Universitat de Lleida

Impacto del manejo del suelo y del sistema de riego y su gestión sobre las emisiones de gases de efecto invernadero bajo condiciones mediterráneas

Samuel Franco Luesma

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Tesis Doctoral 2020

Universitat de Lleida

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A mi familia

A mis padres y mi a hermano

“Al carro de la cultura española le falta la rueda de la ciencia.” “Lo peor no es cometer un error, sino tratar de justificarlo, en vez de aprovecharlo como aviso providencial de nuestra ligereza o ignorancia.”

Santigo Ramón y Cajal

“If you are going through hell, keep going.” “Continuous effort not strength or intelligence is the key to unlocking our potential.”

Winston S. Churchill

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Resumen

El riego y el manejo del suelo son prácticas agrícolas que pueden afectar a los procesos de producción, consumo, transporte y emisión de gases de efecto invernadero (GEI) del suelo. Por tanto, resulta necesario evaluar y documentar el impacto de estas prácticas sobre las emisiones de estos GEI. El objetivo general de esta Tesis doctoral ha sido cuantificar el efecto del sistema de manejo del suelo y el sistema de riego y su gestión sobre la producción, transporte y emisión de GEI del suelo a la atmósfera en sistemas de monocultivo de maíz bajo condiciones mediterráneas. Para alcanzar este objetivo, entre los años 2015 y 2017 se realizaron dos ensayos de campo en la finca experimental de la Estación Experimental de Aula Dei (EEAD-CSