the study period. The line represents the chronology of an author, the size of the circle is proportional to the number of documents, and the intensity of the colour is proportional to the total number of citations per year. (Aria & Cuccurullo, 2017). The authors with the longest chronologies are R. Lal R., K. Paustian K. and C. Bayer, spanning from the late 20th century to the 2020s. R. Lal R stands out as one of the most prolific authors due to the length of the timeline associated with his publications, along with a continuous increase in output even during the third period, both in terms of number of articles and total citations. Additionally, it is worth noting that H.L. Zhang and X. Zhao, whose timelines started after 2010, are experiencing rapid growth in the number of articles and total citations per year.

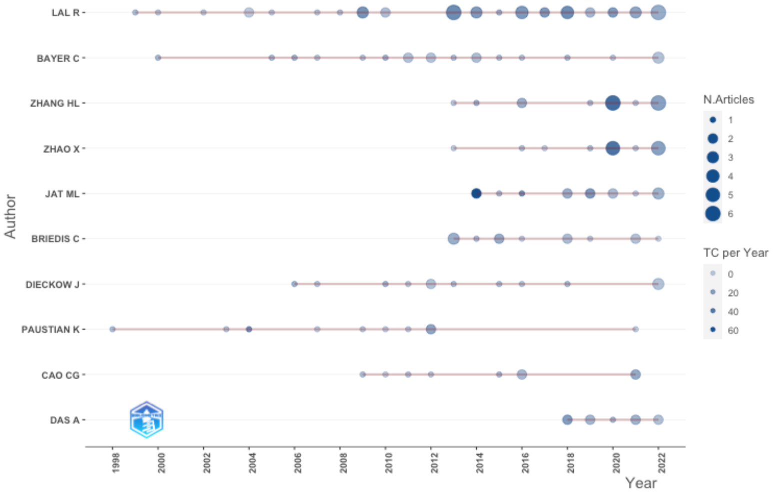

Figure II-4. Production by the author in the studied period.
Source: Own elaboration based on the Bibliometrix tool (Aria & Cuccurullo, 2017).

If we analyse the country of origin of the authors, it is not surprising that the ten most relevant authors carried out their research in the three most significant countries in this field (Figure II-5). Two authors, R. Lal and K. Paustian come from the USA, where CA originated and where research in this field started. These authors have been publishing since the early days when this field of research emerged. In Brazil, where CA and related studies started in the 1970s, we have three authors: C. Briedis, C. Bayer and J. Dieckow. Finally, we have authors from China (H.L. Zhang and X. Zhao) and India (A. Das. and C.G. Cao). With the exception of C.G. Cao, who appeared in the last years of the second period, these authors started publishing in the third period and are experiencing rapid growth.

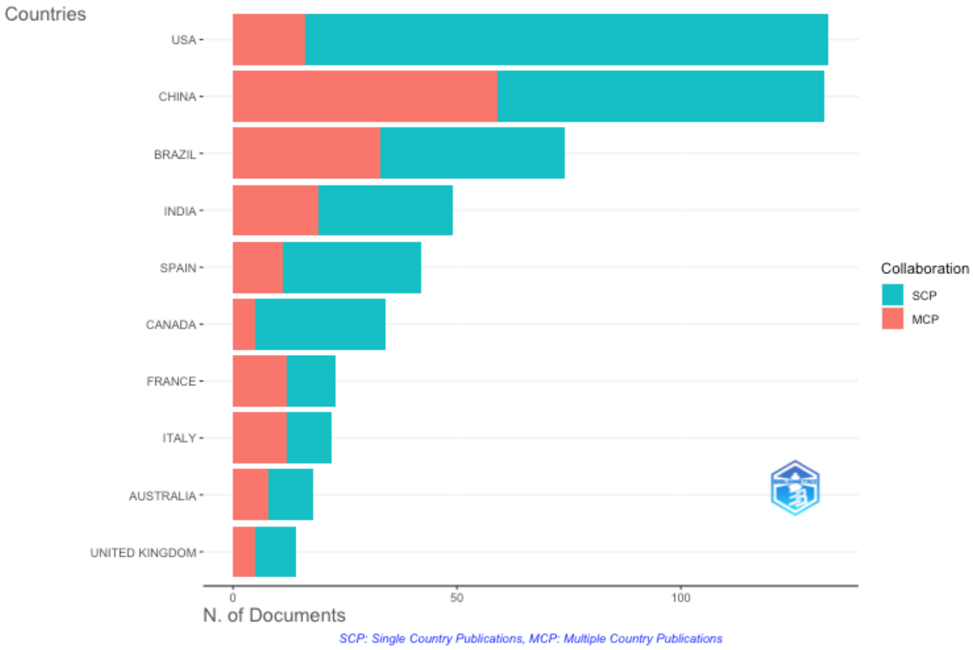

Figure II-5. Countries corresponding to the authors. MCP: Multi-Country Publication. SCP: Single-Country Publication.
Source: Own elaboration based on the Bibliometrix tool (Aria & Cuccurullo, 2017).

In terms of international collaboration, the network of collaboration between countries depicted in Figure II-6 reveals several distinct groups. We observe three main clusters (red, blue, and green), a smaller one (purple), and individual countries collaborating with one or more other countries.

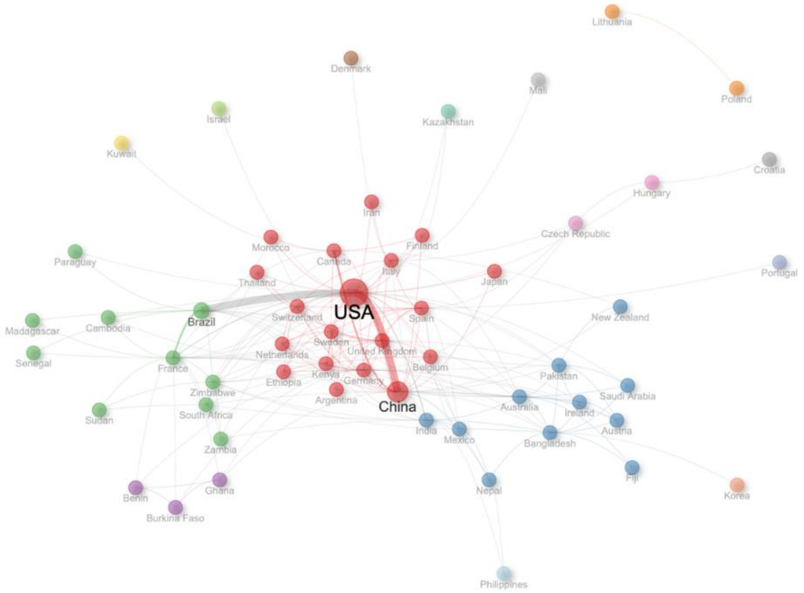

Figure II-6. Network of collaboration between countries.
Source: Own elaboration based on the Bibliometrix tool (Aria & Cuccurullo, 2017).

The most prominent partnerships are those of the US, which has significant links with China and Brazil, as can be seen from the density of the connecting lines. The US is located in the red group, where it shares space with many European countries, such as Germany, Spain, and Italy. These European nations not only collaborate extensively with each other but also engage in partnerships with countries in other clusters.

China, which is also part of the red cluster, has an important collaboration with the United States, as mentioned above. It also connects with the blue cluster, which includes other Asian countries, such as India, Pakistan, and Nepal, as well as Oceania countries, such as Australia and New Zealand.

In contrast, the green cluster shows lower levels of collaboration than the red cluster. The green cluster includes Brazil and Paraguay from South America, but most of the countries in this cluster are African, such as South Africa, Zimbabwe and Senegal. This cluster shares similarities with the smaller purple cluster, which includes African nations, such as Ghana, Burkina Faso, and Benin. Neighbouring countries in the network show limited collaboration with each other. For example, Lithuania and Poland collaborate only with each other without engaging with any other country in the network.

Another analysis that can be performed around authors is co-citation (Figure II-7). The co-citation network reflects the frequency in which two papers are cited in a third paper

(Small, 1973). In this respect, four clusters were identified, of which two encompassed the most authors and were the most important (green and red). Here, we note that the most important authors are in the red cluster, as indicated by the size of the nodes and strong connections between R. Lal, J. Six. and T.O. West. These authors also have connections to other clusters, as represented by the grey lines connecting them.

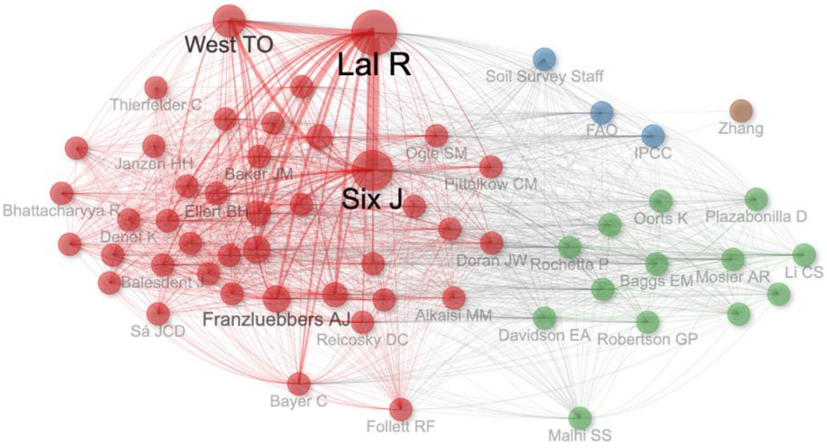

Figure II-7. Author co-citation network.
Source: Own elaboration based on the Bibliometrix tool (Aria & Cuccurullo, 2017).

II-3. Document Analysis

By analysing the selected documents, it is possible to understand the conceptual structure of the scientific field under study. This structure provides information on the main topics dealt with in the field of science (Callon et al., 1983) as well as its evolution over time. This can be done not only by analysing the documents in general and their interactions with each other through a co-citation analysis, but also by analysing the keywords and the study of the co-occurrence networks between them.

Figure II-8 shows the structure of the co-citation network of the documents in the field studied, which is articulated around two clusters. In the blue cluster, the most significant document, indicated by the size of the node, is "A synthesis of carbon sequestration, carbon emissions, and net carbon flux in agriculture: comparing tillage practices in the United States" (West & Marland, 2002). In this study, the authors found that the carbon sequestration potential of minimum tillage is negligible. In contrast, no-tillage has the potential to reduce CO_2 emissions and enhance carbon sequestration by increasing the soil biomass and soil organic matter. Robertson et al. (2000) comparing agricultural ecosystems with nearby non-agricultural ecosystems, found that, in terms of soil carbon accumulation, no-till is the cropping system that most offsets emissions from other sources of greenhouse gases (GHG), including CH_4 (Lu et al., 2009) studying the growing regions of China, suggested that no-till and straw return have the potential to sequester carbon in these areas and mitigate carbon emissions in their country.

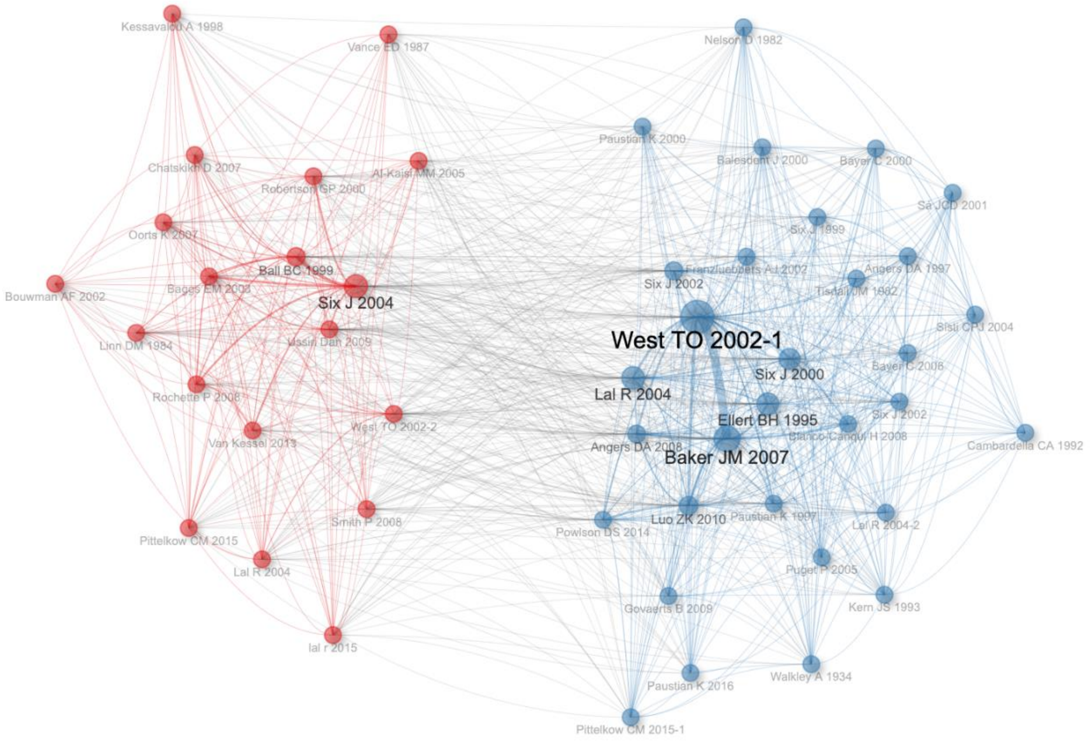

Figure II-8. References co-citation network.
Source: Own elaboration based on the Bibliometrix tool (Aria & Cuccurullo, 2017).

Although many authors have reported a higher soil carbon content in no-tillage compared to conventional tillage around the world (Aguilera et al., 2013; Grandy & Robertson, 2007; Robertson et al., 2000; West & Marland, 2002) and that the potential of soil to sequester carbon has been demonstrated (Gonzalez-Sanchez et al., 2012; Lal, 2004), some authors have presented divergent views. For example, Luo et al. (2010) found that conversion from conventional tillage to no-tillage increases carbon content in the top 5 cm of soil, whereas below 40 cm, there was no difference between the two management systems. In addition, Powlson et al. (2016) suggested that no-till has the potential to mitigate climate change, but its effectiveness varies depending on location and specific circumstances.

The red cluster appears to be less important than the blue one, as indicated by the smaller labels. The article "The potential to mitigate global warming with no-tillage management is only realized when practiced in the long term" (Six et al., 2004) stands out as the most significant of this group. This indicates that no-tillage must be practiced in the long term to effectively reduce GHG emissions. This document also underlines the importance of studying N_2O emissions in agriculture, especially as this gas is mostly released by nitrogen fertilisers. Baggs et al. (2003) reported higher N_2O emissions from fertilised no-tillage treatments compared to fertilised conventional tillage treatments. However, Robertson et al. (2000) concluded that it is not only fertiliser or tillage that accelerates N_2O fluxes from cropping systems, but also the high availability of nitrogen in the soil. Malhi et al. (2006) found that conventional tillage with nitrogen fertiliser promoted higher N_2O emissions than no-tillage with fertiliser application.

II-4. Keyword analysis

As discussed above, a conceptual analysis of a field of research can also be carried out based on the keywords of a paper. Keywords are terms or phrases that summarise and describe the main topics addressed in the scientific article. These keywords were selected to accurately and concisely represent the content of the article, facilitating the search and retrieval of relevant information by other researchers, students, or professionals interested in the topic.

Based on the frequencies found for each keyword (Table II-3), most of them were distributed between those referring to the soil management system (no-tillage, tillage, no-till, conservation tillage, conservation agriculture, and conventional tillage) and those referring to carbon (soil organic carbon, carbon sequestration, soil organic matter). We can consider the high frequency of those keywords related to the management system to be normal, as the scientific field analysed how one of them influences climate change (no-tillage, no-tillage, conservation tillage, conservation agriculture) compared to the other (tillage, conventional tillage). On the other hand, although the search terms varied in terms of the parameters used to measure the mitigating effect of the management systems studied, all those relating to carbon prevailed over the others.

Table II-3. Most relevant Author's Keywords.
Source: own compilation.

Author's Keywords	**Occurrences**
no-tillage	99
soil organic carbon	96
carbon sequestration	93
tillage	83
no-till	50
conservation tillage	49
conservation agriculture	47
nitrous oxide	46
soil organic matter	35
conventional tillage	34

Figure II-9 shows the evolution of the frequency of occurrence of the main keywords in the scientific field studied over time. The increase in frequency over time is partly explained by the increase in the number of documents published; however, the rate of growth of each keyword varied. For example, from the second period onwards, the term "soil organic carbon" has grown faster than "soil organic matter", indicating that the former term has been replacing the latter. Soil Organic Carbon content has long been considered an indicator of soil quality (Potter et al., 1998). Although soil organic matter remains an important keyword, this shift in thematic emphasis is noteworthy.

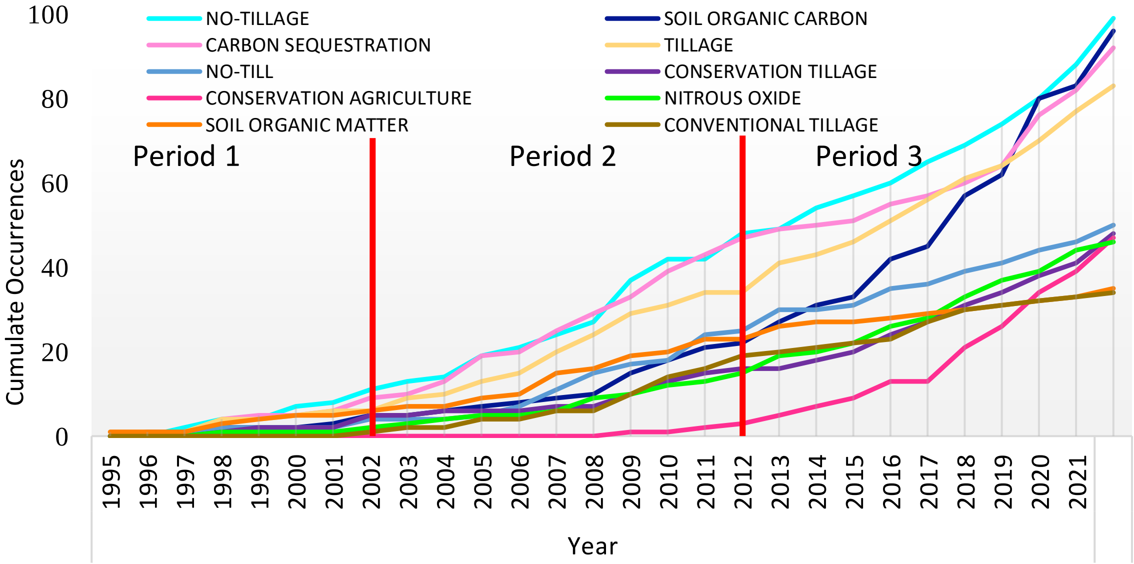

Figure II-9. Author's Keywords over time.
Source: Own elaboration based on the Bibliometrix tool (Aria & Cuccurullo, 2017).

In this analysis, we also found two very similar keywords, such as "no-till" and "no-tillage", both used from the first period. However, we observed a preference for "no-till" over "no-tillage", as evidenced by the higher number of occurrences of "no-tillage" (99 occurrences) compared to "no-tillage" (50 occurrences). A similar trend is observed with "tillage" and "conventional tillage", where "tillage" is preferred over "conventional tillage".

Within this thematic area, the keyword "conservation agriculture" has shown growth since the second period. It is important to note that CA is based on three principles, with no-tillage being one of them (Derpsch et al., 2024), although it represents a broader concept. The importance of GHG emissions is underlined by keywords such as "carbon sequestration" and "nitrous oxide". While the importance of carbon is evident (93 occurrences), there has also been notable growth in the occurrence of "nitrous oxide", especially in the third period.

Focusing on the co-occurrence analysis, we can see how the keywords were grouped into three different clusters (Figure II-10), mainly divided by management system and carbon sequestration ("no-tillage", "soil organic carbon", "tillage"), which represents the largest cluster with the most keywords. In addition, "nitrous oxide" (GHG emissions, "carbon dioxide", "N_2O emissions ") forms another cluster, with a smaller cluster linking aggregate stability and tillage systems. These clusters are interconnected, reflecting the interrelated nature of the keywords and their respective themes.

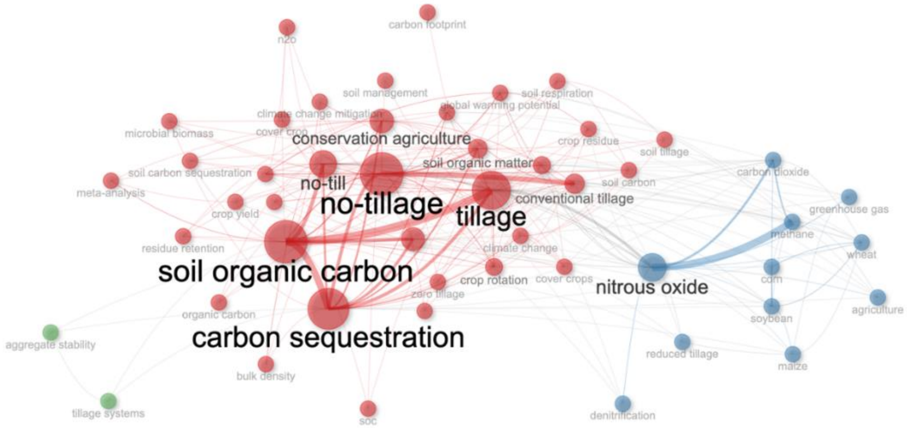

Figure II-10. Co-occurrence network by Author's Keywords.
Source: Own elaboration based on the Bibliometrix tool (Aria & Cuccurullo, 2017).

II-5. Themes and thematic areas

To understand the evolution of the scientific field studied, Figure II-11 shows a map of the temporal evolution of the topics addressed based on the previously selected periods of study.

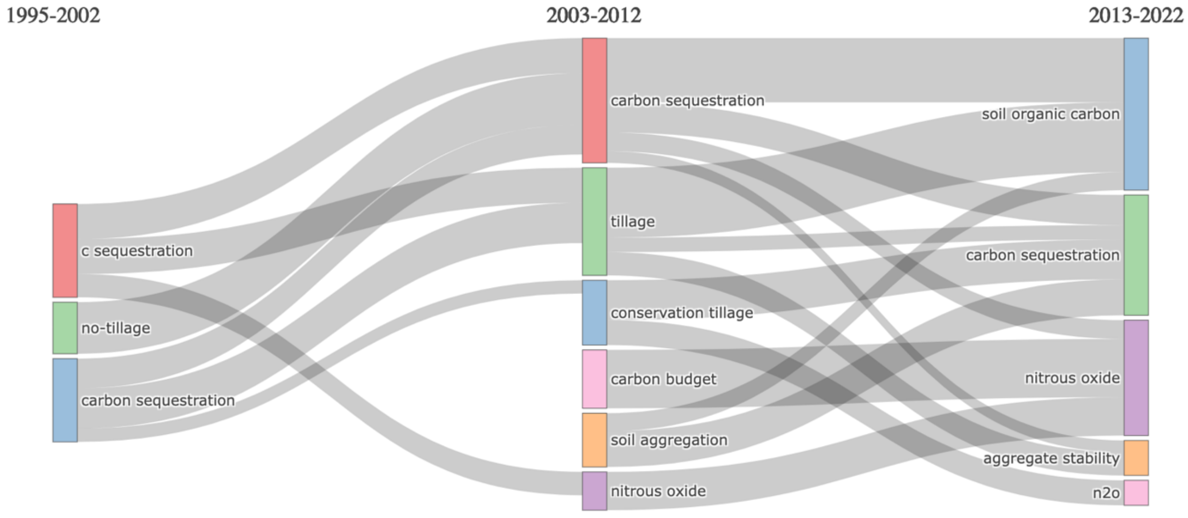

Figure II-11. Thematic evolution Author keywords.
Source: Own elaboration based on the Bibliometrix tool (Aria & Cuccurullo, 2017).

Although these issues were later split and merged, carbon has remained an important topic from the early period (Campbell et al., 1996; Díaz-Zorita & Grove, 2002; Franzluebbers et al., 1995) to the present day (González-Sánchez et al., 2012; Kiran Kumara et al., 2020; Yadav et al., 2019). These authors studied the behaviour of carbon sequestration (C sequestration) and emissions under different management systems, especially no-tillage, conventional tillage, and reduced tillage. No-tillage was a topic of great importance in the early period and has been widely studied worldwide, including in North America (Hendrix et al., 1998; W. N. Smith et al., 2000), South America (Bayer et al., 2000; Díaz-Zorita & Grove, 2002), Africa (Mrabet et al., 2001) and Oceania (Aslam et al., 2000). The objective that motivated and continues to motivate this scientific field is to find a system that can better sequester carbon and, more importantly, prevent soil loss.

In the second period, there were a larger number of themes, some of which will be merged in the third period, as they appear as synonyms for other themes. For example, the "carbon budget" (Hollinger et al., 2005) was an important theme during this period, but then merged in the third period. One explanation for the significant importance of the carbon budget between 2003 and 2012 is that the Kyoto Protocol and the environmental policies began to gain momentum during this period to meet the commitments outlined in the protocol. It can be seen how the issue of soil aggregation appears in this period, due to the relationship it has with carbon content (Churchman et al., 2010; Fernandez et al., 2010) and as aggregate stability in the third period (Fiorini et al., 2020; Guo et al., 2022) both pertaining to the physical characteristics of the soil.

In addition, nitrous oxide gained prominence in both the second and third periods (Figure II-11). As one of the most released GHGs, nitrous oxide is influenced by nitrogen inputs in agricultural systems, such as fertilisers, which can increase these emissions. Therefore, it is very important to study this to mitigate its effects. Numerous authors have carried out research on this topic (Boeckx et al., 2011; Li et al., 2008; Metay et al., 2011; Piva et al., 2012; J. Smith et al., 2010; Yao et al., 2009). in the second period and its importance continued to grow in the third period. In thematic evolution, nitrous oxide is also listed as N_2O and its chemical formula (Corrochano-Monsalve et al., 2021; Glenn et al., 2021; Wang et al., 2022).

II-6. Final considerations

In general, we can conclude that the scientific field of CA and the solutions that this system offers to the problem of climate change are booming, given the increase in scientific production in recent years. This field has an international scope with leading countries in this type of research, such as the USA, China, and Brazil, which maintain close and stable collaboration networks not only among themselves but also with other countries in Europe and Oceania.

In relation to the topics dealt with, there is a clear evolution of the research carried out on the three main subjects of study, which have become basic themes in the scientific field. On the one hand, there are those studies focused on the analysis of the effects of the management system on the content of organic carbon present in the soil. However, there are studies that deal with the mitigating effect of CA from the perspective of its capacity to sequester carbon, while considering the increase of this element in the soil, the reductions in CO_2 emissions from the soil are included. The last of the major current core issues is the study of the effects of CA on N_2O emissions, which is the main GHG reported in the agricultural sector. In addition to these three topics, there is another topic related to aggregate stability, but due to its size, it is residual, and it is possible that it will disappear in the future.

The articles that have served as the basis for the preparation of this thesis cover all the basic topics currently addressed by the scientific field of no-tillage and its benefits for climate change. Thus, the article "Meta-analysis on carbon sequestration through Conservation Agriculture in Africa" is included in the topics of "soil organic carbon" and "carbon sequestration". The articles "The Effect of Conservation Agriculture and Environmental Factors on CO_2 Emissions in a Rainfed Crop Rotation" and "Soil Management, Irrigation, and Fertilisation Strategies for N_2O Emissions Mitigation in Mediterranean Agricultural Systems" fall under the topic of GHG emissions, with “nitrous oxide” being the most predominant theme.

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Chapter III

Meta-analysis on carbon sequestration through Conservation Agriculture in Africa

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Chapter III: Meta-analysis on carbon sequestration through Conservation Agriculture in Africa

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III-Abstract

Africa is the smallest contributor to global greenhouse gas emissions among the continents, but the most vulnerable to the impacts of climate change. The effects will not be limited to a rising average temperature and changing rainfall patterns, but also to increasing severity and frequency in droughts, heat stress and floods.

Agriculture is not only impacted upon by climate change but also contributes to global warming. However, not all agricultural systems affect negatively climate change.

Conservation Agriculture is a farming system that promotes continuous no or minimum soil disturbance (i.e. no tillage), maintenance of a permanent soil mulch cover, and diversification of plant species. It enhances biodiversity and natural biological processes above and below the ground surface, so contributing to increased water and nutrient use efficiency and productivity, to more resilient cropping systems, and to improved and sustained crop production. Conservation Agriculture is based on the practical application of three interlinked principles along with complementary good agricultural practice. The characteristics of CA make it one of the systems best able to contribute to climate change mitigation by reducing atmospheric greenhouse gas concentration.

In this article, the carbon sequestration potential of CA is assessed, both in annual and perennial crops, in the different agro-climatic regions of Africa. In total, the potential estimate of annual carbon sequestration in African agricultural soils through CA amounts to 145 M t of C per year, that is 533 M t of CO_2 per year. This figure represents about 95 times the current sequestration figure.

Keywords: carbon sequestration; no-tillage; groundcovers; climate change

III-1. Introduction

Africa is the smallest contributor to global greenhouse gas emissions (GHGs) among the continents, but the most vulnerable to the impacts of climate change (UNFCCC, 2016). According to the Intergovernmental Panel on Climate Change (IPCC), temperatures across Africa are expected to increase by 2-6 ºC within the next 100 years (IPCC, 2014). The effects will not be limited to a rising average temperature and changing rainfall patterns, but also to increasing severity and frequency in droughts, heat stress and floods (Niang et al, 2014; Hummel, 2015; Rose, 2015). These climatic risks have a direct negative impact on the natural resources supporting agricultural production processes with a detrimental impact on food security and livelihoods (Awojobi and Tetteh, 2017, Abebe, 2014; Science for Environmental Policy, 2015). The agricultural sector in Africa has been impacted by flooding, droughts, soil erosion, land degradation and deforestation, leading to human migration within Africa and to out migration from Africa.

Agriculture is not only impacted upon by climate change but also contributes to global warming. Even if agriculture would not be the only productive sector affected by global warming, the impacts on it would definitely have negative effects on food security and social welfare. Crops need adequate land, water, sunlight and heat to grow and complete their production cycles. Global warming has already altered the duration of the growing season in some areas. The periods of flowering and harvest of cereals are already several days ahead. It is foreseeable that these changes may continue to occur in many regions (EEA, 2016). The sector needs to adapt to the changes in climatic conditions and also help in mitigation. Agriculture which is part of the AFOLU sector (Agriculture, Forestry, and Other Land Use) is unique, since its climate change mitigation potential is derived from both an enhancement of removals of GHGs from the atmosphere, and a reduction of emissions through management of land, crops and livestock (Smith et al., 2014).

Africa remains a food deficit region, yet it has potential to become a future ‘bread basket’, and the sustainable intensification of agricultural output, with a focus of soil and water conservation and optimum use of production inputs with minimum negative impact on the environment is part of the solution (Conway, 2012). Lal, (2018) alerts of the effects of projected climate change on yield of food crops in Africa that may reach significant declines of 17.2% in wheat, 14.6% in sorghum and 13.1% in maize. For many developing countries, the main concern regarding agriculture relates to food security, poverty alleviation, economic development and adaptation to the potential impacts of climate change.

A well designed and executed soil management system has the potential to increase yields (e.g., in sub-Saharan Africa) while also providing a range of co-benefits such as increased soil organic matter (Keating et al., 2013; Kassam et al., 2017). Two-thirds of developing countries have implemented strategic plans to mitigate greenhouse gas (GHG) emissions from agriculture (Wilkes et al., 2013).

In this context, Conservation Agriculture (CA) is a sustainable agriculture system, able to produce food and other agricultural products in all land-based agroecologies (Kassam et al., 2018). According to the Food and Agriculture Organization of the United Nations (FAO, 2018a), CA is a farming system that promotes continuous no or minimum soil disturbance (i.e. no tillage), maintenance of a permanent soil mulch cover, and diversification of plant species. It enhances biodiversity and natural biological processes above and below the ground surface, so contributing to increased water and nutrient use efficiency and productivity, to more resilient cropping systems, and to improved and sustained crop production. CA is based on the practical application of three interlinked principles along with complementary good agricultural practice, namely:

(1) Avoiding or minimizing mechanical soil disturbance involving seeding or planting directly into untilled soil, eliminating tillage altogether once the soil has been brought to good condition, and keeping soil disturbance from cultural operations to the minimum possible.

(2) Maintaining year-round biomass mulch cover over the soil, including specially introduced cover crops and intercrops and/or the mulch provided by retained biomass and stubble from the previous crop.

(3) Diversifying crop rotations, sequences and associations, adapted to local environmental and socio-economic conditions, and including appropriate nitrogen fixing legumes; such rotations and associations contribute to maintaining biodiversity above and, in the soil, add biologically fixed nitrogen to the soil-plant system, and help avoid build-up of pest populations. In CA, the sequences and rotations of crops encourage agrobiodiversity as each crop will attract different overlapping spectra of microorganisms and natural enemies of pests.

No-tillage is clearly identified as a CA technique, whereas the application of Conservation Agriculture in perennial crops has been less studied. The agronomical practise of CA in woody crops are the groundcovers, whereby the soil surface between rows of trees remains protected against erosion by a cover. With this technique, at least 30% of the soil is protected either by sown cover crops, spontaneous vegetation or inert covers, such as pruning residues or tree leaves. For the establishment of sown cover crops and the spread of inert covers, farmers must use methods in coherence with CA principle of minimum soil disturbance (Gonzalez-Sanchez et al., 2015).

In both type of crops, annual or perennial, the characteristics of CA make it one of the systems best able to contribute to climate change mitigation by reducing atmospheric GHGs concentration. On the one hand, the changes introduced by CA in the carbon dynamics in the soil lead directly to an increase in soil C (Reicosky, 1995; Lal, 2008). This effect is known as 'soil's carbon sink'. At the same time, the drastic reduction in the amount of tillage and the mechanical non-alteration of the soil reduce CO_2 emissions arising from energy saving and the reduction in the rates of the mineralization of soil organic matter (Carbonell-Bojollo et al., 2011; Kassam et al., 2017a). CA adoption requires a much lower level of capital investment and production inputs and is thus more readily applicable to smallholder farmers in low income countries (Kassam et al., 2017b).

Soil carbon sequestration is a process in which CO_2 is removed from the atmosphere and stored in the soil carbon pool. This process is primarily mediated by plants through photosynthesis, with carbon stored in the form of soil organic carbon (SOC) (Lal, 2008). In terms of climate change mitigation, CA contributes the increase of SOC, whilst reducing the emissions of carbon dioxide. On the one hand, the decomposition of the crop biomass on the soil surface increase soil organic matter and soil organic carbon. On the other hand, emissions are reduced as a result of less soil carbon combustion due to no-tillage, and less fuel burning because of fewer field operations and lower energy use for seeding and crop establishment. The net sum effect of these processes results in an increase in the carbon sink effect in the soil, leading to a net increase of soil organic carbon; measured in tonnes of carbon in soil per hectare per year (t ha^{-1} yr^{-1}). Numerous scientific studies confirm that soils are an important pool of active carbon (González-Sánchez et al., 2012), and play a major role in the global carbon cycle.

Several international initiatives have identified CA as a major contributor to the mitigation and adaptability of agricultural land use to climate change. The initiative "4 per 1000" (4p1000, 2015), launched by France on 1 December 2015 at the COP 21 in

Paris, aims to demonstrate that agriculture, and in particular agricultural soils, can play a crucial role where food security and climate change are concerned. The following year, the Adaptation of African Agriculture (AAA, 2016) was identified as one of the priorities of the Moroccan presidency for COP22 in Marrakesh. The Triple A aims to reduce the vulnerability of Africa and its agriculture to climate change. Both 4p1000 and AAA are governmentally supported, and show that agriculture can provide some practical solutions to the challenge and threats posed by climate change. The promotion of CA is among the key solutions and recommendations identified in both initiatives. The "4 per 1000" initiative intends to increase soil organic matter and carbon sequestration through the implementation of agricultural systems and practices adapted to local environmental, social and economic conditions, whereas the AAA promotes and supports three over-arching solution clusters to enhance soil management through soil fertility and crop fertilisation; arboriculture and agroforestry; and agroecological innovations and carbon sequestration. CA has also been incorporated into the regional agricultural policies, and increasingly, has been 'officially' recognized as a core element of climate-smart agriculture (FAO, 2016, 2017; Kassam et al., 2017b).

Since soils occupy about 30% of the global surface area, a major shift from tillage-based agriculture to climate smart systems, such as CA, would have a significant impact on global climate, food security and society. The aim of this study is to provide knowledge with a solid scientific base on the carbon sequestration potential of CA, both in annual and perennial crops, in the different agro-climatic regions of Africa.

III-2. Material and Methods

The results presented in this paper are based on a literature review of scientific articles published in peer reviewed journals. The terms "Conservation Agriculture; carbon sequestration; Africa; climate change mitigation, no-tillage, groundcovers" have been consulted at the scientific databases *sciencedirect.com* and *webofknowledge.com*.

This review has been carried out based on the different climatic zones of Africa (Figure III-1) and focused on CA annual and perennial systems, carbon sequestration based on current area of CA adoption in African countries, and potential of carbon sequestration based on conversion of conventional tillage agriculture to CA across Africa. Figure III-2 shows the geographical distribution of the studies. No data for carbon sequestration in desert areas is presented, as no articles with a carbon sequestration rate of CA have been found, and there is little expectation of a significant carbon increase in those environments as a result of farming activities.

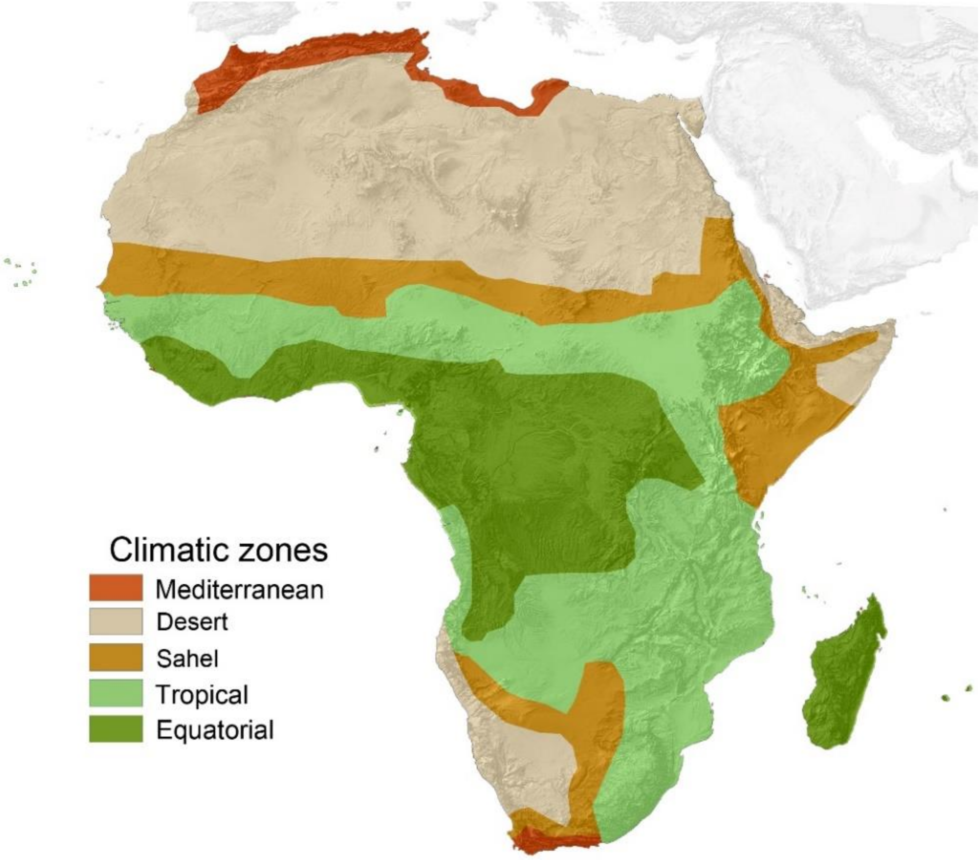

Figure III-1. Climatic zones of Africa.
Source: Authors' diagram based on Ngaira (2007) and www.gifex.com.

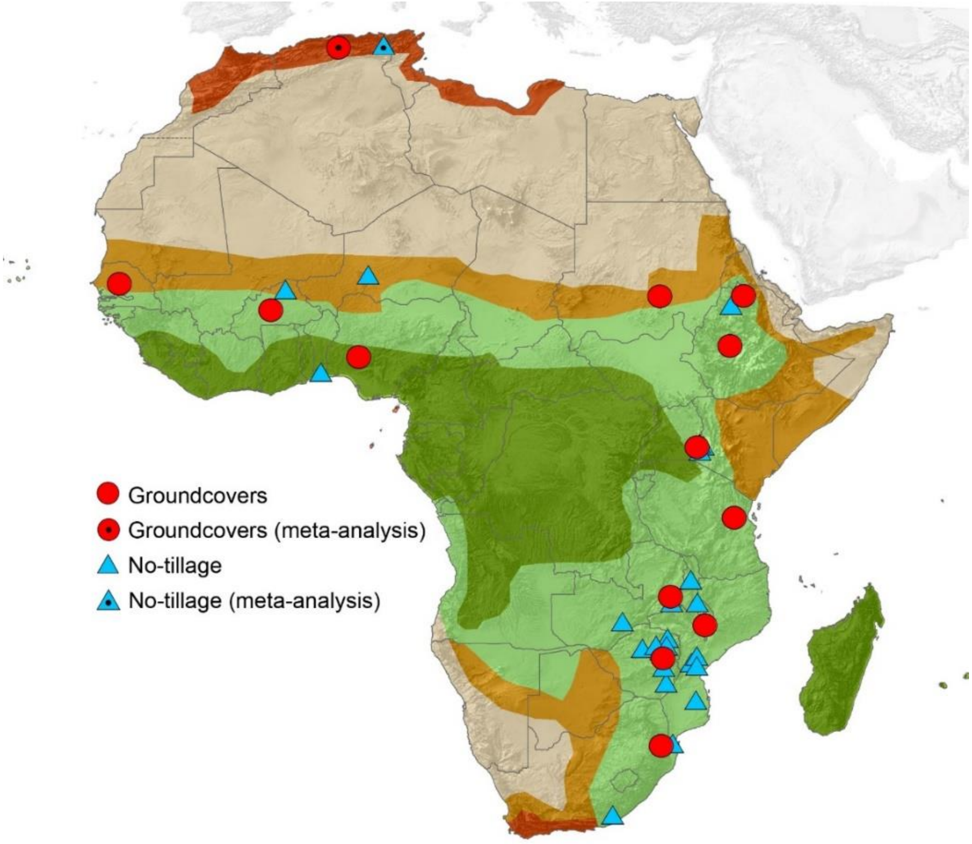

Figure III-2. Geographical distribution and per climatic zone of studies addressing carbon sequestration.

The full methodology for obtaining the carbon sequestration rates is described in González-Sánchez et al. (2012). A description of the methodology to obtain potential areas of CA follows. Country statistics of crops were obtained from FAOSTAT (FAO, 2018b). Among the annual crops, those best adapted to no-tillage CA systems were selected: cereals, pulses, oilseeds, cotton, among other crops that do not need soil disturbance for harvesting. Most of the woody perennial crop areas were found suitable for CA.

In climate change international agreements, emissions are referred to carbon dioxide; however, soil carbon studies refer to carbon. For transforming carbon into carbon dioxide, the coefficient of 3.67 was used. The atomic weight of carbon is 12 atomic mass units, while the weight of carbon dioxide is 44, because it also includes two oxygen atoms that each weigh 16. So, to switch from one to the other, one tonne of carbon equals 44/12 = 3.67 tonnes of carbon dioxide.

III-3. Results and Discussion

According to the latest statistics available, farmers in almost 20 African countries are practising CA, including Algeria, Ghana, Kenya, Lesotho, Madagascar, Malawi, Morocco, Mozambique, Namibia, South Africa, Sudan, Swaziland, Tanzania, Tunisia, Uganda, Zambia and Zimbabwe (Kassam et al., 2018).

The most recent figures of adoption of CA for annual crops in Africa (season 2015/16) totaled 1.5 M hectares. This corresponds to some 211% increase from 0.48 M ha in 2008/09 (Kassam et al., 2018). This significant increase is because of the many years of research showing positive results for CA systems, plus increasing attention being paid to CA systems by governments, NEPAD (New Partnership for Africa's Development), and NGOs such as ACT (African Conservation Tillage), and the private sector, international organizations and donors.

Average rates of carbon sequestration by CA in agricultural soils for each climatic zone in Africa are presented in Table III-1. The total carbon sequestration estimated for the whole of Africa, of 1,543,022 t C yr^{-1} is shown in Table III-2. On average, the carbon sequestered for Africa due to CA is thus around 1 t C ha^{-1} yr^{-1}, corresponding to a total amount of 5,657,747 t CO_2 yr^{-1}. This relatively high figure is because degraded soils are 'hungry' for carbon, as the degradation caused by years of tillage, soil mining and crop biomass removal has resulted in a drastic reduction of soil's organic matter (Reicosky, 1995; Jat et al., 2014; Kassam et al., 2017b).

Table III-1. Carbon sequestration rates in Conservation Agriculture (CA) for each climatic zone. Source: Authors diagram based on the papers reviewed and listed in the references.

Climatic zones	Carbon sequestration rate for CA in annual crops (Mg ha^{-1} yr^{-1})	Carbon sequestration rate for CA in woody crops (Mg ha^{-1} yr^{-1})
Mediterranean	0.44	1.29
Sahel	0.50	0.12
Tropical	1.02	0.79
Equatorial	1.56	0.26

Table III-2. Current soil organic carbon (SOC) fixed annually by CA cropland systems compared to systems based on tillage agriculture in Africa.
Source: Kassam et al., 2018.

Country	**No-tillage adoption (ha)**	**Carbon sequestration rate in no-tillage (Mg ha^{-1} yr^{-1})**	**Current annual carbon sequestration (Mg yr^{-1})**	**Climatic zone**
Algeria	5,600	0.44	2,464	Mediterranean
Ghana	30,000	1.56	46,800	Equatorial
Kenya	33,100	1.02	33,762	Tropical
Lesotho	2,000	1.02	2,040	Tropical
Madagascar	9,000	1.56	14,040	Equatorial
Malawi	211,000	1.02	215,220	Tropical
Morocco	10,500	0.44	4,620	Mediterranean
Mozambique	289,000	1.02	294,780	Tropical
Namibia	340	0.50	170	Sahel
South Africa	439,000	1.02	447,780	Tropical
Sudan	10,000	0.50	5,000	Sahel
Swaziland	1,300	1.02	1,326	Tropical
Tanzania	32,600	1.02	33,252	Tropical
Tunisia	12,000	0.44	5,280	Mediterranean
Uganda	7,800	1.56	12,168	Equatorial
Zambia	316,000	1.02	322,320	Tropical
Zimbabwe	100,000	1.02	102,000	Tropical
TOTAL	**1,509,240**		**1,543,022**	

Results presented in this paper are in agreement with previous meta-analyses and studies, where CA in annual and perennial crops have been found to have incremented soil organic carbon (González-Sánchez et al., 2012; Gonzalez-Sanchez et al., 2017; and the studies referenced for obtaining the C sequestration rates for Africa).

In CA systems major inputs in carbon can be expected through the retention of crop biomass, crop rotation and the reduction in soil disturbance (Cheesman et al., 2016). Conversely to the results presented for Africa in this article, Gonzalez-Sanchez et al. (2012) in a study for European agriculture found that C sequestration rates for perennials were higher than for annual crops. This might be because African perennial crops are not as intensive as yet as European ones, and therefore their soils are closer to the carbon sequestration plateau or the equilibrium.

Sometimes there can be found in the literature controversial results attributed to CA when in fact some of the key CA principles were not applied, thus not dealing with real CA systems. Indeed, according to Derpsch et al., (2014), broad understanding is lacking of what CA systems research means. This has led to a situation of conflicting research results because different technologies, methodologies, and erroneous definitions of CA systems have been applied. A practice such as no-tillage can only be considered to be a CA practice if it is part of a CA system as per the definition provided earlier, otherwise it is just a no-tillage practice. Similarly, for soil mulch practice and crop diversification practice both of which can only be considered to be CA practices if they are part of a CA system based on the application of the three interlinked principles. When the three principles of CA are applied in field, the best results are achieved, including for carbon sequestration, as confirmed in a recent study for Africa by Corbeels et al. (2018).

These positive results from CA systems are compared with the “business as usual” tillage agriculture cases. Conventional farming globally is based on soil tillage which promotes the mineralization of soil organic matter whilst increasing the release of CO_2 into the atmosphere due to C oxidation. Also, tillage operations can incorporate crop biomass into soil layers where microorganisms and moisture conditions favour their decomposition and thus resulting in more carbon oxidation. Moreover, soil tillage physically breaks down soil aggregates and leaves carbon in them exposed to the action of soil microorganisms which were encapsulated and thus protected within the soil aggregates that existed prior to the performance of tillage (Reicosky et al., 2007).

One of the consequences of management systems based on tillage is the reduction of the soil carbon sink effect, which has as a consequence the decrease in the content of organic carbon. This decrease is the result of (1) the lower contribution of organic matter in the form of crop stubble and biomass from previous crops; and (2) the higher rate of mineralization of soil humus caused by tillage. Tillage facilitates the penetration of air into the soil and therefore the decomposition and mineralization of humus, a process that includes a series of oxidation reactions, generating CO_2 as the main byproduct. One part of CO_2 becomes trapped in the porous space of the soil, while the other part is released into the atmosphere through diffusion across the zones of the soil with different concentration; and (3) the higher rate of soil erosion and degradation which causes significant losses of organic matter and minerals as well as soil health. In conventional tillage agriculture, the preparation of soil for sowing and crop establishment leaves the soil exposed to erosive agents for longer periods of time.

For all of the above reasons, many researchers agree that mechanical soil disturbance by tillage is one of the main causes of organic carbon reduction in the soil (Balesdent et al., 1990; Six et al., 2004; Olson et al., 2005). Reicosky (2011) argues that intensive tillage agriculture has contributed to the loss of between 30% and 50% of soil organic C in the last two decades of the 20th century. Kinsella (1995) estimates that, in only 10 years of tillage, some 30% of the original soil organic matter was lost.

Even though CA has positive effects, the increase of soil C is not permanent in time, and after a number of years, the rate of accumulation slows down towards a plateau level depending on the soil type, length of growing period and climatic conditions, and the rate of turnover of C. The time to reach the plateau level varies but is considerable, and may take over 10-15 years before a deceleration in the rate of C increase is observed (González-Sánchez et al, 2012). Therefore, even if after 10-15 years C sequestration rates are lower, carbon is still being captured in the soil which supports the value of a long-term and continuing engagement with CA land management. Also, even when top soil layers may be reaching plateau levels, deeper soil layers continue to sequester C through the action of earthworms and biomass and carbon exudates provided by deeper root systems. As CA adoption rates in Africa are improving more significantly over the last decade, the sequestration coefficients presented in this paper can be considered as those applicable to the initial period of transformation from conventional agriculture.

In Figures III-3 and III-4, the potential area that could be shifted from conventional tillage agriculture to CA is presented, for both annual and permanent crop systems. Multiplying the rates of C sequestration presented in Table III-2 by the potential areas per country and per type of crop (Tables III-3 and III-4) permits estimates of the potential carbon sequestration following the application of CA in the agricultural lands of Africa. Where more than one climate affects a single country, the climate of the major cropping area has been selected, i.e. Algeria’s rate of C sequestration has been that of the

Mediterranean climate, as most of its cropland is affected by that climate. In cases where there were two co-dominant climates, two rates of C sequestration have been applied.

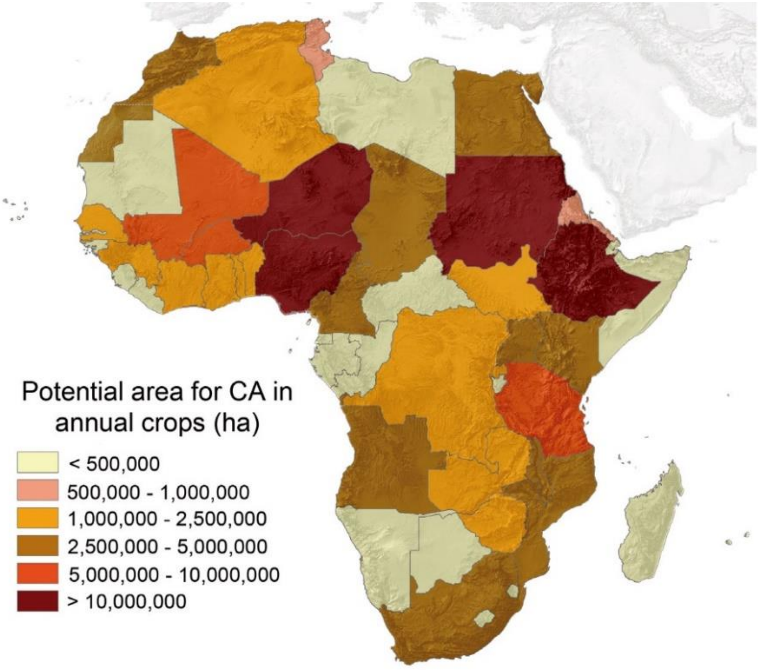

Figure III-3. Potential application surface of CA in annual crops in Africa in 2016.
Source: Authors diagram based on FAOSTAT, 2018.

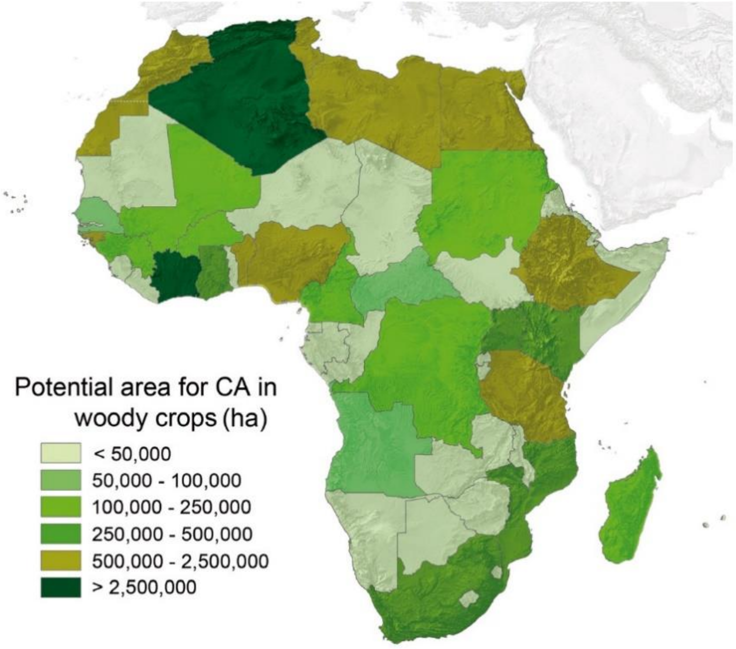

Figure III-4. Potential application surface of groundcovers in woody perennial crops in Africa in 2016.
Source: Authors diagram based on FAOSTAT (2018).

Table III-3. Potential annual carbon sequestration in annual crops due to no-tillage. Potential adoption of no-tillage elaborated on country statistics of eligible crops based on FAOSTAT (FAO, 2018b).

Country	**Potential adoption of no-tillage (ha)**	**Carbon sequestration rate in no-tillage (Mg ha^{-1} yr^{-1})**	**Potential annual carbon sequestration in no-tillage (Mg yr^{-1})**	**Climatic zone**
Algeria	2,298,018	0.44	1,011,128	Mediterranean
Angola	1,294,527	1.56	2,019,462	Equatorial
Angola	1,294,527	1.02	1,320,418	Tropical
Benin	1,763,758	1.56	2,751,462	Equatorial
Botswana	120,460	0.50	60,230	Sahel
Burkina Faso	6,290,742	1.02	6,416,557	Tropical
Burundi	446,863	1.02	455,800	Tropical
Cabo Verde	63,396	1.02	64,664	Tropical
Cameroon	1,630,294	1.56	2,543,258	Equatorial
Cameroon	1,630,294	1.02	1,662,899	Tropical
Central African Republic	330,367	1.56	515,373	Equatorial
Chad	2,052,614	0.50	1,026,307	Sahel
Chad	2,052,614	1.02	2,093,666	Tropical
Comoros	22,362	1.02	22,809	Tropical
Congo	49,484	1.56	77,195	Equatorial
Côte d'Ivoire	1,046,568	1.56	1,632,646	Equatorial
Democratic Republic of the Congo	2,435,696	1.56	3,799,686	Equatorial
Eritrea	598,467	0.50	299,234	Sahel
Ethiopia	3,032,626	0.50	1,516,313	Sahel
Ethiopia	9,097,877	1.02	9,279,835	Tropical
Gabon	40,598	1.56	63,333	Equatorial
Gambia	213,313	1.02	217,579	Tropical
Ghana	1,879,696	1.56	2,932,326	Equatorial
Guinea	676,016	1.56	1,054,585	Equatorial
Guinea	676,016	1.02	689,536	Tropical
Guinea-Bissau	57,660	1.02	58,813	Tropical
Kenya	2,300,622	0.50	1,150,311	Sahel
Kenya	2,300,622	1.02	2,346,634	Tropical
Lesotho	89,068	1.02	90,849	Tropical
Liberia	8,532	1.56	13,310	Equatorial
Libya	326,268	0.44	143,558	Mediterranean
Madagascar	361,970	1.56	564,673	Equatorial
Malawi	2,864,440	1.02	2,921,729	Tropical
Mali	2,876,307	0.50	1,438,154	Sahel
Mali	2,876,307	1.02	2,933,833	Tropical
Mauritania	342,236	0.50	171,118	Sahel

Table III-3 (continuation).

Country	**Potential adoption of no-tillage (ha)**	**Carbon sequestration rate in no-tillage (Mg ha^{-1} yr^{-1})**	**Potential annual carbon sequestration in no-tillage (Mg yr^{-1})**	**Climatic zone**
Mauritius	395	1.56	616	Equatorial
Mauritius	395	1.56	616	Equatorial
Morocco	4,164,886	0.44	1,832,550	Mediterranean
Mozambique	3,004,979	1.02	3,065,079	Tropical
Namibia	303,653	0.50	151,827	Sahel
Niger	16,362,647	0.50	8,181,324	Sahel
Nigeria	10,557,289	1.56	16,469,370	Equatorial
Nigeria	10,557,289	1.02	10,768,434	Tropical
Reunion	5,066	1.56	7,903	Equatorial
Rwanda	519,023	1.56	809,676	Equatorial
Rwanda	519,023	1.02	529,403	Tropical
Sao Tome and Principe	949	1.56	1,480	Equatorial
Senegal	724,221	0.50	362,111	Sahel
Senegal	724,221	1.02	738,705	Tropical
Sierra Leone	253,887	1.56	396,064	Equatorial
Somalia	435,096	0.50	217,548	Sahel
South Africa	587,257	0.44	258,393	Mediterranean
South Africa	587,257	0.50	293,629	Sahel
South Africa	1,761,771	1.02	1,797,006	Tropical
South Sudan	1,230,241	1.02	1,254,846	Tropical
Sudan	15,262,789	0.50	7,631,395	Sahel
Swaziland	86,070	1.02	87,791	Tropical
Tanzania	9,693,740	1.02	9,887,615	Tropical
Togo	1,524,877	1.56	2,378,808	Equatorial
Tunisia	997,413	0.44	438,862	Mediterranean
Uganda	1,523,709	1.56	2,376,985	Equatorial
Uganda	1,523,709	1.02	1,554,183	Tropical
Zambia	1,648,278	1.02	1,681,244	Tropical
Zimbabwe	2,171,103	1.02	2,214,525	Tropical
TOTAL	**142,172,059**		**130,746,653**	

Table III-4. Potential annual carbon sequestration in woody crops due to groundcovers. Potential adoption of groundcovers elaborated on country statistics of eligible crops based on FAOSTAT (FAO, 2018b).

Country	**Potential adoption of groundcovers (ha)**	**Carbon sequestration rate in groundcovers (Mg ha^{-1} yr^{-1})**	**Potential annual carbon sequestration in groundcovers (Mg yr^{-1})**	**Climatic zone**
Algeria	813,371	1.29	1,049,249	Mediterranean
Angola	39,795	0.26	10,347	Equatorial
Angola	39,795	0.79	31,438	Tropical
Benin	785,872	0.26	204,327	Equatorial
Botswana	32	0.12	4	Sahel
Burkina Faso	167,148	0.79	132,047	Tropical
Burundi	15,981	0.79	12,625	Tropical
Cabo Verde	443	0.79	350	Tropical
Cameroon	60,607	0.26	15,758	Equatorial
Cameroon	60,607	0.79	47,879	Tropical
Central African Republic	55,932	0.26	14,542	Equatorial
Chad	4,316	0.12	518	Sahel
Chad	4,316	0.79	3,409	Tropical
Comoros	989	0.79	781	Tropical
Congo	18,790	0.26	4,885	Equatorial
Côte d'Ivoire	4,312,885	0.26	1,121,350	Equatorial
Democratic Republic of the Congo	113,234	0.26	29,441	Equatorial
Equatorial Guinea	11,587	0.26	3,013	Equatorial
Ethiopia	201,770	0.12	24,212	Sahel
Ethiopia	605,309	0.79	478,194	Tropical
Gabon	520	0.26	135	Equatorial
Gambia	3,841	0.79	3,034	Tropical
Ghana	329,980	0.26	85,795	Equatorial
Guinea	94,616	0.26	24,600	Equatorial
Guinea	94,616	0.79	74,746	Tropical
Guinea-Bissau	558,346	0.79	441,093	Tropical
Kenya	133,040	0.12	15,965	Sahel
Kenya	133,040	0.79	105,102	Tropical
Liberia	7,294	0.26	1,896	Equatorial
Libya	509,133	1.29	656,782	Mediterranean
Madagascar	227,889	0.26	59,251	Equatorial
Malawi	16,138	0.79	12,749	Tropical
Mali	96,010	0.12	11,521	Sahel
Mali	96,010	0.79	75,848	Tropical
Mauritius	203	0.26	53	Equatorial
Morocco	1,686,040	1.29	2,174,992	Mediterranean

Table III-4 (continuation)

Country	**Potential adoption of groundcovers (ha)**	**Carbon sequestration rate in groundcovers (Mg ha^{-1} yr^{-1})**	**Potential annual carbon sequestration in groundcovers (Mg yr^{-1})**	**Climatic zone**
Mozambique	260,859	0.79	206,079	Tropical
Namibia	7,061	0.12	847	Sahel
Niger	40,600	0.12	4,872	Sahel
Nigeria	888,532	0.26	231,018	Equatorial
Nigeria	888,532	0.79	701,940	Tropical
Reunion	690	0.26	179	Equatorial
Rwanda	24,318	0.26	6,323	Equatorial
Rwanda	24,318	0.79	19,211	Tropical
Sao Tome and Principe	429	0.26	112	Equatorial
Senegal	32,019	0.12	3,842	Sahel
Senegal	32,019	0.79	25,295	Tropical
Seychelles	81	0.79	64	Tropical
Sierra Leone	36,034	0.26	9,369	Equatorial
Somalia	4,299	0.12	516	Sahel
South Africa	46,198	1.29	59,595	Mediterranean
South Africa	46,198	0.12	5,544	Sahel
South Africa	138,593	0.79	109,488	Tropical
South Sudan	1,943	0.79	1,535	Tropical
Sudan	117,096	0.12	14,052	Sahel
Swaziland	13,746	0.79	10,859	Tropical
Tanzania	1,263,844	0.79	998,437	Tropical
Togo	48,816	0.26	12,692	Equatorial
Tunisia	2,196,810	1.29	2,833,885	Mediterranean
Uganda	191,748	0.26	49,854	Equatorial
Uganda	191,748	0.79	151,481	Tropical
Zambia	8,534	0.79	6,742	Tropical
Zimbabwe	27,886	0.79	22,030	Tropical
TOTAL	**17,832,438**		**12,413,790**	

Finally, Figure III-5 shows the total amount of potential carbon sequestration for Africa, for each climatic region, with respect to current carbon sequestration status. Table III-5 offers the same result as Fig 5, but split by country. In total, the potential estimate of annual carbon sequestration in African agricultural soils through CA amounts to 145 M t of C per year, that is 533 M t of CO_2 per year. This figure represents about 95 times the current sequestration figure. To put this figure into context, according to the United Nations Framework Convention on Climate Change, South Africa, the world's 13th largest

CO_2 emitter, total national emissions by 2025 and 2030 will be in a range between 398 and 614 M t CO_2–eq per year (UNFCCC, 2018). Thus, the carbon dioxide sequestration potential of CA for Africa is almost 3 time higher than that document for Europe by Gonzalez-Sanchez et al. (2017), i.e. 189 M t CO_2 per year.

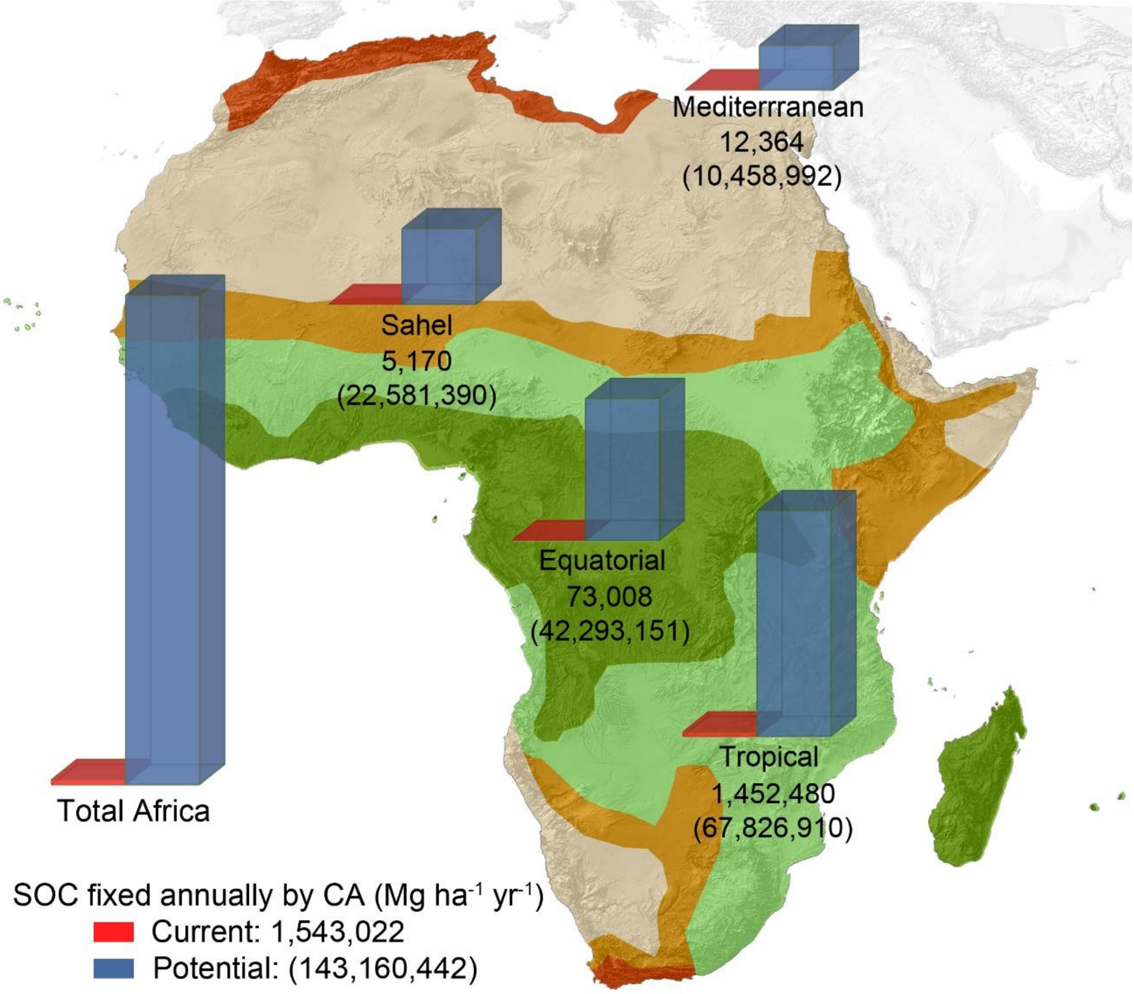

Figure III-5. Potential soil organic carbon (SOC) fixed annually by CA cropland systems compared to systems based on tillage agriculture in Africa. Authors diagram.

Table III-5. Potential annual carbon sequestration in Conservation Agriculture over conventional tillage-based agriculture (annual plus woody crops).

Country	**Potential annual carbon sequestration in Conservation Agriculture (Mg yr^{-1})**	**Climatic zone**
Algeria	2,060,377	Mediterranean
Angola	2,029,809	Equatorial
	1,351,855	Tropical
Benin	2,955,789	Equatorial
Botswana	60,234	Sahel
Burkina Faso	6,548,604	Tropical

Table III-5 (continuation).

Country	Potential annual carbon sequestration in Conservation Agriculture (Mg yr^{-1})	Climatic zone
Burundi	468,425	Tropical
Cabo Verde	65,014	Tropical
Cameroon	2,559,016	Equatorial
	1,710,779	Tropical
Central African Republic	529,915	Equatorial
Chad	1,026,825	Sahel
	2,097,075	Tropical
Comoros	23,591	Tropical
Congo	82,080	Equatorial
Côte d'Ivoire	2,753,996	Equatorial
Democratic Republic of the Congo	3,829,127	Equatorial
Equatorial Guinea	3,013	Equatorial
Eritrea	299,234	Sahel
Ethiopia	1,540,525	Sahel
	9,758,029	Tropical
Gabon	63,468	Equatorial
Gambia	220,614	Tropical
Ghana	3,018,121	Equatorial
Guinea	1,079,185	Equatorial
	764,283	Tropical
Guinea-Bissau	499,907	Tropical
Kenya	1,166,276	Sahel
	2,451,736	Tropical
Lesotho	90,849	Tropical
Liberia	15,206	Equatorial
Libya	800,339	Mediterranean
Madagascar	623,924	Equatorial
Malawi	2,934,478	Tropical
Mali	1,449,675	Sahel
	3,009,681	Tropical
Mauritania	171,118	Sahel
Mauritius	669	Equatorial
Morocco	4,007,541	Mediterranean
Mozambique	3,271,157	Tropical
Namibia	152,674	Sahel
Niger	8,186,196	Sahel
Nigeria	16,700,388	Equatorial
	11,470,375	Tropical
Reunion	8,082	Equatorial

Table III-5 (continuation).

Country	**Potential annual carbon sequestration in Conservation Agriculture (Mg yr^{-1})**	**Climatic zone**
Rwanda	815,998	Equatorial
	548,614	Tropical
Sao Tome and Principe	1,592	Equatorial
Senegal	365,953	Sahel
	764,000	Tropical
Seychelles	64	Tropical
Sierra Leone	405,433	Equatorial
Somalia	218,064	Sahel
South Africa	317,988	Mediterranean
	299,172	Sahel
	1,906,494	Tropical
South Sudan	1,256,381	Tropical
Sudan	7,645,446	Sahel
Swaziland	98,651	Tropical
Tanzania	10,886,052	Tropical
Togo	2,391,500	Equatorial
Tunisia	3,272,747	Mediterranean
Uganda	2,426,840	Equatorial
	1,705,664	Tropical
Zambia	1,687,985	Tropical
Zimbabwe	2,236,555	Tropical
TOTAL	**143,160,442**	

III-4. Conclusions

Conservation Agriculture is a promising sustainable agricultural system, as it can effectively contribute to mitigating global warming, being able to sequester carbon in the soil, thus offsetting agricultural and non-agricultural CO_2 emissions. CA is a proven and effective agricultural system that African countries need to promote to fulfill the international agreements and initiatives related to climate change mitigation and adaptation, such as the Paris agreement on climate change, the 4p1000 initiative and the Adaptation of African Agriculture (AAA).

Carbon sequestration rates in Africa are in agreement with those recorded d in other meta-analyses performed in other agroclimatic regions. The reporting of carbon sequestration in agricultural soils should be described relative to that which is possible in conventional tillage-based agriculture, as done in this article. With regards to adoption, new hectares under CA in Africa would be eligible to be counted as new net carbon sequestration.

The potential of CA in Africa with regards to climate change mitigation is considered far superior to the current situation, about 95 times greater than the current situation. CA systems with annual crops as well as with perennial crops lead to increased carbon sequestration in the soil in any climate in Africa.

Acknowledgements

The authors would like to thank the LIFE financial instrument of the European Union for co-financing the LIFE+ ClimAgri project “Best agricultural practices for Climate Change: Integrating strategies for mitigation and adaptation” LIFE13 ENV/ES/000541, and the support of the Plan Propio de Fomento de la Investigación (Internal University Research Plan) (2018) of the Universidad de Córdoba that allowed the first author visiting the Imperial College London.

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Chapter IV

The Effect of Conservation Agriculture and Environmental Factors on CO_2 Emissions in a Rainfed Crop Rotation

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Carbonell-Bojollo, R., Veroz-González, O., Ordóñez-Fernández, R., Moreno-García, M., Basch, G., Kassam, A., Repullo-Ruibérriz De Torres, M.A., González-Sánchez, E.J. (2019). Effect of Conservation Agriculture and environmental factors on CO2 emissions in a rainfed crop rotation. Sustainability, 11, 3955; https://doi.org/10.3390/su11143955

Chapter IV: The Effect of Conservation Agriculture and Environmental Factors on CO_2 Emissions in a Rainfed Crop Rotation

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IV-Abstract

There are many factors involved in the release of CO_2 emissions from the soil, such as the type of soil management, the soil organic matter, the soil temperature and moisture conditions, crop phenological stage, weather conditions, residue management, among others. This study aimed to analyse the influence of these factors and their interactions to determine the emissions by evaluating the environmental cost expressed as the kg of CO_2 emitted per kg of production in each of the crops and seasons studied. For this purpose, a field trial was conducted on a farm in Seville (Spain). The study compared

Conservation Agriculture, including its three principles (no-tillage, permanent soil cover, and crop rotations), with conventional tillage. Carbon dioxide emissions measured across the four seasons of the experiment showed an increase strongly influenced by rainfall during the vegetative period, in both soil management systems. The results of this study confirm that extreme events of precipitation away from the normal means, result in episodes of high CO_2 emissions into the atmosphere. This is very important because one of the consequences for future scenarios of climate change is precisely the increase of extreme episodes of precipitation and periods extremely dry, depending on the area considered. The total of emission values of the different plots of the study show how the soils under the conventional system (tillage) have been emitting 67% more than soils under the conventional agriculture system during the 2010/11 campaign and 25% for the last campaign where the most appreciable differences are observed.

Keywords: soil management; climate change; mitigation; conventional tillage; conservation agriculture; GHG emissions

IV-1. Introduction

In a world in which the concern for food security is increasing, there are important questions to be addressed about the impact of climate change on the production and availability of food [1–3]. According to the Food and Agriculture Organization (FAO), in 2050 there will be more than 9 billion people on the planet. Therefore, feeding the growing population, without exhausting natural resources will be a challenge, especially when even today about 795 million people are undernourished globally [4].

The agricultural sector is one of the most affected by climate change, as a result of the close relationship between agricultural activities and the climate. However, it is also a net source of greenhouse gases emissions (GHG), as evidenced by the fact that, at European level, agriculture currently ranks third in the GHG set of issuing activities (EEA Report 5/2018: Annual European Union greenhouse gas inventory 1990–2016 and inventory report 2018).

The different management systems in agriculture regulate soil nitrogen and carbon dynamics and affect the emissions of nitrous oxide (N_2O) and carbon dioxide (CO_2) [5,6].

For many developing countries, food security, economic development and the impact of climatic change are the main concerns related to agriculture. A significant proportion of these countries have expressed interest in mitigating GHG in the agriculture sector and two-thirds of them are developing strategic plans to mitigate GHG emissions from agriculture [7].

Both political and social concerns are currently focused on understanding and predicting the effects of the interaction between human activity, the carbon cycle and the expected climate change impact [8,9]. This coincides with growing scientific evidence that continued global warming is due (in part) to the rates of GHG emissions such as CO_2, methane (CH_4) and N_2O from the earth [10]. Land-use may have direct and indirect effects on carbon stocks in the soil and these may be associated with changes in the use of land conditioned to meet social needs such as the production of foods, energy and water supply and the management of crop residues.

Since the COP 21 celebrated in Paris at the end of 2015, agriculture has been assigned three roles in the context of climate change: on the one hand, it is an issuing activity (14% of the total GHG that could reach 25% if we include forest land) secondly, agriculture itself suffers from the consequences of global warming, as demonstrated by the IPCC reports for 2013; but it is also a mitigating activity, which is undoubtedly an opportunity to alleviate the negative consequences of climate change. Soil management systems account for 25% of total anthropogenic emissions [11].

Anthropogenic activities have affected 40% of the Earth's surface. Land-use conversion has depleted the terrestrial ecosystem carbon stock with a big loss of soil organic carbon and future climate change scenarios can affect this carbon stock by increasing the rate of decomposition of organic matter (OM) [12]. In the specific case of agriculture, the use of ploughs for tilling the soil in conventional farming provokes the mineralization of soil organic matter (SOM) while increasing the release of CO_2 into the atmosphere due to oxidation [13]. Likewise, the tillage operation can incorporate crop residues from the surface into deeper soil layers where microorganisms and moisture conditions favour their decomposition and, thus, carbon oxidation [14]. Furthermore, soil tillage physically disrupts aggregates and leaves the soil unprotected from the action of microorganisms which were encapsulated within the soil. Soil tillage practices are also conducted by farmers to alleviate soil compaction, but only temporarily [15]. These practices also promote the decomposition of OM and losses of carbon (C) to the atmosphere in the form of CO_2 [16–18].

According to FAO [19] and many other authors [20], Conservation Agriculture (CA) is an agricultural system based on three interlinked principles:

i. Minimum mechanical soil disturbance (which is not minimum tillage, i.e., no tillage) through direct seeding and/or fertilizer placement.

   Minimum tillage is a tillage method that does not turn the soil over, while no tillage is a way of farming without disturbing the soil.

ii. Permanent soil organic cover, (at least 30 percent) with crop residues and/or cover crops.

iii. Species diversification through varied crop sequences and associations involving at least three different crops.

Whereas CA is an agricultural system, no-tillage (NT) is an agricultural technique needed for performing CA (Principle 1). The adoption of CA has significant environmental benefits [21]. The accumulation of soil organic carbon (SOC), i.e., due to the sequestration of carbon in the soil, is certainly one of the major benefits, making CA systems be considered as being effective in helping to mitigate the increase in atmospheric CO_2 concentration in annual, perennial and mixed cropping systems [22], whether rainfed or irrigated. At the same time, NT systems are acknowledged for being more profitable for farmers [23].

There are international initiatives, such as the United Nations Framework Convention on Climate Change (the 21st Conference of the Parties agreements reached in Paris), where growth of the “4 per 1000” initiative that aims to demonstrate that agriculture and agricultural soils, in particular, play a crucial role where food security and climate change are concerned. This initiative fosters implementing practical programs for carbon sequestration into the soil. Reviewing the available literature on climate change and agricultural soil management systems, it can be concluded that agricultural operations have different effects on CO_2 emissions depending on the activity, soil type, and climate conditions in the area. Different authors [24] suggested that crops managed under CA could capture between 0.1 and 1 tonne of carbon per hectare annually depending on the climate characteristics of the area; the lower figure applicable for dry areas and the higher for humid areas. In Spain, several studies corroborate the findings that different types of tillage practices strongly increase short-term CO_2 emissions [25–27]. These studies suggest that under different tillage and soil management practices, a range of interactions between the crop and soil quality clearly has an influence on CO_2 emissions, and that these relations are even more complex under the influence of climate change in the Mediterranean area [28,29]. The global climate variabilities are estimated to be responsible for 32% to 39% of yield variability [30].

The climate conditions in the study area are characterized by long and hot dry summers, high inter-annual and intra-annual variations in rainfall, which, in combination with the high temperatures during the summer period, greatly limit biomass production. However, depending on the management practices, soil quality and land productivity potential could be enhanced or reduced by affecting soil physical, hydrological, chemical and biological properties. Good agricultural practices can reduce soil erosion and degradation, decrease greenhouse gases emissions from the soil, and help maintain or even improve production under changing climate conditions in the Mediterranean basin.

The objectives of the study reported in this paper were (a) to quantify the short-term and long-term impacts of different management systems on CO_2 fluxes from the soil; and (b) to determine the influence of climatic conditions of the area and of crop phenology on soil CO_2 fluxes. The variability in the data obtained is presented from both a spatial and a temporal perspective.

IV-2. Material and Methods

IV-2.1. Experimental Sites

A field experiment was conducted to study the dynamics of CO2 emissions from the soil as influenced by soil management and weather conditions.

For this purpose, a farm in the cereal-growing area of Andalusia (southern Spain) situated in the municipal area of Las Cabezas de San Juan (Seville): 36º56’37,8” N 5º55’13,6” W was selected to carry out the trial during four agricultural seasons 2009/10, 2010/11, 2011/12 and 2012/13. Figure IV-1 presents the location of the study area.

Once the farm was selected, a first sampling was carried out in order to characterize the soil where the trials were going to be conducted. Table 1 presents the soil properties of the study site.

Since 2003, the techniques of Conservation Agriculture were implemented in part of the farm, concretely in the NT. The trial plots under this technique were established in those areas and the plots where traditional management systems were used in areas where NT is not practised.

Traditionally the farmer would make a wheat/sunflower rotation and every 4 years a legume was included in that rotation. In our trial, and as can be seen in next point Section 2.2, the rotation was cereal (wheat), sunflower, legume. The dates of the carried out operations are also included in the next section.

The farm is located in the Mediterranean area with a Xeric moisture regime, according to the standards set [31]. The region is characterized by a typical Mediterranean climate pattern with a mild rainy autumn and winter season, which accounts for 80% of the annual rainfall, and warm to hot and dry springs and summers.

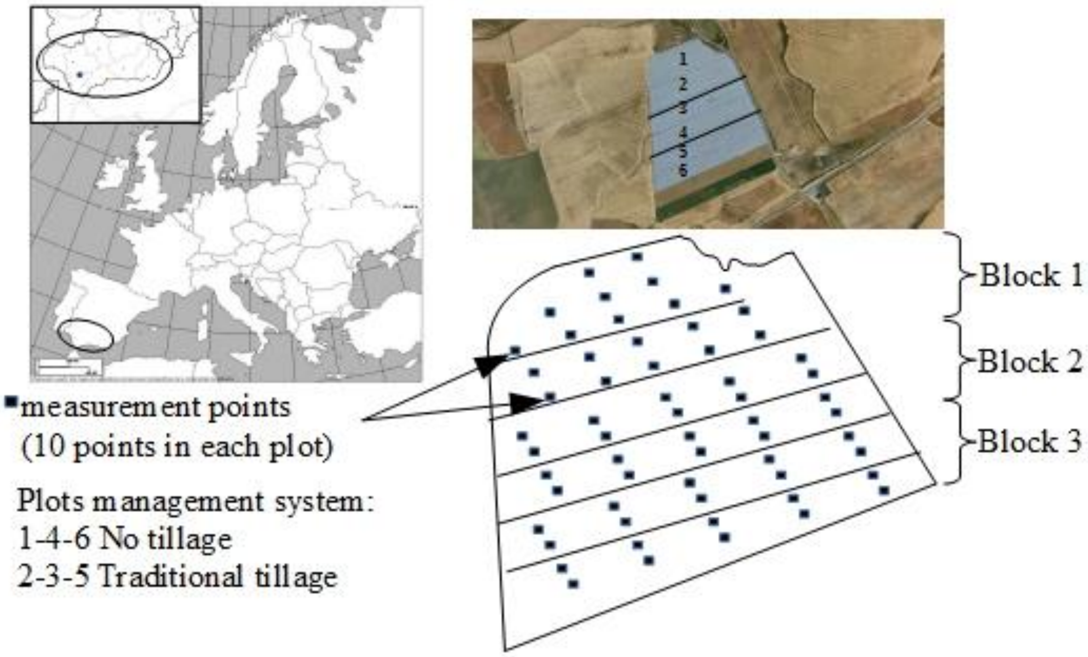

Figure IV-1. The location of the study area.

Table IV-1. The physical and chemical characteristics of several soil layers (0.2, 0.4 and 0.6 m) at the study sites.

System	Depth	Ntotal	OC	OM	$CO_3^=$	pH	CEC	K	P	Sand	Lime	Clay	Texture
	cm		*%*				*meq/100 gr*	*ppm*			*%*		
							BLOCK 1						
NT	0–20	0.13	0.91	1.55	11.87	8.56	36.2	482.6 b	6.40 b	16.10	23.40	60.50	Clayey
	20–40	0.11	0.88	1.48	11.11	8.62	35.3	433.94 b	6.0 b	16.00	22.60	61.40	Clayey
	40–60	0.10	0.80	1.36	11.46	8.43	37.2	358.58 b	5.0 b	16.00	23.70	60.30	Clayey
T	0–20	0.10	0.98	1.66	13.45	8.32	39.3	674.04 a	13.05 a	16.90	30.80	52.30	Clayey
	20–40	0.10	1.00	1.70	13.17	8.46	42.4	625.16 a	11.21 a	19.20	32.70	48.10	Clayey
	40–60	0.10	0.99	1.69	13.30	8.68	43.3	689.36 a	13.10 a	14.90	32.90	52.20	Clayey
							BLOCK 2						
NT	0–20	0.12	1.17	1.99	6.3 a	8.25	31.36 b	481.82	23.19 b	20.60	22.80	56.60	Clayey
	20–40	0.12	1.15	1.96	5.0a	8.33	29.53 b	407.64	17.03 b	20.40	22.40	57.20	Clayey
	40–60	0.11	0.99	1.69	7.1 a	8.36	30.23 b	344.58	30.36 a	20.90	23.90	55.20	Clayey
T	0–20	0.11	1.21	2.07	3.2 b	8.23	41.08 a	432.06	32.89 a	13.40	26.10	60.50	Clayey
	20–40	0.10	1.13	1.92	4.7 b	8.25	40.40 a	375.62	28.92 a	13.60	24.60	61.80	Clayey
	40–60	0.10	1.10	1.87	2.18 b	8.29	40.56 a	424.2	13.57 b	14.10	24.70	61.20	Clayey
							BLOCK 3						
NT	0–20	0.13	1.12	1.90	24.52 a	8.57	27.20	802.87 a	12.23 b	17.60	27.60	54.80	Clayey
	20–40	0.10	0.97	1.65	24.53 a	8.63	25.90	682.60 a	10.77 b	19.90	34.30	45.80	Clayey
	40–60	0.10	0.89	1.51	23.32 a	8.69	23.57	459.88 b	10.17 b	23.10	34.50	42.40	Clayey
T	0–20	0.10	1.16	1.98	10.74 b	8.46	29.30	663.36 ab	16.66 a	16.10	23.40	60.50	Clayey
	20–40	0.10	1.09	1.86	11.26 b	8.53	30.50	547.38 b	11.66 b	16.00	22.60	61.40	Clayey
	40–60	0.10	1.00	1.70	9.36 b	8.49	34.27	531.00 b	22.34 a	16.00	23.70	60.30	Clayey

Table 2 shows the statistical analysis of the main climatic variables with data from the last ten years. The data have been obtained from a climatic station located in the same municipality.

Table IV-2. The descriptive statistics of the main climatic variables.

	Max. Temp.	**Min. Temp**	**Med. Temp**	**Humidity (máx.)**	**Humidity (min.)**	**Radiation**	**Rainfall**	**ET_0**
Number of values	3816	3816	3816	3816	3816	3816	3816	3816
Minimum	8.2	−7.9	2.5	53	0	0.9	0	0.34
Maximum	44.9	26.8	33.3	100	100	32.5	80.2	10.05
Mean	25.49	10.85	17.94	92.78	41.56	18.25	1.47	3.93
Median	24.9	11.6	17.9	95.4	38.9	18.2	0	3.72
Standard error	0.1218	0.0951	0.1022	0.1347	0.2936	0.1330	0.0856	0.03
Variance	56.62	34.55	39.87	69.21	329	67.49	27.99	4.83
Standard deviation	27.5	5.87	6.31	8.31	18.14	8.21	5.29	2.19

Data from the Climatic station situated in Las Cabezas de San Juan; UTM coord: X: 243351.0; Y: 4100490.0; Latitude:37°00ʹ56” N; Longitude: 05°53ʹ04” W; Altitude: 13.0.

IV-2.2. Soil Management Systems and Experimental Design

The experimental design is a randomized complete block (see Figure IV-1), in order to compare NT with conventional tillage (T), the experimental area consisted of three blocks with two plots inside of each one. In one plot of each block was CA, more specifically, NT with a soil mulch cover, was applied, whereas T with bare soil was the soil management system followed in the other plot of the different blocks. Each plot was approximately five hectares in size. Inside each plot, 10 point samples were taken initially in order to characterize the soil. As a result, it was possible to grow all three crops of the wheat-sunflower-legume rotation simultaneously every year (See Table 3). One reason why these crops have been chosen is due to the fact that the common agricultural policy framed within the European strategy called Horizon 2020 addresses economic, environmental and territorial challenges, including a mandatory “green” component in the aid (Regulation (EU) 1307/2013) and simplifying conditionality. The green component or “greening” which makes 30% of the basic payment (Royal Decree 1075/2014 and Royal Decree 1076/2014), includes measures that should provide environmental benefits, where crop diversification and the area of ecological interest are considered beneficial agricultural practices:

- Crops diversification: Whenever the cultivation land covers more than 30 hectares, there must be at least 3 different crops.
- Count on Ecological Focus Area (EFA) on the agricultural surface. Farms with more than 15 ha should allocate 7% of the arable land to EFA. The main EFAs chosen by the European countries are N-fixing crops such as grain and forage legumes.

Table IV-3. The crop rotation in each block of the study. NT: no-tillage; T: conventional tillage.

Block	Soil Management System	Area (ha)	Season 2009/2010	Season 2010/2011	Season 2011/2012	Season 2012/2013
1	T	5	Wheat	Sunflower	Legume	Wheat
	NT	5	*Triticum durum*	*Helianthus annus*	*Pisum sativum*	*Triticum durum*
2	T	5	Sunflower	Legume	Wheat	Sunflower
	NT	5	*Helianthus annus*	*Cicer arietinum*	*Triticum durum*	*Helianthus annus*
3	T	5	Legume	Wheat	Sunflower	Legume
	NT	5	*Cicer arietinum*	*Triticum durum*	*Helianthus annus*	*Pisum sativum*

The sowings of the crops were carried out by the farmer who owns the farm. The doses of the used seeds are those used in the rest of the farm since our intention is to reproduce what happens in the field and not recreate situations that do not occur (Table 4).

In the case of NT, all crop residues were left on the soil surface. As soil cover is one of the principles of CA, an NT seeder equipped with cutting disks in the seeding line was used for sowing in NT plots, whereas a conventional tine seeder was used for sowing in the T plots. Both machines are well adapted to the study area and are the same as those used by local farmers. Table 5 shows the agricultural operations performed throughout the study in both soil management systems.

Table IV-4. The seed doses and working widths of the different crops in the study.

Crop	Seed Doses	Working Width (m)
Sunflower	75,000 plants/ha	3.9
Wheat	220 kg/ha	2.85
Legume (chickpea)	120 kg/ha	3.9
Legume (pea)	250 kg/ha	3.2

With the aim of obtaining representative data, each of the five-hectare experimental plots has ten points marked and all of them were geo-referenced. Knowing the precise location of each sampling point made it possible to evaluate the seasonal variability of the CO_2 emissions of the specific area.

In order to evaluate the production and quality of each crop and soil management system, data provided by a harvester equipped with a Ceres 8000 i RSD yield monitor were used.

Soil cover was measured in order to relate the production and soil moisture to the soil management. The percentage of soil cover was calculated following the sector evaluation method, which takes pictures using a frame of 1 m2 divided into 100 0.01 m2 squares. The frame was placed in the points marked out for soil samples and soil moisture. Along the study period, 1480 points were measured for soil cover by taking two pictures per point.

IV-2.3. Emission Measurements

The emission measurements were made monthly over four seasons (2009/10, 2010/11, 2011/12, 2012/13), with an infrared portable EGM-4 absolute and differential gas analyser, coupled with a soil respiration chamber. The respiration chamber was approximately 15 cm high with a diameter of 10 cm and a CO_2 flow measurement capacity ranging between 0 and 9.99 g CO_2 m^{-2} h^{-1}. The measurement accuracy was ± 1 SD (standard deviation), with a resolution of 1 ppm. The measurement procedure consisted of placing the chamber over the soil surface for a period of 2.5 min. The measurements were taken automatically every 4 s during that 2.5 min period, the final value being the mean of the whole period. The technique principle is based on calculating the CO_2 concentration in the air present inside the chamber using fits to quadratic equations. The gas analyser is equipped with a column with space for approximately 10 mL of a silica-derived substance, which absorbs the moisture in the air circulating within the closed system, preventing interferences. The use of static or automatic chambers and gas analysers has been widely recommended by other authors [32–35].

We estimated the soil respiration as the flux emitted from the soil surface that represents the sum of the CO_2 produced by the heterotrophic decomposition of root exudates, plant litter, soil organic matter decomposition and root respiration. The influence of autotrophic soil microorganisms is small in most situations [36] as well as non-biological reactions (precipitation or dissolution of soil carbonates and biological reactions).

During the study period, CO_2 measurements were conducted simultaneously in both plots: NT and T. Two gas analysers were used at the same time in order to work with similar conditions, making the measurements comparable.

IV-2.4. Temperature and Soil Moisture Measurements

At the same time that the gas emission measurements were performed, the soil temperature was recorded at a depth of 5 cm using a thermometer. Soil moisture measurements were taken using a Diviner 2000 capacitance probe (Sentek Pty Ltd.) that was inserted into tubes positioned in each CO_2 measurement point (ten points in each plot) at ± 1 m of distance. Those tubes, in permanent contact with the soil, were previously introduced into a hole made in the soil. The probe automatically records the soil moisture at 10 cm intervals and saves the data in internal memory, from which it could be downloaded later onto a computer using the appropriate software. The probe took measurements to an effective depth of 80 cm, although manual measurements could be taken directly by recording the reading on the built-in screen on the probe. Rainfall data were obtained from nearby agro-climatic stations.

Table IV-5. The field operations performed each season per crop and per soil management system. NT: no-tillage; T: conventional tillage.

SEASON 2009/10								
LEGUME			**SUNFLOWER**			**WHEAT**		
Date	**T**	**NT**	**Date**	**T**	**NT**	**Date**	**T**	**NT**
14/10/09		Herbicide Glyphosate (42%) Vol. 1.5 L/ha	14/09/09		Herbicide Glyphosate (42%) Vol. 1.5 L/ha	14/10/09		Herbicide Glyphosate (36%) Vol. 1.5 L/ha
29/10/09	Disk harrow		29/10/09	Disk harrow		30/10/09	Disk harrow	
07/11/09	Disk harrow		06/11/09	Chisel plough		05/11/09	Chisel plough	
20/11/09	Disk harrow		11/11/09	Disk harrow		10/11/09	Disk harrow	
22/03/10	Herbicide Glyphosate (42%) Vol. 4 L/ha Seeding		14/05/10	Herbicide Granstar (50%) Vol. 37.5 g/ha		04/12/09	Spring tine cultivator	
28/04/10	Fungicide Clortaronil Vol. 1 L/ha		15/03/10	Spring tine cultivator		04/12/09	Seeding	
13/05/10	Fungicide Clortaronil Vol. 1 L/ha		03/04/10	Seeding		24/01/10	Fertilizer	
						16/03/10	Fertilizer	
						19/03/10	Herbicide Topik + sekator Vol. 250 cc y 300 g/ha	
						28/04/10	Fungicide Topik + Lovit Vol. 250 cc y 1 L/ha	

SEASON 2010/11								
LEGUME			**SUNFLOWER**			**WHEAT**		
Date	**T**	**NT**	**Date**	**T**	**NT**	**Date**	**T**	**NT**
19/01/11	Herbicide Pulsar Vol. 1 L/ha		27/09/10	Disk harrow		08/10/10	Disk harrow	
27/04/11	Fungicide Clortaronil Vol. 1 L/ha		07/10/10	Chisel plough		19/11/10	Fertilizer	
20/05/11	Fungicide Clortaronil Vol. 1 L/ha		14/03/11	Spring tine cultivator		20/11/10	Spring tine cultivator	
07/07/10	Disk harrow		21/03/11	Seeder	Seeder Herbicide Glyphosate (42%) + Oxifluorfen (24%) Vol. 1.5 + 0.15 L/ha	24/01/11	Spring tine cultivator Herbicide Glyphosate (36%) + U46combi Vol. 1.5 L/ha	
20/11/10	Spring tine cultivator		31/03/11	Herbicide Glyphosate (36%) + Granstar (50%) Vol. 1 L/ha + 40 g/ha		25/01/11	Seeder	
17/03/11	Spring tine cultivator		25/05/11	Herbicide Granstar (50%) + Ceres Vol. 40 g/ha y 1 L/ha		24/02/11	Fertilizer	
18/03/11	Seeder					19/03/11	Herbicide U46combi + Sekator Vol. 0.75 L/ha y 0.225 L/ha	
						19/04/11		Fertilize
						25/04/11	Fungicide Lovit Vol. 1 L/ha	

NT: no-Tillage; T: conventional tillage; DH: Disk harrow; S: Seeding; CP: Chisel plough; C: Cultivator.

Table IV-5 (continuation)

SEASON 2011/12								
LEGUME			**SUNFLOWER**			**WHEAT**		
Date	**T**	**NT**	**Date**	**T**	**NT**	**Date**	**T**	**NT**
24/09/11	Disk harrow		26/10/11	Chisel plough		12/08/11	Disk harrow	
			30/11/11		Herbicide Glyphosate + U46ombi Vol. 1.15 L/ha y 150 cc	17/11/11		Herbicide Glyphosate + U46combi Vol. 1.5 L/ha y 750 cc
			14/01/12	Herbicide Glyphosate + Oxifluorfen Vol. 1.5 L/ha y 300 cc		18/11/11	Spring tine cultivator Seeder	Seeder
			30/01/12	Disk harrow		13/01/12	Fertilizer	
			09/02/12	Spring tine cultivator		26/01/12	Herbicide Sekator + Topik Vol. 300 cc + 250 cc	
22/12/11		Herbicide Glyphosate Vol 3 L/ha	05/04/12	Seeder		19/04/12	Fertilizer	
24/12/11	Seeder		07/04/12	Herbicide Glyphosate + Oxifluorfen Vol. 3 L/ha y 300 cc				
25/12/11	Spring tine cultivator Fertilizer	Fertilizer	18/05/12	Herbicide Pulsar Vol. 1 L/ha				
15/02/12	Herbicide Pulsar Vol. 1 L/ha							

SEASON 2012/13								
LEGUME			**SUNFLOWER**			**WHEAT**		
Date	**T**	**NT**	**Date**	**T**	**NT**	**Date**	**T**	**NT**
10/11/12	Disk harrow		04/10/12	Chisel plough		11/10/12	Disk harrow	
			04/12/12	Herbicide Glyphosate + Oxifluorfen Vol.2 L/ha + 150cc				
21/12/12	Herbicide Glyphosate + Pulsar Vol. 3 L/ha + 0.75 L/ha		04/02/13	Herbicide Glyphosate + Oxifluorfen Vol.2 L/ha + 150cc		15/11/12		Herbicide
24/12/12	Seeder		27/02/13	Vibro-cultivator		21/11/12	Vibro-cultivator	
12/05/13	Herbicide Glyphosate + Oxifluorfen Vol. 2.5 L/ha + 250 cc		16/04/13	Herbicide Glyphosate + Oxifluorfen Vol. 3 L/ha + 250 cc		04/12/12	Seeder	
			22/04/13	Seeder		16/01/13	Fertilizer	
						14/02/13	Herbicide Sekator + U46Combi Vol.1.8 L/ha + 750 cc	
						03/04/13	Fertilizer	
						10/04/13	Herbicide Traxos + Lovit Vol. 300 g + 1 L/ha	

NT: no-Tillage; T: conventional tillage; DH: Disk harrow; S: Seeding; CP: Chisel plough; C: Cultivator.

IV-2.5. Data Analysis

The data obtained from the EGM-4 CO_2 emission analyser throughout the different campaigns of the study have been the object of different statistical analyses. First, an analysis of variance was carried out, which allows us to test the null hypothesis that the means of the two populations (T, NT) are equal. The emission values of CO_2 are related and are affected by multiple variables, such as temperature, precipitation collected during measurement periods, soil moisture, etc. In order to be able to study the relationship that each of them has over the emitted gas, a Pearson correlation analysis was made. The null hypothesis $\rho = 0$, from which we start, states that the values of r must be compared with the probability tables for n-2 degrees of freedom. The calculation of the correlation coefficient requires that the population follow a normal distribution of two variables. Therefore, it has been previously studied whether the variables' object of the correlation analysis complies with this premise of linearity, which is our case. The result of this correlation analysis is found in Table 6, which is presented in the Section 3.

Table IV-6. The yield (kg ha^{-1}) and environmental cost (kg CO_2/kg production) during the four seasons in each soil management system.
NT: no-tillage; T: conventional tillage. Different letters indicate statistically different results at $p < 0.05\%$ $p^* < 0.01\%$, $p^{**} < 0.001\%$ Test Tuckey.

Season	**2009/10**		**2010/11**		**2011/12**		**2012/13**		**Average**	
	NT	**T**	**NT**	**T**	**NT**	**T**	**NT**	**T**	**NT**	**T**
Yield (kg ha^{-1})										
Wheat	2620a	2972a	4060a	2922b	870b	1378a	3040a	3144a	2648a	2604a
Legume	492b**	1282a**	558a	833a	860a	980a	420a	620a	583a	928a
Sunflower	1312a	1140a	907a	1265a	466a	394a	1190a	684b	969a	871a
kg CO_2 /kg yield										
Wheat	4.4	40.2	1.6	36.0	13.9	82.0	4.8	35.4	6.2	48.4
Legume	15.7	92.2	2.6	63.3	6.4	51.6	19.3	80.3	11.0	71.8
Sunflower	10.7	54.2	12.6	88.4	26.4	341.1	6.6	170.6	14.1	163.6

As we have already mentioned, soil CO_2 emissions are related to the moisture present in the soil at the time of emission, while the moisture content is influenced by soil management. For this reason, a map of the distribution of gas emissions has been carried out. The distribution maps allowed us to represent the spatial variability of any variable measured in the experimental plots. CO_2 emission distribution maps were prepared using ordinary kriging for points, with intervals of 1 m in both directions to evaluate the spatial variability of the CO_2 emissions. As mentioned before, the sample points were georeferenced, therefore, their coordinates in the area are known. For the geostatistical analysis, the Surfer 10 program was used, while the data was analysed using the Statistix v.9 program.

IV-3. Results

Figure IV-2 shows the evolution of CO_2 emissions for the two soil management systems studied in the different test periods and crops.

The annual rainfall ranged from 815 mm registered in 2009/10 to 268 mm in 2011/12. None of the agricultural years showed values close to the average annual rainfall which, in this area, and considering the 10-year average, is 552 mm. Not only did this rainfall variability affect CO_2 emissions during different crop phenological stages, but it also affected the field operations carried out.

Figure IV-3 depicts the accumulated daily rainfall, the total accumulate over all the different farming periods, and the average annual rainfall over the last 10 years and shows the water content in the soil over the different periods and soil management systems.

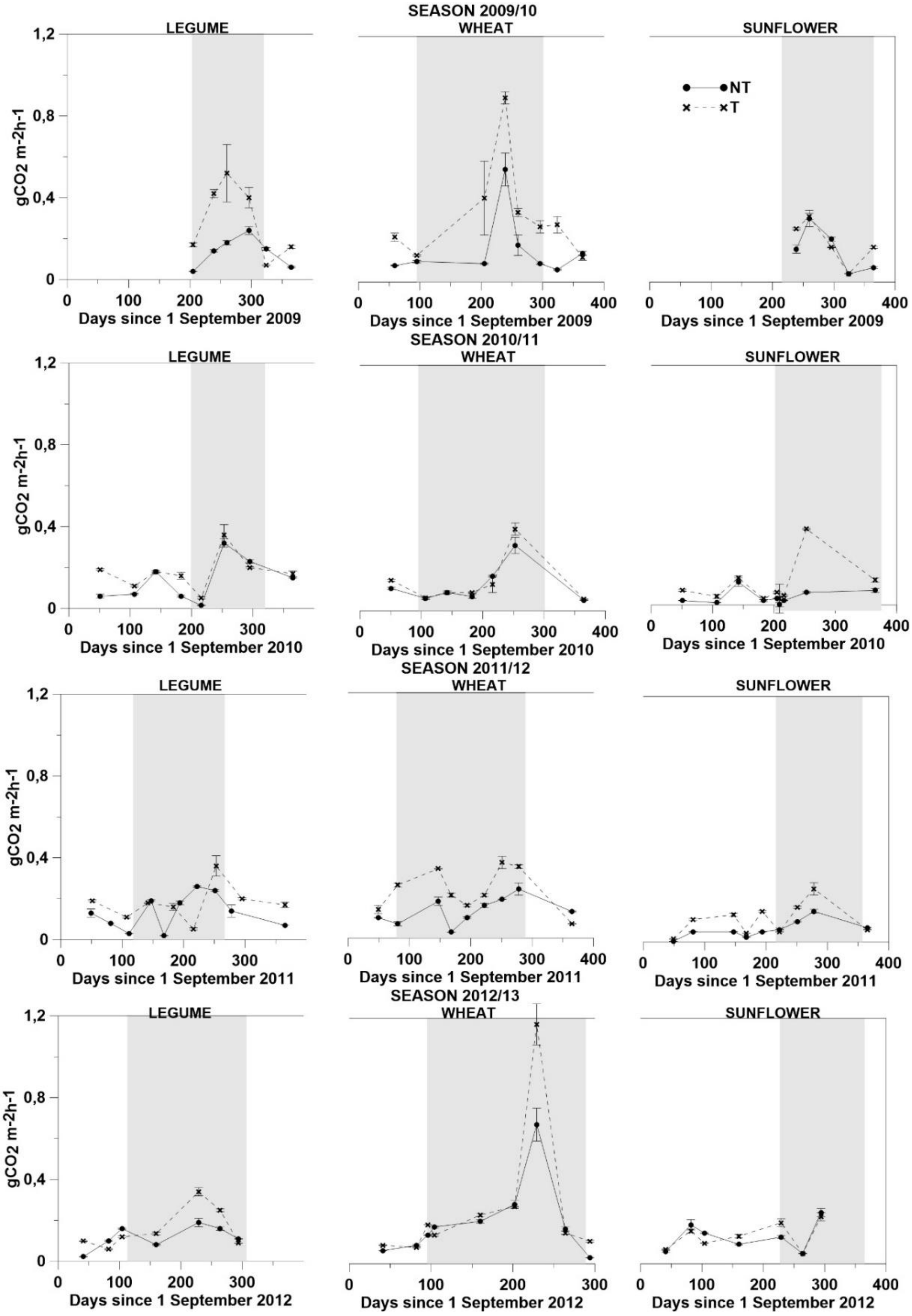

Figure IV-2. The evolution of CO_2 emissions for the two soil management systems studied in the differenttest periods and crops.

Each line corresponds to a management system. Every point shows the averageof 20 readings. The highlighted (grey) zones correspond to the time period during which the crop is onthe field. The vertical lines denote the standard error of the data obtained in the field samplings.

In Figure IV-3, a series of maximum and minimum values can be seen, corresponding to times of recharge due to rainfall and drying of the soil profile. Worthy of highlight is the fact that NT soils always had a larger amount of water than T soils, and these differences have been larger during periods of low rainfall.

Soil moisture data shown in Figure IV-4 indicate the total value for the entire profile assessed by the probe (1 m).

With regards to the crops, if root respiration emits CO_2 when the plant is growing, then the yield would have a direct relationship with the amount of gas emitted. Thus, the yield collected in each soil management system (NT vs. T) may explain the differences found in the respiration processes presented in Figure IV-2. To assess this effect, Table 5 shows the yields obtained in the test farm for different crops during the four seasons studied. Additionally, Table 6 presents the CO_2 emitted per unit of production, which has been named the environmental cost.

As can be seen in Table 6, there are no significant differences in production among T and NT, except in the legume in the first season, wheat in the second season and sunflower in the third season. As an example and considering the case of the sunflower, the largest difference in the amount of CO_2 emitted between NT and T is shown in the third season and yet, in this period, the yield is similar without statistical differences.

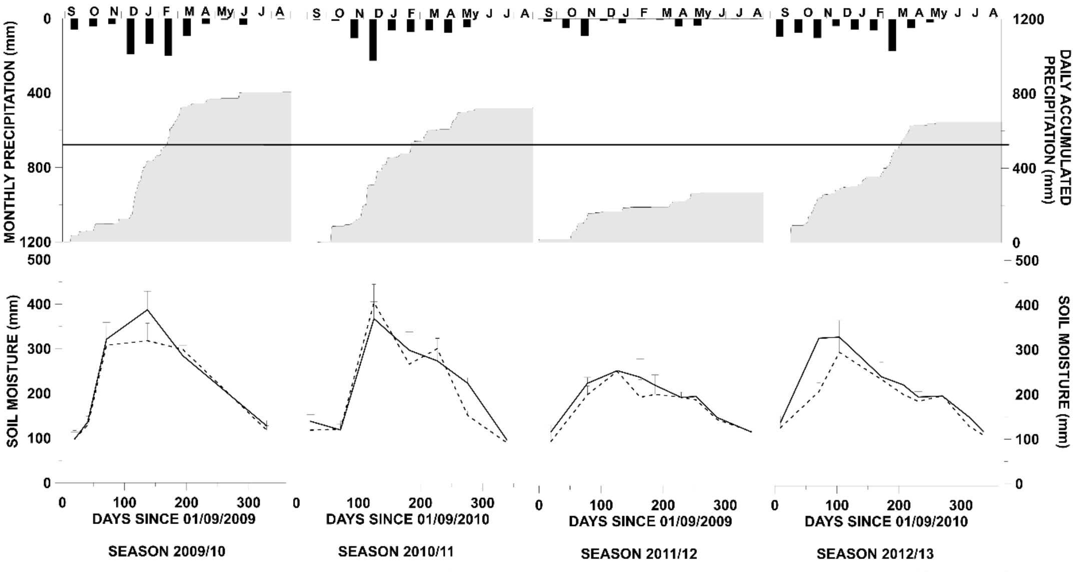

Figure IV-3. The accumulated daily rainfall, the total accumulate over all the different farming periods and the average annual rainfall over the last 10 years (horizontal line). Changes in soil moisture content during the test period for both soil management systems. NT = no-tillage; T = tillage.

Irrespective of the agricultural season and crop considered in the rotation, the production entails a higher environmental cost in T than in NT. Considering the average of the four agricultural seasons, for each kg produced in T, 42.2 kg more CO_2 is emitted in wheat, 60.8 kg more CO_2 in legume and 149.5 kg more CO_2 in sunflower, than those emitted in NT.

In this sense, CA fulfils the challenges of sustainability that are demanded by agriculture nowadays, which are used to improve yields and the efficiency in the use of inputs, whilst mitigating the environmental impact of conventional agriculture, better than tillage agriculture [37].

The emissions produced in the main phenological stages of the different crops analysed during the four seasons studied are shown in Table 7.

In most of the cases, there is a clear relationship between CO_2 emissions and the phenological stage of the crop. In the case of wheat and legumes, the highest percentage of emissions took place during the flowering period and this coincides across all four growing seasons. However, in the case of sunflower, no single stage can be specified as being that of maximum emission, a fact which can be explained due to the crop developing entirely during the summer months when high temperatures are recorded and the soil contains relatively little moisture, which results in the emissions not following a defined pattern as in the other cases.

To assess the influence of climatic and productive conditions in the area of study on the flux of CO_2 gas to the atmosphere, we analysed the Pearson correlation between these variables and the results are shown in Table 8.

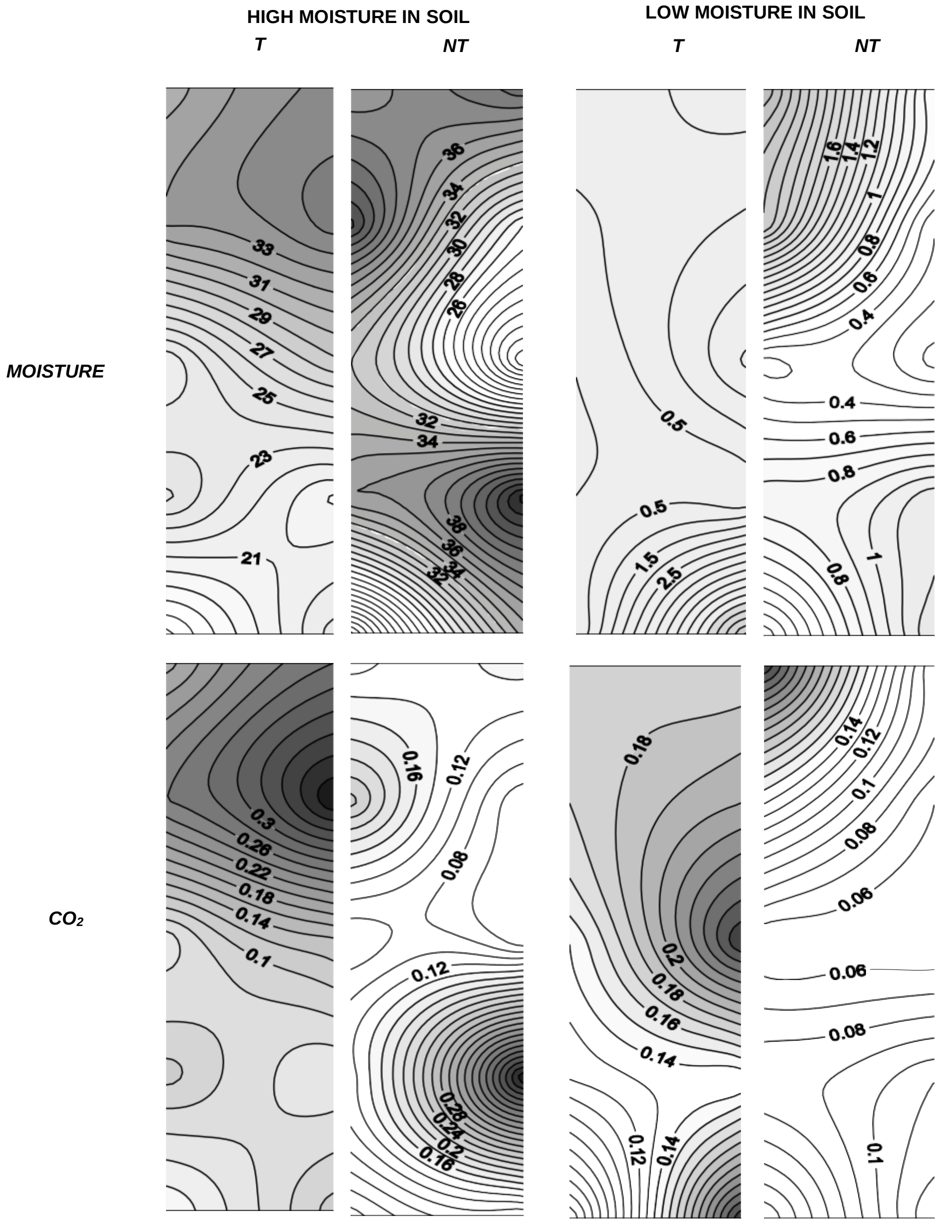

Figure IV-4. The spatial distribution of soil moisture and CO_2 emissions into the atmosphere.

As can be seen in the correlation matrix, CO_2 emissions are highly correlated with precipitation (approximately 58.6%) and with the presence or absence of crops at the time of measurement of the emissions (41.5%). It also shows a correlation with temperature, but with a lower percentage. The correlation matrix also shows that soil moisture is one of the variables with the highest correlation with the measured emissions. In order to assess this relationship, spatial distribution maps that reflect the data of both parameters were drawn.

In Figure IV-4, the result of the spatial distribution is given, specifically for the first season in the wheat plot, when one of the largest CO_2 emissions was recorded. This case is referred to as “high moisture in soil”. On the other hand, for the third season, when the lowest amount of annual precipitation and one of the lowest volumes of emissions was recorded at a time of very low moisture in the soil during the cultivation of wheat, is referred to as “low moisture in soil”.

It can be observed for the two moisture conditions studied, at the time the measurements of gas flows were carried out, that the areas of the plots which registered greater water content coincided with the areas where a higher value of emissions was registered, which corresponds to the darker areas of the maps. There is evidence that the soil moisture content at the time when the measurements of CO_2 emissions were made was decisive in the volume of CO_2 emitted.

Table IV-7. The breakdown in the percentage (%) of CO_2 emissions in each of the main phenologicalstages of the crop rotation for the seasons 2009/10, 2010/11, 2011/12 and 2012/13.

PhenologicalStage	**2009/10**	**2010/11**	**2011/12**	**2012/13**
		Wheat		
Stage 0	13	31	18	21
Stages 1 to 4	18	24	18	24
Stage 5 and 6	54	39	24	43
Stage 7 to 9	15	6	22	15
		Legume		
Stage 0	8	31	22	17
Stages 1 to 4	51	40	41	30
Stage 5 and 6	28	15	16	30
Stage 7 to 9	13	14	21	23
		Sunflower		
Stage 0	23	34	37	51
Stages 1 to 4	36	18	26	17
Stage 5 and 6	21	34	26	5
Stage 7 to 8	20	14	11	27

Note: the different phenological states based on the BBCH-scale (Biologische Bundesanstalt, Bundessortenamt und CHemische Industrie [38], are the following.

*Stage 0: Germination

*Stage 1: Leaf development

*Stage 2: Tillering

*Stage 3: Stem elongation

*Stage 4: Booting

*Stage 5: Inflorescence emergence

*Stage 6: Flowering

*Stage 7: Development of fruit

*Stage 8: Ripening

Table IV-8. The correlation matrix.

	CO_2	**CROP**	**MAX. T**	**MED. T**	**MIN. T**	**RAINFALL**
CROP	0.4149					
p-value	0.0000					
MAX. T	0.2476	0.1556				
	0.0007	0.0339				
MED. T	0.2043	0.1077	0.9562			
	0.0052	0.1435	0.0000			
MIN. T	0.1135	0.0264	0.7477	0.9021		
	0.1228	0.7202	0.0000	0.0000		
RAINFALL	0.5859	0.0128	−0.4622	−0.3504	−0.1189	
	0.0002	0.8619	0.0000	0.0000	0.1061	
SOIL MOISTURE	0.6987	0.3435	−0.2123	−0.1321	−0.1118	0.7879
	0.0005	0.1359	0.0001	0.0002	0.0001	0.0000
SOC	−0.2890	0.4243	0.1211	0.2204	0.0891	0.4124
	0.0000	0.0033	0.0012	0.0121	0.0009	0.0011

IV-4. Discussion

CO_2 emissions are closely related to soil moisture and temperature throughout the several growing seasons of the study period.

There are several studies that show the relationship between environmental conditions and the flux of CO_2 into the atmosphere [39,40]. Soil moisture and temperature are the most influential factors [41,42] since both affect crop growth and microorganism activity, which are crucial factors in soil formation.

Figure IV-2 shows that the CO_2 emissions were higher during the first season (2009/10) when the highest rainfall events were recorded. SOM and CO_2 emissions are influenced by weather conditions. In that season (2009/10), the higher rainfall and soil moisture boosted the gases emissions.

In the season of 2010/2011, differences in the amount of gas emitted between NT and T were obtained and the latter system showed a larger CO_2 flux. Considering all emissions measurements, T produced 67% more CO_2 than the NT system. The different increment percentages of emissions for the several seasons are due to weather conditions that affect the soil respiration regardless of the soil management system. As is shown in Figure IV-3, precipitation was dramatically different in the third season; it was the factor that varied more widely. Productions were also affected by the scarce precipitation in the third season (Table IV-5), which was also reflected in the environmental cost. In any case, the T system had a substantially greater environmental cost than NT (Table IV-5).

There are studies that give more relevance to the soil temperature, showing a strong relationship with the daily CO_2 emissions [43] whereas others show a high correlation between soil moisture content and CO_2 emissions [44]. The decomposition of OM and, with it, soil respiration is more intense when the temperature is moderate (about 25 ◦C) and soil moisture is in the range between 60% to 80% of the maximum retention capacity [3,40,45]. Indeed, moisture is a key factor in the activity of soil biota that breaks down OM, the process by which CO_2 is emitted into the atmosphere.

Regarding the results of the correlation matrix [46], in a study on the evolution of CO_2 over time from Thermic Xerollic Calciothird soil and with a semi-arid climate, the authors also observed how climatic variables and the presence or absence of crops in development had a clear influence on soil respiration. These authors suggest that a precipitation event of 22 mm induced increments of about 0.10–0.15 g CO_2 m^{-2} h^{-1} in the three soil management systems studied; NT, T and minimum tillage. In Mediterranean areas, soil respiration during summers, characterized by being very dry, is limited by scarce soil moisture, while in the remainder of the growing season, respiration is more controlled by temperature [47]. This affirmation is consistent with our results in which the lowest gas emission values occurred in summer. Conversely, in very wet soil, aeration is restricted because a large proportion of pore space is filled with water and CO_2 flux to the atmosphere decreases [48]. Related to that, some authors [39] found more specific emissions from soil with larger-sized pores since it lets a greater flux of air that oxidised the organic matter.

A high correlation was obtained in almost all cases between CO_2 emission and soil moisture content (Table IV-7). Comparing the data obtained for the different variables studied, it must be highlighted how CO_2 values presented a higher correlation with moisture than with temperature [49]. It suggests that these small changes in soil water content and temperature allow interpreting differences in CO_2 fluxes between tillage treatments. Conservationist practices such as NT also have influence in the water storage capacity, improving the biopores and soil structure.

Furthermore, in most of the sampling dates, the values of CO_2 fluxes were higher in T soils than in NT soils, especially in those areas where mechanical cultivation activity was carried out on the soil. Under NT, the minimum soil disturbance produces changes in soil conditions that benefit the physical soil properties and reduce the rate of decomposition of SOM and, with it, the flux of CO_2 into the atmosphere [50].

IV-5. Conclusions

Conservation Agriculture fulfils the challenges of sustainability that are demanded to nowadays agriculture better than tillage-based agriculture. In productivity terms, Conservation Agriculture has improved yields in the crop rotation studied, whilst mitigating the environmental impact of agriculture. Carbon dioxide emissions from agricultural soils comprise complex processes. Among them, soil tillage has a great influence on CO_2 emissions, as the deeper the soil is ploughed, the more emissions it releases. In this article, Conservation Agriculture where mechanical soil tillage is avoided is presented as a feasible alternative to mitigate climate change in Mediterranean areas. In our case, in all crops studied, conventional tillage increased the CO_2 emissions compared to Conservation Agriculture. Conservation Agriculture not only reduces CO_2 net emissions, but also reduces the emissions related to yield. Additionally, the presence or absence of crops also significantly influences the emission of CO_2, which is increased when a crop is set. In our study in most of the cases, there is a clear relationship between CO_2 emissions and the phenological stage of the crop.

Carbon dioxide emissions are closely related to the soil moisture and temperature of the area. In the Mediterranean region, annual rainfall variability is a major characteristic of the agricultural environment. This variability has a strong influence on the changes in soil moisture content and in soil microbial activity. Consequently, the CO_2 emitted into the atmosphere and the CO_2 stored within soil pores vary between cropping seasons. In this regard, carbon dioxide emissions have been found to be positively correlated to the moisture content of the soil. It must be highlighted that the results were obtained in a specific period and area.

To contextualise for a bigger scale, reference values are necessary to take into account the spatial and temporal variability of the agro-ecosystems [23]. Even if the deliverables of Conservation Agriculture are promising, in terms of adoption, the Mediterranean region lags behind other regions in the world. Proper policies supporting the shift from conventional tillage to a more sustainable system are considered essential.

Author Contributions: Conceptualisation, R.C.B., R.O.F.; Methodology, R.C.B., M.M.G., M.A., R.R.T.; Original Draft Preparation and Writing, R.C.B., O.V.G., E.J., G.S.; Review and Editing, G.B., A.K., E.J., G.S; Supervision and Validation, R.C.B., R.O.F.

Funding: Project LIFE+ AGROMITIGA: Developmente of climate change mitigation strategies through carbon-smart agriculture. (LIFE17 CCM/ES/000140) and the project PP.AVA.AVA2019.007: Gestión del suelo y tecnologías de la fertilización nitrogenada para la mejora agronómica y medioambiental.

Acknowledgments: To the field and laboratory staff of the Soil Physics and Chemistry team at the IFAPA centre Alameda del Obispo for their collaboration in the assays.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

GHG	(greenhouse gases)
CO_2	(carbon dioxide)
N_2O	(nitrous oxide)
CH4	(methane)
SOM	(soil organic matter)
OM	(organic matter)
C	(carbon)
CA	(Conservation Agriculture)
NT	(no-Till)
SOC	(soil organic carbon)
T	(conventional tillage/tillage)

IV-6. References

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Chapter V

Soil Management, Irrigation and Fertilisation Strategies for N_2O Emissions Mitigation in Mediterranean Agricultural Systems

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Carbonell-Bojollo, R., Veroz-González, O., González-Sánchez, E.J., Ordóñez-Fernández, R., Moreno-García, M., Repullo-Ruibérriz De Torres, M.A. (2022). Soil Management, Irrigation, and Fertilisation Strategies for N_2O Emissions Mitigation in Mediterranean Agricultural Systems. Agronomy, 12, 1349. https://doi.org/10.3390/agronomy12061349

Chapter V: Soil Management, Irrigation and Fertilisation Strategies for N_2O Emissions Mitigation in Mediterranean Agricultural Systems

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V-Abstract

Feeding a growing population, which will reach 10 billion in 2050, is a major challenge. Another major challenge is to increase crops' productivity in a sustainable way, as the increase in agricultural inputs may lead to greenhouse gas emissions, including N_2O fertiliser. Several factors can influence N_2O emissions such as irrigation, the soil management system, or the type of fertiliser used. The aim of this research is to study the impact of each above-mentioned factor on N_2O emissions during three growing seasons in a maize field, considering three nitrogen fertilisers: urea (U), ammonium nitrate (AN), and a fertiliser with the nitrification inhibitor 3,4-

dimethylpyrazole phosphate (DMPP); two irrigation strategies: on demand (100%) and deficit irrigation (75% of demand); and a comparison of two soil management systems: conventional tillage (T) systems and no-tillage (NT) system. The interactions among the three factors and their effects on emissions were analysed through a principal component analysis. Higher emissions were recorded in plots that received the highest irrigation dose. The most favourable management to reduce N_2O emissions derived from agricultural activity for maize crops under a Mediterranean climate was the NT soil management, using a fertiliser with nitrification inhibitor and an irrigation dose of 75% of conventional irrigation.

Keywords: climate change; irrigation doses; nitrogen fertiliser; no-tillage systems; maize

V-1. Introduction

Because of the exponential population growth in different parts of the world, the population will reach 10 billion this century. Currently, the world population is 7.3 billion inhabitants, but it will reach 8.5 billion in 2030 and 9.7 billion in 2050, according to a recent UN report [1]. To meet this increasingly growing demand for food throughout the world, it is necessary to use higher inputs in agriculture, i.e., water and fertiliser, leading to a potential increase in nitrous oxide (N_2O) emissions. In fact, the use of nitrogen fertilisers over the last 60 years has multiplied seven times [2,3].

In the mid-twentieth century, N_2O emissions to the atmosphere, caused directly or indirectly by the use of nitrogen fertilisers, did not reach 50%. However, the trend has changed, and fertiliser use accounts for more than 66% of the total emissions [4].

Soils naturally emit N_2O due to two microbiological processes that are part of the N cycle, such as denitrification and nitrification, with the denitrification process (anaerobic)presenting greater N_2O production than the nitrification process (aerobic) [5,6]. However, the application of fertilisers (organic and synthetic) is considered to be the most important anthropogenic source of N_2O emissions (c. 70% of the total worldwide), mainly produced as a by-product or intermediate product of microbial processes (nitrification and denitrification) [7,8]. Over-fertilising crops leads to an exponential increase in N_2O emissions in the atmosphere [9]. Over the last 150 years, the levels of N_2O emissions have increased from 11 to 18 Tg N $year^{-1}$ [10].

In terms of climate change, the importance of this gas is given by its global warming potential: one kg of N_2O is equivalent to 298 kg of CO_2, lasting in effect for 114 years [11]. Another environmental concern worth mentioning is that nitrous oxide also contributes to the destruction of stratospheric ozone [12]. Thus, the factors that most intervene in its production should be studied, as should the agricultural practices that can reduce its emissions. The main factors involved in nitrification and denitrification processes are soil moisture [13], texture, nutrient content, and vegetation [14], which are all influenced by environmental conditions and soil management.

Regarding fertiliser, several aspects influence the emissions of N_2O, such as the fertiliser application method [15], the dose and formulation of the fertiliser, and the timing of its application during the crop cycle [16]. Studies on the optimal dose and number of top dressings of fertiliser to apply in order to reduce greenhouse gases (GHG) indicate that average N_2O reduction percentages can be nearly 40% [17,18]. However, the success of these measures is highly influenced by the climatic conditions of the study area, which, in most cases, have a greater impact on the efficiency of the fertiliser than the form of application. Other studies have focused on comparing the effect of traditional fertilisers on N_2O emissions with other fertilisers that include inhibitors of biochemical processes in their formulas, such as nitrification and urease inhibitors. In Mediterranean environments, nitrification inhibitors have been effective in reducing gas flow [19–22]. Nevertheless, the success of this measure is affected by soil factors and climatic conditions. Regarding urease inhibitors, although their purpose was to reduce NH3 emissions, recent studies have reported their effectiveness in reducing N_2O in extensive crops [23,24].

Soil management systems have a high impact on GHG emissions [25,26]. Therefore, a great effort has been made at the research level to find agricultural practices that favour emission reductions. Not all agricultural systems are considered large GHG producers; conservation agriculture includes a series of soil management practices, including no-tillage practices, which help minimize CO_2 emissions and increase soil carbon sequestration [27,28]. However, regarding N_2O emissions, there is no clear consensus in the scientific community related to the influence of soil management practices on these emissions. The controversy is due to the large number of parameters (physical, chemical, and biological) that may have an influence.

The soil organic carbon is the most important factor, affecting a wide range of denitrifying microorganisms [29]. In soils with high carbon content and good humidity, which are the characteristics of systems based on no-tillage practices, the nitrification and denitrification processes are expected to be altered, influencing the N_2O emissions to the atmosphere [30].

On the other hand, when the soil is tilled, organic C and N forms are released from the aggregates that provide a substrate for the mineralization of soil organic matter as well as for nitrification and denitrification [31], which affect the nitrogen gas generation potential. In addition, according to several authors [32,33] long-term tillage reduces the soil's ability to retain N, stimulates the production of nitrate (NO_3−) through nitrification, and decreases the ability to immobilize N due to the decrease in the C availability.

While some studies have concluded that N_2O emissions are higher in conservation tillage systems [34,35], others show that they are higher in conventional tillage systems [36,37], and others conclude that the tillage system does not influence emissions [38–40].

Regarding irrigation, the amount of water in the soil is a key factor that affects the bio- logical processes in the soil, generating conditions that can favour the emission of gases and condition the success of other implemented gas reduction practices. Sanz-Cobena et al. [23] observed that an excess in irrigation water application, in a maize crop, decreased the capacity of the inhibitor to reduce nitrogen losses in the form of N_2O and NO. Similar results were seen in Carbonell et al. [41].

Some of the reviewed studies refer to deficit irrigation strategies, associating the lower use of water with a reduction in energy consumption, up to 30% in some studies, and consequently, a decrease in CO_2-eq. rates [42,43]. Other studies refer to the introduction of technologies, such as drip irrigation, that imply a more efficient use of irrigation water and that, through more frequent irrigations, generate “dry” and “wet” areas in the soil, decreasing general soil moisture and favouring nitrification over denitrification, which ends up reducing N_2O emissions [44–46].

Most current studies focus on one or two factors, such as fertilisation or tillage systems, but there is a lack of multivariable studies that consider fertiliser, soil management systems, and deficit irrigation at the same time. This research tests the hypothesis that a multivariable analysis allows for a clearer understanding on the dynamic of N_2O emissions in Mediterranean environments. Thus, the impact of different management strategies based on those factors was studied for a maize field in the Mediterranean-climate, aiming to establish which system has a greater influence on reducing N_2O emissions.

V-2. Materials and Methods

V-2.1. Experimental Site

A field experiment was conducted to study the dynamics of N_2O emissions from the soil as influenced by different variables: soil management, type of fertiliser, and irrigation doses.

The study plots are located in a Mediterranean area with a xeric regime. The climatic conditions of the study area follow the pattern of the Mediterranean climate, which is characterized by a temperate climate with a rainy season in autumn and winter that concentrates 80% of the total annual precipitation, and very dry and hot summers.

The selected farm is located in Córdoba (Southern Spain: 37◦51′48′′ N; 4◦47′29′′ W), and the studies were carried out over three agricultural seasons: 2016, 2017, and 2018. Maize (*Zea mays* L.) under irrigation was the crop implanted during the whole study.

V.2.2. Experimental Design

As an experimental design, a split-split plot was chosen with three replicates. The factors considered in the study were the following:

1. Soil management system

   Two different systems were implemented:

   1.1. No-tillage (NT);

   1.2. Conventional tillage (T).

   The list of tasks performed in both management systems is shown in Table V-1.

Table V-1. The field operations performed each season per soil management system.

Conventional Tillage					
Season 2016		**Season 2017**		**Season 2018**	
Date	**Field operation**	**Date**	**Field operation**	**Date**	**Field operation**
17 February 2016	Disk plough				
10 March 2016	Chisel plough	01 February 2017	Chisel plough	22 February 2018	Chisel plough
06 April 2016	Disk + tine harrow	06 April 2017	Disk + tine harrow	05 April 2018	Disk + tine harrow
07 April 2016	Seeding	06 April 2017	Seeding	06 April 2018	Seeding
07 May 2016	Cultivator	08 May 2017	Cultivator	16 May 2018	Cultivator
20 October 2016	Disk plough	22 October 2017	Chisel plough		
No Till					
Season 2016		**Season 2017**		**Season 2018**	
Date	**Field operation**	**Date**	**Field operation**	**Date**	**Field operation**
16 February 2016	Herbicide Glyphosate + Fluroxypyr	29 March 2017	Herbicide Glyphosate + Fluroxypyr	27 March 2018	Herbicide Glyphosate + Fluroxypyr
07 April 2016	Seeding	06 April 2017	Seeding	06 April 2018	Seeding
24 May 2016	Selective herbicide	09 May 2017	Selective herbicide	22 May 2018	Selective herbicide
21 October 2016	Herbicide Glyphosate	22 October 2017	Herbicide Glyphosate		

Residues after harvest were not removed from the field in either soil management. The soil management conducted before the experiment consisted of conventional tillage, alternating between cereal and sunflower as crop rotation. The no-tillage area was not ploughed in the season prior to the experiment.

2. Irrigation dose

After sowing the maize and fertilizing the plots, the irrigation calendar began. Then, the experimental field was irrigated three days per week. Irrigation was carried out using drippers in alternate rows. Two doses were used:

2.1. Full dose on crop demand: 100%;

2.2. Deficient dose, up to 75%.

Preliminary tests had been carried out to establish that the deficit irrigation of 75% did not compromise the final production. A total of 100% of the crop water demand was determined through evapotranspiration, according to FAO-56 [47]. Reference evaporation data were taken from a meteorological station located 1200 m from the experimental field, belonging to the network of agricultural weather stations (RIA, “Red de Información Agroclimática”) of the Andalusia Regional Ministry of Agriculture, Livestock, Fisheries and Sustainable Development (Spain). An efficiency of 90% was used for drip irrigation.

3. Type of the used nitrogen fertiliser

All plots received 400 kg ha^{-1} of basic fertiliser 8-15-15 (N-P_2O_5-K_2O). Although different types of fertiliser were used, the total N was the same for all the experimental plots. The amount of fertiliser was adjusted according to the N-richness of each type of used fertiliser. In order to calculate the dose of fertiliser to be applied, 300 kg N ha^{-1} was used, which is the dose normally used for irrigated maize crops in the area. The equivalent amount of each formulation was calculated, and the amount of N that had been applied with the initial fertilisation (32 kg N ha^{-1}) was subtracted. The three fertilisers used in the study were urea (U), calcium ammonium nitrate (AN), and a fertiliser with a nitrification inhibitor that consists of ammonium sulphate nitrate (18.5% NH_4^+-N; 7.5% NO_3^--N) with 0.8% (regarding ammoniacal N) of the nitrification inhibitor 3,4-dimethylpyrazole phosphate (DMPP). The doses and the application dates are shown in Table V-2.

Table V-2. Fertilisers used in the trial; N-richness, doses, and application dates are indicated.

Basic fertiliser (kg ha^{-1})	400 (8-15-15)		
Differentiated Fertilisation	Urea (U): 46% N	Calcium Ammonium Nitrate (AN): 27% N	Ammonium Sulphate Nitrate with Nitrification Inhibitor (DMPP): 26% N
Total amount of fertiliser (kg ha^{-1})	583	993	1030
1st application (35%) How much? (kg ha^{-1})	204	348	360
When?	2 weeks after emergence	2 weeks after emergence	With seeding
2nd application (65%) How much? (kg ha^{-1})	379	645	670
When?	1 month after emergence	1 month after emergence	3 weeks after emergence

Given the experimental unit size, fertilisation tasks were carried out manually, spreading the fertiliser homogenously.

In the experimental design, the main factor was the soil management system (NT, T), which included irrigation (100, 75%) as the subplot factor and the fertilisation strategy (U, AN, DMPP) as the sub subplot factor. Each experimental unit (sub-subplot) had a dimension of 5 × 10 m^2, and nine sub-subplots were established per irrigation dose and soil management system (Figure V-1).

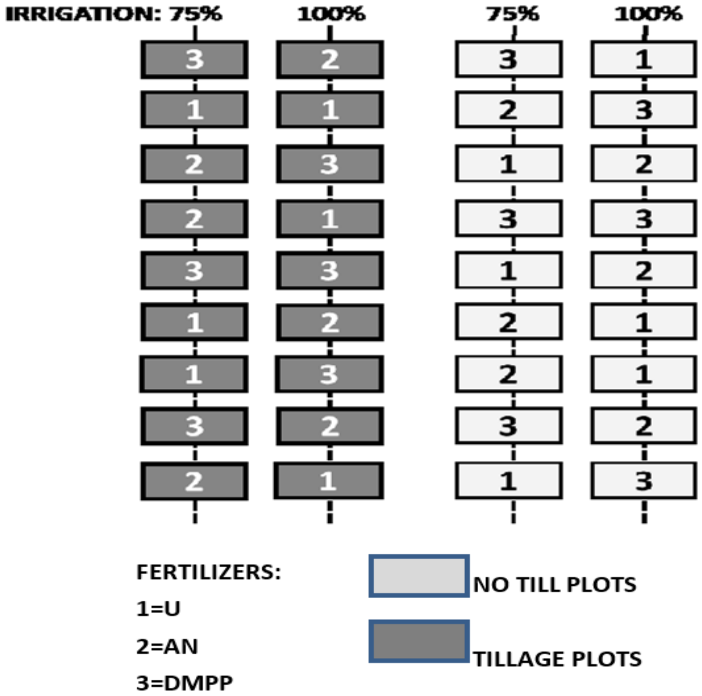

Figure V-1. Experimental design of the test plots. U: urea; AN: ammonium nitrate; DMPP: ammonium sulphate nitrate with DMPP nitrification inhibitor.

V-2.3. Soil and Irrigation Water Analysis and Maize Production

Soil samples were taken at two depths (0–20 and 20–40 cm) with an Edelman auger during the study period in order to analyse the nitrate content through the method de- scribed by Griess–Ilosvay [48]. The nitrate in the irrigation water was also measured periodically in order to assess all sources that affect the soil nitrate. Nitrate concentration in water was also analysed by the method described by Griess–Ilosvay after reduction in a copperised cadmium column. At the beginning of the study, a soil sampling was taken at several depths (up to 60 cm) in order to define the physical and chemical characteristics of the study site (Table V-3).

Table V-3. The physical and chemical characteristics of different soil layers at the study site.

Soil System	**Depth**	**pH H_2O**	**pH $CaCl_2$**	**P**	**K**	**OC**	**OM**	**CO_3^{-2}**	**CEC**	**Sand**	**Lime**	**Clay**	**Texture**
	cm			**mg kg^{-1}**		**%**			**meq(100g)$^{-1}$**		**%**		
Tillage	0–5	8.60	7.77	12.23	252.1	0.41	0.69	18.63	11.92	47.49	34.99	17.52	Loamy
	5–10	8.58	7.73	9.86	202.1	0.40	0.68	17.93	12.09	46.39	36.41	17.20	Loamy
	10–20	8.63	7.78	9.36	123.5	0.40	0.68	18.21	12.69	47.29	36.68	16.03	Loamy
	20–40	8.76	7.85	6.21	99.4	0.28	0.48	20.59	11.40	49.42	34.59	15.99	Loamy
	40–60	8.66	7.88	6.01	103.8	0.22	0.37	19.99	11.85	51.38	33.71	14.91	Loamy
No-Till	0–5	8.55	7.75	6.52	235.9	0.44	0.75	19.98	10.95	52.53	32.31	15.16	Sandy–Loam
	5–10	8.65	7.77	4.43	126.2	0.40	0.68	20.04	11.88	53.44	32.34	14.22	Sandy–Loam
	10–20	8.58	7.66	5.01	179.9	0.44	0.74	20.28	10.84	47.1	36.63	16.27	Loamy
	20–40	8.64	7.84	2.90	95.2	0.30	0.51	21.56	11.35	49.35	34.71	15.94	Loamy
	40–60	8.67	7.78	2.21	102.6	0.27	0.46	20.27	9.73	51.73	34.75	13.52	Loamy

P: available phosphorus; K: exchangeable potassium; OC: organic carbon; OM: organic matter; CEC: cation exchange capacity

Maize production was measured by the manual harvest of two crop rows in each experimental unit.

V.2.4. Emission Measurements

In order to measure gases, the closed-chamber approach described by Ryden and Rolston [49] was used. Cylindrical chambers (30 cm height and 31.5 cm diameter) were installed in the middle of every plot at the beginning of each gas sampling period, taking special care that they were perfectly embedded in the soil (approximately 3 cm) to avoid gas exchange with the environment. Sampling was always performed between 10:00 and 14:00 to avoid the effect of diurnal variability. The chambers were placed in the inter-rows with a drip line to test the effect of the different irrigation doses.

The chambers were closed for about 60 min, allowing us to determine the concentration of N_2O. The procedure for collecting gas is as follows: from each chamber, a 20 mL gaseous sample was extracted with a syringe and collected in vials with a septum, in which the gas was deposited under pressure. In addition to the samples taken from different chambers, environmental samples were also taken at the beginning and at the end of the sampling period. The linearity of flux was checked through measurement at 0, 20, 40, 60, and 80 min in one chamber per block, soil management, and irrigation dose. The extracted gas samples were analysed with a gas chromatograph (PerkinElmer Clarus gas chromatograph fitted with a Turbomatrix 110 automated head-space sampler and an electron capture detector for N_2O analysis). The sampling frequency is shown in Table V-4.

Table V-4. Dynamic of emission measurements during the three seasons studied.

SEASON	**2016**	**2017**	**2018**
1st N_2O measurement	14 April 2016	17 April 2017	9 April 2018
Dynamic of measurement	From 14 April 2016 to 28 July 2016 2 measurements a week	From 17 April 2017 to 27 July 2017 2 measurements a week	From 9 April 2018 to 26 July 2018 2 measurements a week
	From 2 August 2016 to 14 September 2016 Once a week	From 10 August 2017 to 7 September 2017 Once a week	From 2 August 2018 to 6 September 2018 Once a week
Last N_2O measurement	14 September 2016	7 September 2017	6 September 2018

V-2.5. Data Analysis

For the soil and production data, the Statistix v.8.0 program was used. The comparison of means was made using the least significant difference (LSD) test with $p < 0.05$.

For the gas emission data, a principal component (PC) study was made [50], as was an analysis with hierarchical conglomerates, using the Statistix v.8.0 and SPSS v.11 programs. The purpose of these analyses was to study the importance of different factors for the gas emission to the atmosphere. The analysis began with an initial number of variables, and finally obtained a lower number of variables, which was a linear combination of the initial variables. The number of components was obtained following the rule of choosing those ones whose values were higher than the unit value.

The first principal component (PC1) explains most of the variance of the data series, and each successive PC adds smaller amounts of the remaining variance.

V-3. Results

V-3.1. Soil Nitrate, Irrigation Doses, and Maize Production

The soil assessment carried out during the study period shows a descending trend along the crop development, considering the fertilisations applied in the first stages of the growing season. In the first season, the values ranged between 80 mg NO_3 kg^{-1} (first stages) and 5 mg NO_3 kg^{-1} (end of irrigation) at 0–20 cm, and 50–5 mg NO_3 kg^{-1} at 20–40 cm depth. In the second year, the highest values were lower than the previous season, and the lowest values were higher: 70–12 mg NO_3 kg^{-1} at 0–20 cm and 30–10 mg NO_3 kg^{-1} below 20 cm. The third season showed a different pattern: a peak of soil nitrate was measured 20 days after the second top dressing fertilisation and 10 days after the start of irrigation. The peak value was 75 mg NO_3 kg^{-1} for T and 72 for NT at 0–20 cm. At 20–40 cm, the highest value was 51 mg NO_3 kg^{-1} under T and 34 mg NO_3 kg^{-1} in NT. The soil nitrate at a depth of 20–40 cm was higher in T than in NT in this season, without statistically significant differences.

The nitrate content in the irrigation water was between 3–7 mg NO_3 L^{-1}, depending on the volume of the source, but significant differences in soil nitrate content between the plots with differentiated irrigations were not found during the study period.

The total volume of irrigation for each dose (100% and 75%) was 8000 and 6000 m3 ha−1 in the first season, and 7400 and 5550 m^3 ha^{-1} for both the second and third seasons. The maize yields in the different seasons are shown in Table V-5, according to the irrigation dose. Statistically significant differences in maize production for the three studied factors (irrigation dose, soil management system, and type of fertiliser) were not found in the three seasons.

Table V-5. Maize production (kg ha^{-1}) in each season according to the irrigation dose.

Irrigation Dose	2016	2017	2018
100%	11,393	12,133	10,381
75%	11,050	11,383	10,465

V-3.2. Influence of the Soil Management System on N_2O Emissions

Figure V-2 shows the values obtained in different gas extractions in the maize field during three study seasons and for the two management systems, considering all the emission values for every fertilisation and irrigation thesis in each management system.

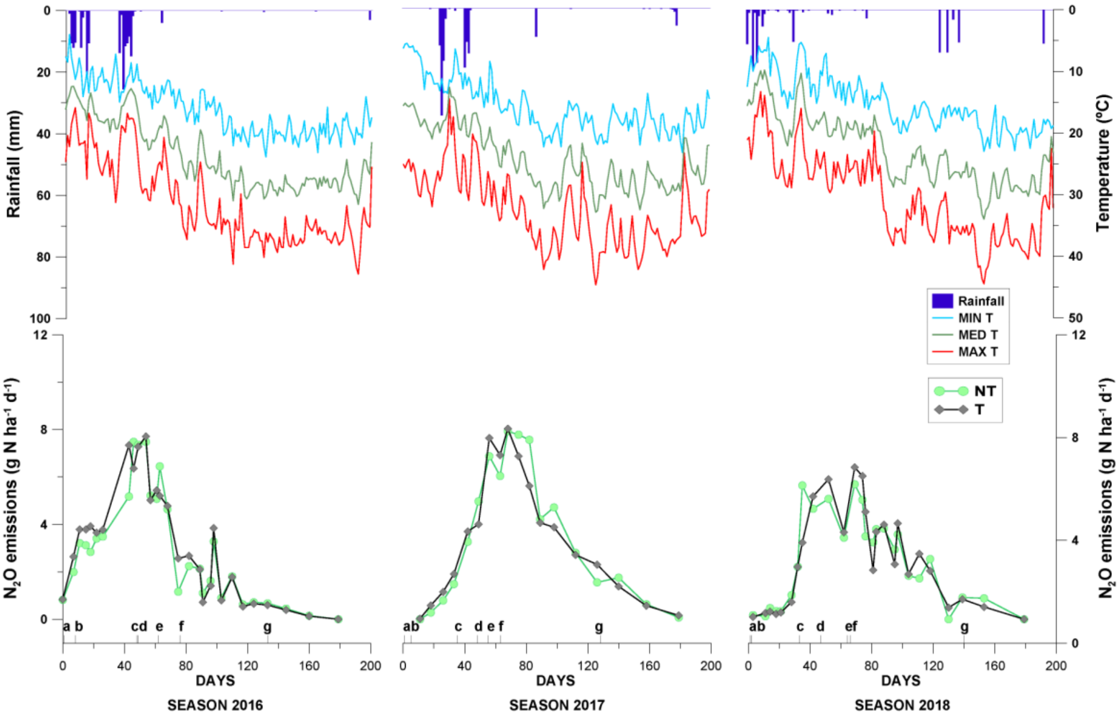

Figure V-2. Daily emission of N_2O according to the implemented management system. The different letters indicate: a = seeding; b = first fertilisation with DMPP; c = first fertilisation with U and AN; d = second fertilisation with DMPP; e = second fertilisation with U and AN; f = first irrigation; g = last irrigation.

In the case of the first season (2016), significant differences were not observed in the emissions related to the soil management system, but the peaks or highest values in the daily data were generally higher in the conventional tillage. The emissions in T became 3% higher than the maximum value in NT.

In the following season (2017), a clear emission peak can be observed that corresponds to the application of the fertiliser. The peak in NT was delayed regarding the T system. An emission of 8 g N2O-N ha−1 day−1 was reached in T system. In NT, the highest daily emission was slightly lower.

Finally, in the last study season (2018), lower peak values were reached than in the others, which could have been caused by the temperature factor since the summer was milder with lower average temperatures during this season. The emissions in T became 4% higher than the maximum value in NT.

V-3.3. N_2O Emissions and Type of the Used Nitrogen Fertiliser

The following figure shows the values obtained in different gas extractions in the maize crop during three study seasons for the three nitrogen fertilisers applied in the study (Figure V-3).

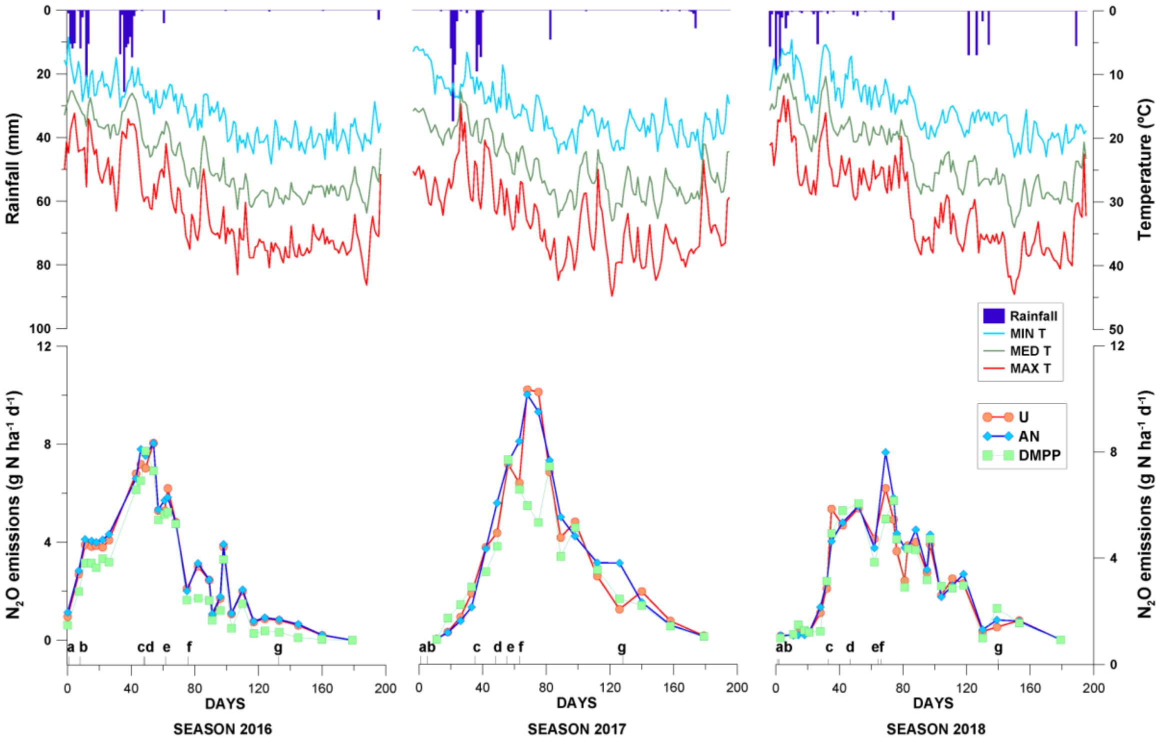

Figure V-3. Daily emission of N_2O according to the type of the used fertiliser.
The different letters indicate: a = seeding; b = first fertilisation with DMPP; c = first fertilisation with U and AN; d = second fertilisation with DMPP; e = second fertilisation with U and AN; f = first irrigation; g = last irrigation.

In the first season, it can be observed that the emission pattern was similar in all treatments. The emissions had no differences between U and AN at the beginning, as only the basic fertiliser had been applied at this stage. The fertiliser with the nitrification inhibitor was applied at a dose of 35% of its top-dressing N needs at the sowing. However, the emissions with DMPP were lower than the others. During the whole season, the treatments reached peaks between 5 and 8 g N ha−1 day−1, although without significant differences between treatments.

In the second season, the usual pattern of N_2O emissions began with very low levels since the plant was still small and the soil had received only basic fertiliser. Increasing emissions were observed after the first application of U and AN. DMPP started emitting earlier, but the increase was smoother. Moreover, the peak obtained with U and AN was 25% higher than that for DMPP. The treatment with the nitrification inhibitor had two peaks of about 7 g N ha^{-1} day^{-1}; the other fertilisers reached maximum values of 10 g N ha^{-1} day^{-1} after starting irrigation and the second fertiliser application. Although there was a progressive decrease in N_2O emissions in all treatments, the values remained relatively high until about 140 days after the first fertiliser doses were applied, at which point emissions were below 3 g N ha^{-1} day^{-1}.

Finally, the emission pattern in the third season was similar to that of the other seasons, but with smaller values on average. The maximum recorded value was 7.6 g N ha^{-1} day^{-1} in AN, being 25% higher than the maximum value found in DMPP. The highest peaks were observed at the beginning of irrigation, but the daily pattern of the emission data presented a series of maximums and minimums attributable to the availability of nitric nitrogen in the soil and its humidity conditions. Low emissions were recorded 120 days after the application of the first doses of fertiliser, although it remained after the end of the irrigation. There were no significant differences regarding the type of fertiliser used, reaching some peaks in the different treatments during the season.

V-3.4. N_2O Emissions and Applied Irrigation Dose

As in previous cases, the following figure represents the values obtained in different gas extractions in the maize crop during three study seasons for the two irrigation doses considered in the study (Figure V-4).

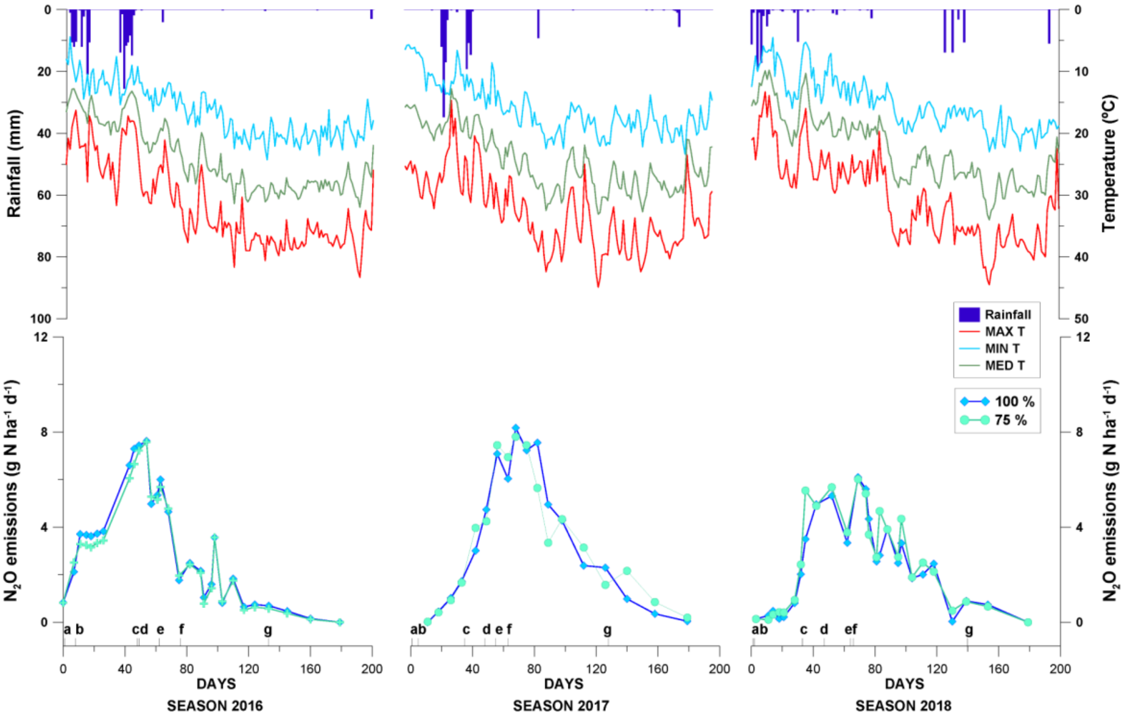

Figure V-4. Daily emission of N_2O according to the applied irrigation dose.
The different letters indicate: a = seeding; b = first fertilisation with DMPP; c = first fertilisation with U and AN; d = second fertilisation with DMPP; e = second fertilisation with U and AN; f = first irrigation; g = last irrigation.

In general, similar emissions in both systems were observed. In the first season (2016), the highest dose had slightly more emissions than 75% of demand at the first stage. Later, there were hardly any differences. In the following two seasons, corresponding to 2017 and 2018, there were some differences in some samplings. Generally, there were higher emissions in the plots that received the highest irrigation dose. At the end of the second season, it is observed that irrigation at 75% had higher N_2O emissions, and most of the emissions in the highest irrigation dose took place previously.

Table V-6 summarizes the total emissions accumulated in each season for all the variables in the study. As can be seen, emissions were reduced in the plots managed under conservation agriculture, with respect to those traditionally managed, except for the second season. That reduction, although not very high (3% in total), does not coincide with the studies in which conservation agriculture is considered to be a system that favours the emission of this gas. In the first season, the plots under NT reduced emissions by 9%, with respect to those in conventional tillage.

Regarding the fertiliser variable, the fertiliser with AN caused the greatest emissions throughout the experiment, and the plots treated with DMPP emitted the lowest amount of gas.

Finally, the 100% irrigation dose caused more emissions in all seasons.

Table V-6. Cumulative N_2O emissions (g N ha^{-1}) for the three studied variables and in all seasons for 180 days (±standard error).

	Management system		**Fertilisation**			**Irrigation**	
	NT	**T**	**U**	**AN**	**DMPP**	**100%**	**75%**
1st season	411.6 ± 20.6	453.6 ± 25.5	475.4 ± 19.9	489.3 ± 31.4	381.2 ± 21.1	445.6 ± 24.9	419.6 ± 21.9
2nd season	510.8 ± 26.8	499.7 ± 21.8	542.0 ± 14.0	575.1 ± 29.2	463.3 ± 20.5	512.8 ± 21.7	497.7 ± 26.8
3rd season	384.2 ± 15.8	395.1 ± 9.74	394.6 ± 16.5	414.3 ± 13.0	388.4 ± 14.3	403.7 ± 10.8	375.6 ± 14.5

V-3.5. Correlation between the Studied Variables and Analysis of Main Components

Numerous studies indicate that there are a great variety of factors, such as the crop rotation, the soil management system, the type of used nitrogen fertiliser, the time of application, etc., which interact with and significantly influence the emission of N_2O from the soil [51–53].

In order to identify the variables responsible for most of the emissions, and with the difficulty posed by the total variability in them, an analysis of the main components was carried out, which also allowed us to study the correlations between the analysed parameters [50]. The data used as the basis for the analysis were N_2O emissions, the irrigation dose (on demand 100% or 75% deficit), the nitrogen fertiliser (U, AN, DMPP), the soil management system (conventional tillage and no-tillage), the days since the last irrigation, and the nitrate content in the soil at the moment of gas emissions measuring. The final variables PC1, PC2, and PC3 were determined by a linear combination of the initial variables. Table V-7 shows the correlation matrix of the variables, together with the final PCs.

In order to study whether there was a trend or behaviour pattern for emissions that can be explained by some variable, each variable has been represented independently (Figure V-5).

The first graph corresponds to the fertiliser variable, and only one group, which includes the emission data collected in all the studied cases, is observed. Therefore, a priori, the fertilisation variable does not explain the behaviour of the N_2O emission pattern. Regarding the irrigation variable, two perfectly differentiated groups are observed—one of them because of the emission values measured in the plots irrigated with the full dose (100%), and the other one because of emission values recorded in the plots irrigated in deficit (75%). The irrigation variable has an important influence on N_2O emissions, regardless of the management system, since in both groups of values there are measurements made on conservation agriculture plots and in the traditionally managed plots.

Table V-7. Correlation matrix of the studied variables.

	Management System	**Irrigation**	**Fertiliser**	**NO_3^-**	**N_2O**	**Days**
Irrigation	0.4240					
p-value	0.0000					
Fertiliser	0.0051	0.2670				
	0.9436	0.0000				
NO_3^-	−0.0062	0.0062	0.9781			
	0.9308	0.9308	0.0000			
N_2O	−0.4303	0.8656	−0.8756	−0.0460		
	−0.0025	0.0025	−0.5038	−0.0047		
Days	0.1910	0.9721	0.8756	0.9474	0.3694	
	0.0000	0.3531	0.0025	0.0344	0.0011	
PC1	−0.0106	−0.0094	−0.8590	−0.0037	−0.1894	0.8622
	0.8824	0.8956	0.0000	0.9584	0.0089	0.0000
PC2	−0.7445	−0.2113	0.0913	−0.5773	−0.6572	−0.0614
	0.0000	0.0027	0.1996	0.0000	0.0000	0.3891
PC3	−0.1898	0.9760	0.0181	−0.5920	−0.0967	0.0055
	0.0072	0.0000	0.7999	0.0000	0.1741	0.9382

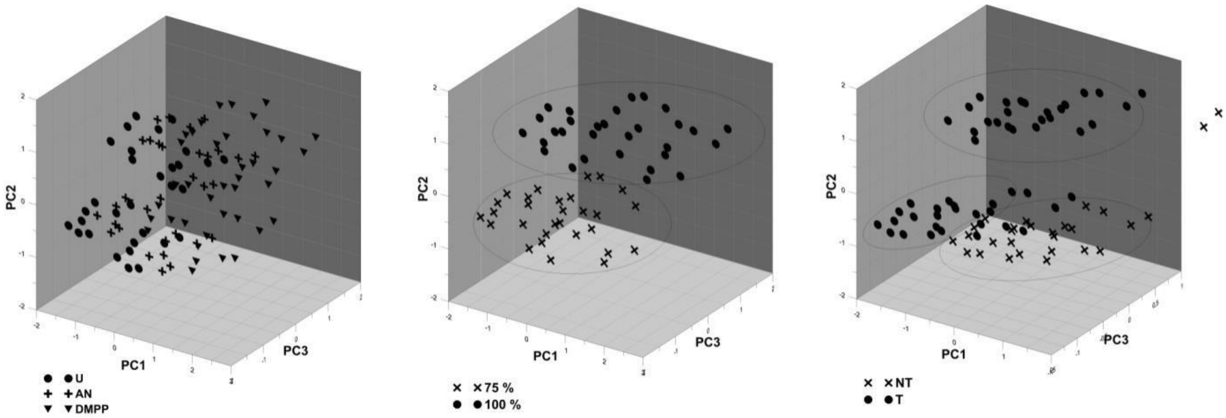

Figure V-5. Spatial representation of the main components for each variable studied independently.

The representation of the main component values of the soil management variable shows that the emission values corresponding to the plots managed by the no-tillage system belong to the same group, while in the case of the traditional tillage system, two different groups were formed. They were formed because of the interaction with another variable, so the next step was to represent the emissions recorded using the value of their main components, considering, in this case, more than one main variable (Figure V-6).

The interaction between the management system and irrigation dose variables represents the first group formed by the emissions generated in the plots under conservation agriculture and the lower irrigation dose (75%). The second group is formed by the emissions in the traditionally tilled plots, which are also 75% irrigated, while the third group is made up of all the emissions generated in the plots irrigated at 100%, regardless of the management system. One conclusion that can be obtained observing the graph is that when a high irrigation dose is used, it favours gas emissions, and the management system will not influence the dynamics of these emissions.

The interaction between the fertiliser and irrigation variables reflects two large groups, the first formed by all the emissions registered on plots irrigated at 100%, regardless of the used fertiliser, and the second group formed by the emissions from the plots irrigated at 75% and fertilized with any of the three fertilisers used in the study. As can be seen, with respect to nitrous oxide emissions, the irrigation variable is still the one that most influences the rest of the variables.

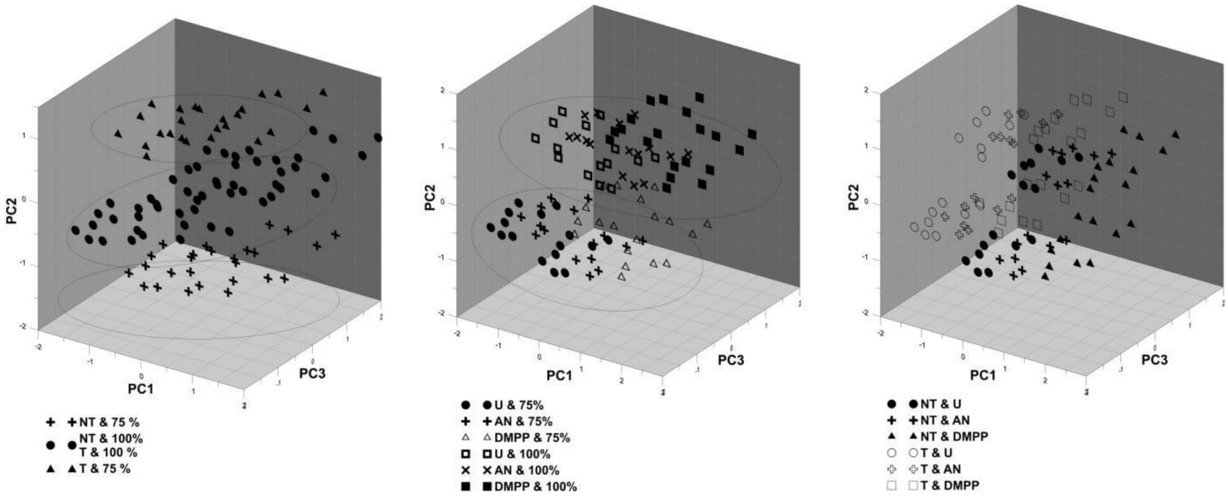

Figure V-6. Spatial representation of the main components as a function of the interaction of the variables studied in pairs.

Finally, if the considered variables are the management system and type of fertiliser, depending on the value of their main components, it can be observed that there is no notable difference between the emission values in all the studied cases.

To conclude, the joint interaction of the three variables considered in the study was evaluated and the nitrous oxide emission values were represented considering the value of their main components (Figure V-7).

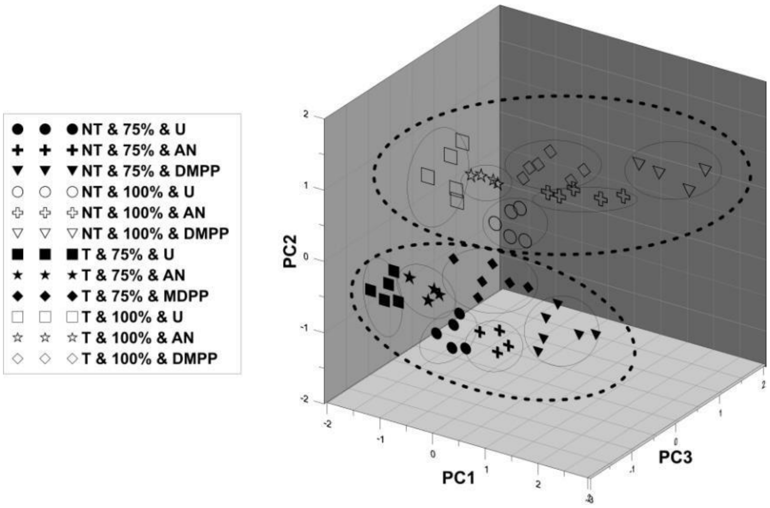

Figure V-7. Spatial representation of the main components as a function of the interaction of the three studied variables.

As can be seen, the interaction between all the variables has been decisive in the dynamics of N_2O emissions. Subgroups were formed for each combination of the three studied variables, but at the same time, two large groups that included the previous ones were also formed. One of these two groups is made up of all the emissions that have been generated with the 75% irrigation variable, and includes data from the plots in both management systems and with any of the three fertilisation formulations. The other large group is formed, as in the previous case, by data generated in any of the combinations of the soil management and fertiliser variables, but in this case, it only includes the variables generated with the 100% irrigation variable.

V-4. Discussion

V-4.1. Soil Management and N_2O Emissions

The effects of soil management systems on N_2O emissions are the result of changes in soil structure, microorganism activity, the decomposition of residues, soil aeration, and the rate of N mineralization, along with soil temperature and moisture [54].

The application of conservation agriculture principles is widely known as a practice that helps reduce atmospheric CO_2 emissions, thanks to the increase in soil organic carbon content due to lower soil disturbance and permanent vegetal soil cover. However, there are many authors who, even in agreeing with the previous statement, do not recognize its importance in mitigating climate change, and they emphasize that this practice also favours an increase in N_2O [55]. Soils under NT favour an increase in soil water content and soluble forms of carbon, favouring nitrification processes that promote atmospheric N_2O [56–58]. Nevertheless, other studies, such as that of Six et al. [59], state that this increase in emissions can be reduced when NT practices are maintained over time.

Our results, as can be seen in Figure V-2 and Table V-6, coincide with the results of those studies that indicate higher emissions of nitrous oxide in tilled soils compared to those under no-tillage systems. That is the case of Omonode et al. [60], who estimated a 40% reduction in the emission values in NT with respect to T in a study on a maize crop. Van Kessel et al. [61], in a meta-analysis compiling 239 studies on the effect of soil management on N_2O emissions, observed an increase in N_2O

emissions under NT in the first year of implementing this system, and a 27% reduction in the gas emitted in NT compared to T 10 years later. In our case, the greatest percentage of reduction regarding T was seen in the first season. In the second one, NT emitted slightly more nitrous oxide without significant differences.

In a study carried out in a tropical oxisol soil in Brazil, Escobar et al. [62] indicate that the N_2O emissions produced after harvest were three times higher in no-till systems compared to conventional ones. This may be due to the characteristics of these tropical systems with greater humidity, higher temperatures, and a greater population of denitrifying microorganisms in no-tillage systems [63].

Corrochano-Monsalve et al. [64] showed lower N_2O emissions in NT than in T when applying a fertiliser with nitrification inhibitor, due to the greater water-filled pore space of NT, which favours the inhibition of the nitrification process too. Our results agree with these authors; emissions were reduced by 9% and 3% with NT in the first and third seasons, respectively. Furthermore, DMPP emitted significantly lower amounts of N_2O in the first and second seasons in both soil management systems. Emissions in the AN plots were significantly higher than in DMPP in the tillage system at the end of the third season. Even without significant differences, when considering the management system factor, the highest emission peaks are either similar in both management systems, or they are higher in the T-plots, generally after irrigation. This is due to the higher soil moisture in NT, which can saturate the pores with water and delay nitrification processes.

In Mediterranean environments, as is our case, Plaza-Bonilla et al. [65] observed a reduction in the amount of N_2O emitted per kg of production in NT with respect to T, although in this case, the crop was grown in dry land. An earlier article written by Plaza-Bonilla et al. [66] also indicated lower or similar emission values in NT compared to T, although the greatest differences can be seen after making changes in the management system and using different management techniques for several years.

Therefore, not all studies agree on higher emissions of N_2O in conservation systems. Metay et al. [67] and Jantalia et al. [68] did not observe differences in N_2O emissions be- tween the NT and T systems in the Brazilian savannah and in southern Brazil. Liu et al. [69] reached the same conclusion for an irrigated maize field in north-eastern Colorado. Despite the fact that several studies consider that conservation agriculture systems increase nitrous oxide emissions [61,70], the presented results do not show a clear increase; only the cumulated emissions in the second season were higher in NT, as seen in Table V-6. Moreover, the importance of the NT system as a variable among all those on which the study of principle components is based does not determine the behaviour of the emission patterns.

V-4.2. Effect of the Type of Nitrogen Fertiliser on N_2O Emissions

The relationship between N_2O emissions and the amount of N fertiliser is not completely clear. Even though there are authors, such as Zhang and Han [71], who state that the existing relationship is linear, there are other studies, such as those of Ma et al. [72], that speak about an exponential relationship. Regarding nitrogen fertilisation, most of the studies have focused on comparing traditional fertilisers with other fertilisers that include inhibitors of microbiological processes, such as nitrification and urease inhibitors [23,73–76]. Our results indicate a higher total volume of emissions on the plots in which the

AN was applied (Table V-6). This result coincides with those obtained by Signor et al. [53], which show how in a sugarcane crop, emissions increased when the fertiliser contained N in ammonia form. Ammonia fertilisers increase N_2O emissions more slowly than nitric fertilisers because the latter kind start denitrification processes immediately, while ammonia sources have to go through the nitrification process first. Two independent studies, both conducted in Brazil, by Zanatta et al. [77] and Signor et al. [53], concluded that nitric fertilisers induced higher N_2O emissions than amide fertilisers (CH_4NO), data which coincide with the results obtained in our study. Compared to the total amount of measured emissions, bigger amounts were observed in the plots fertilized with the AN than in those that received U as fertiliser.

Regarding the moment in which there were the most emissions, Figure V-3 shows that emissions increase after applying the fertiliser, on some occasions after the first application and others after the second one. During the period between the first and second top- dressing fertilisation in the first season, the soil had enough moisture to allow nitrification, since it was raining in that period. These conditions caused all the treatments to emit nitrous oxide to a greater or lesser extent, and the highest values were reached in AN and DMPP treatments. After the rains, the second top-dressing was applied in the treatments with U and AN, but until there were no suitable moisture conditions in the soil, there was no peak of N_2O from the soil. From the beginning of irrigation, there was enough humidity, both with irrigation on demand and at 75% of the needs, to allow for nitrification. However, lower N_2O emission peaks were observed than after the first top-dressing since the crop was more developed, absorbing more nutrients from soil. These results coincide with those obtained by Schils et al. [78], who concluded that the emissions should be measured during the first two weeks after fertilisation.

According to Shaviv [79], the use of N inhibitor fertilisers is an important strategy to reduce N_2O emissions induced by N fertilisers, since they are involved in the nutrients' release. Figure V-3 shows that, on some dates, the plots fertilized with a nitrification inhibitor fertiliser (DMPP) emitted less gas. In the first season, considering that DMPP was applied at sowing, the emissions at the beginning were lower than the others due to the inhibitor that delayed the nitrification. Taking into account the total amount of gas accumulated by the three studied fertilisers, this type of fertiliser emitted the lowest amount of gas during the three studied seasons. DMPP provided N_2O emission reductions regarding U and AN over 19%, 14%, and 3% for 2016, 2017, and 2018, respectively. Therefore, there was a clear behaviour of the nitrification inhibitor, with respect to reducing emissions, compared to the rest of traditional fertilisers. The differences with respect to U and AN were significant the first and second seasons in the accumulated emissions.

Some studies, such as the one conducted by Meijide et al. [19], indicate a high N_2O mitigation efficiency in rain-fed farms and lower efficiencies in irrigated areas, in which the influence of irrigation is the predominant factor. This finding coincides with that indicated by Recio et al. [8] in a study about the impact of the nitrification inhibitor on the N_2O and NH_3 emissions in a maize crop in a Mediterranean climate.

Another factor that can improve the mitigating effectiveness of the nitrification inhibitor is the soil organic C content, which is higher in soils with less C and lower in soils with high C content [20,80]. Other authors, such as Gilsanz et al. [21], highlight the impact of temperature on the effectiveness of the inhibitor, indicating an inverse relationship between the increase in temperature and the impact of the inhibitor on the nitrification process, focusing attention on the importance of choosing the most appropriate time of applying N2O to mitigate effects. In our case, and being a spring–summer crop, the temperatures were generally high.

V-4.3. N_2O Emissions and Irrigation Doses

The plots that received the total irrigation dose (100%) showed higher N_2O emissions than those that were irrigated with the lower dose. These results coincide with those obtained in a large number of studies, according to which soil moisture content is a fundamental factor that stimulates N_2O emissions [81–84]. At the end of the second season, irrigation at 75% had higher N_2O emissions, probably due to that most of the emissions in the highest irrigation dose took place previously, and that the concentration of mineral nitrogen in the soil with a lower irrigation dose was higher.

The amount of water in the soil is a key factor that affects the biological processes in the soil, generating conditions that can favour gas emissions and influence the success of other implemented gas-reduction practices. An example can be seen in Sanz-Cobena et al. [23], who showed that excessive irrigation of maize crop decreases the capacity of an inhibitor to reduce nitrogen losses in the form of N_2O and NO. Similar results are seen in Carbonell et al. [41].

Our results are similar to those of Jamali et al. [85] who, in a study that evaluated the influence of the water amount on the N_2O emissions in a sorghum crop, presented results which showed that when reducing irrigation from 60–120 mm to 30 mm or below, while irrigating the plots more frequently, emissions were reduced by 41–50%.

Scheer et al. [82] carried out a study in Australia on wheat with three irrigation doses, a high dose, a medium dose, and a low dose. The mean daily emissions of N_2O were 5.5 g N_2O ha−1 day^{-1}, 3.2 g N_2O ha^{-1} day^{-1}, and 3.3 g N_2O ha^{-1} day^{-1}. In our study, emissions also decreased at the lowest dose in comparison with the highest dose, which showed a 1.2% emissions increase on average.

V-4.4. Correlation between the Studied Variables

There are several studies that show the correlation between humidity and fertiliser. Lower N_2O emissions are generated when the application of the fertiliser is carried out in a dry period (without irrigation) than when it is carried out in humid conditions [71,78]. Our results coincide with these conclusions because the irrigation strongly affects gas emissions, as the results reached in the study about main components show. Similarly, Passianoto et al. [86] concluded that the coincidence of fertilisation with rainy periods causes emission increases.

Kostyanovsky et al. [87] found, in a study carried out in four different locations in the US, that the highest emission peaks occurred in the treatments in which N fertiliser was applied together with irrigation, compared to those registered in the treatment with fertilisation only.

Studies by Robertson et al. [88–90] showed that emissions after a rainy period or applied irrigation are probably more controlled by the availability of nitrogen in the soil, together with the organic matter mineralization rate, than by irrigation only. They could also be affected by the soil treatment. In other words, the interaction between all the variables should be studied.

Jamali et al. [91] carried out a study to evaluate the influence of the amount of irrigation applied, of the optimal and reduced dose, and of fertilisation with a nitrification inhibitor of a wheat crop. Their results show that, considering the treatment of reduced irrigation and the inhibitor individually, both treatments reduce N_2O emissions; however, the lowest emission values were seen in the combination of both variables. These data coincide with those obtained in our study, in which the lowest N_2O values were observed in the plots fertilized with the nitrification inhibitor and with deficit irrigation. This is in agreement with the results by Scheer et al. [92], Liu et al. [93], and Cui et al. [94], who observed maximum emissions when fertilisation and irrigation variables interacted.

V-5. Conclusions

The reduction in N_2O emissions as a climate change -mitigation process is influenced by many aspects, including environmental factors, factors related to soil characteristics, and agronomic factors. It is recommended to consider the joint evaluation of three agricultural factors, such as soil, water, and fertiliser management.

Considering each of the factors individually, fertilisation has a significant impact on the increase in emissions, higher usually after the second top-dressing, which is applied during a period of higher temperature and the in a greater amount (65%). The type of fertiliser also affected the emissions; the highest values were measured in the plots fertilized with AN, being reduced with the fertiliser with a nitrification inhibitor. Irrigation also had an important impact on the amount of emitted gas. The highest emissions were observed normally after irrigating the plots, regardless of the amount of applied water, or after precipitations.

Under the conditions of our study, the joint consideration of the three factors determined that the most favourable management method for reducing N_2O emissions derived from agricultural activity in a maize crop in a Mediterranean area was managing the soil with the no-tillage system, using a fertiliser with a nitrification inhibitor, and adjusting the water application to 75% of the conventional irrigation dose.

The role of agriculture as a mitigating action within the climate change scenario is demonstrated by the obtained results, which show that the adoption of certain practices, such as conservation agriculture, the choice of fertiliser, and the volume of irrigation, decreases the amount of N_2O emissions. Furthermore, the adoption of conservation agriculture principles, which result in fewer inputs by reducing the number of field tasks, and using less irrigation are recommended as adaptation practices for future scenarios.

Author Contributions: Conceptualization, R.M.C.B. and R.O.F.; methodology, R.M.C.B., Ó.V.G., M.M.G., and M.A.R.R.d.T.; software, E.J.G.S. and M.M.G.; validation, Ó.V.G. and R.O.F.; formal analysis, R.M.C.B. and Ó.V.G.; investigation, R.M.C.B., R.O.F., and M.A.R.-R.d.T.; resources, R.M.C.-B. and E.J.G.-S.; data curation, R.O.-F. and M.A.R.-R.d.T.; writing—original draft preparation, R.M.C.B.; writing—review and editing, R.M.C.B., Ó.V.G., R.O.F., E.J.G.-S., and M.A.R.-R.d.T.; visualization, R.M.C.-B., Ó.V.-G., and M.M.-G.; supervision, R.O.-F.; project administration, Ó.V.-G. and R.O.-F.; funding acquisition, R.O.-F. and E.J.G.-S.. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the LIFE AGROMITIGA project (LIFE17 CCM/ES/000140), financed by the financial instrument LIFE of the European Union, and by the Research and Tech- nological Innovation project PP.AVA.AVA2019.007, financed at 80% by the Andalusian Operational Program 2014–2020 of the European Regional Development Fund (ERDF).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors give thanks to the field and laboratory staff of the soil physics and chemistry team of the IFAPA Alameda del Obispo Centre for their collaboration in this study.

Conflicts of Interest: The authors declare no conflict of interest.

V-6. References

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Chapter VI

General conclusions

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1. Conservation Agriculture is a promising sustainable agricultural system, as it can effectively contribute to mitigating global warming, being able to sequester carbon in the soil, thus offsetting agricultural and non-agricultural CO_2 emissions. Conservation Agriculture is a proven and effective agricultural system that African countries need to promote to fulfil the international agreements and initiatives related to climate change mitigation and adaptation, such as the Paris agreement on climate change, the 4p1000 initiative and the Adaptation of African Agriculture.
2. Carbon sequestration rates in Africa are in agreement with those found in other meta-analyses performed in other agroclimatic regions. The accounting methodology for carbon sequestration in agricultural soils should be based on the relative gains when compared to conventional tillage-based agriculture. In addition, and with regard to African carbon sinks, areas of annual and perennial cropping systems when converted to Conservation Agriculture should be accounted for as new net carbon gains, both in the carbon markets and the international climate change agreements.
3. According to the estimation of the climate change mitigation capacity through Conservation Agriculture in Africa there exists an enormous carbon sink potential which is around 93 times greater than under the current situation, i.e. at present only around 1.1% of the overall carbon sequestration potential through Conservation Agriculture is used.
4. Conservation Agriculture fulfils the challenges of sustainability that are demanded to nowadays agriculture better than tillage-based agriculture. In productivity terms, Conservation Agriculture has improved yields in the crop rotation studied, whilst mitigating the environmental impact of agriculture.
5. Carbon dioxide emissions from agricultural soils comprise complex processes. Among them, soil tillage has a great influence on CO_2 emissions, as the deeper the soil is ploughed, the more emissions it releases. Conservation Agriculture where mechanical soil tillage is avoided is presented as a feasible alternative to mitigate climate change in Mediterranean areas. In all crops studied in the present thesis, conventional tillage increased the CO_2 emissions compared to Conservation Agriculture. Conservation Agriculture not only reduces CO_2 net emissions, but also reduces the emissions related to yield. Additionally, the presence or absence of crops also significantly influences the emission of CO_2, which is increased when a crop is set. In our study in most of the cases, there is a clear relationship between CO_2 emissions and the phenological stage of the crop.

6. Carbon dioxide emissions are closely related to the soil moisture and temperature of the area. In the Mediterranean region, annual rainfall variability is a major characteristic of the agricultural environment. This variability has a strong influence on the changes in soil moisture content and in soil microbial activity. Consequently, the CO_2 emitted into the atmosphere and the CO_2 stored within soil pores vary between cropping seasons. In this regard, carbon dioxide emissions have been found to be positively correlated to the moisture content of the soil. It must be highlighted that the results were obtained in a specific period and area.
7. To contextualise for a bigger scale, reference values are necessary to take into account the spatial and temporal variability of the agro-ecosystems. Even if the deliverables of Conservation Agriculture are promising, in terms of adoption, the Mediterranean region lags behind other regions in the world. Proper policies supporting the shift from conventional tillage to a more sustainable system are considered essential.
8. The reduction in N_2O emissions as a climate change -mitigation process is influenced by many aspects, including environmental factors, factors related to soil characteristics, and agronomic factors. It is recommended to consider the joint evaluation of three agricultural factors, such as soil, water, and fertiliser management.
9. Considering each of the factors individually, fertilisation has a significant impact on the increase in emissions, higher usually after the second top-dressing, which is applied during a period of higher temperature and the in a greater amount (65%). The type of fertiliser also affected the emissions; the highest values were measured in the plots fertilized with calcium ammonium nitrate, being reduced with the fertiliser with a nitrification inhibitor. Irrigation also had an important impact on the amount of emitted gas. The highest emissions were observed normally after irrigating the plots, regardless of the amount of applied water, or after precipitations.
10. Under the conditions of the study presented in this thesis, the joint consideration of the three factors determined that the most favourable management method for reducing N_2O emissions derived from agricultural activity in a maize crop in a Mediterranean area was managing the soil with the no-tillage system, using a fertiliser with a nitrification inhibitor, and adjusting the water application to 75% of the conventional irrigation dose.
11. The role of agriculture as a mitigating action within the climate change scenario is demonstrated by the obtained results, which show that the adoption of certain practices, such as conservation agriculture, the choice of fertiliser, and the volume of irrigation,

decreases the amount of N_2O emissions. Furthermore, the adoption of Conservation Agriculture principles, which result in fewer inputs by reducing the number of field tasks, and using less irrigation are recommended as adaptation practices for future scenarios.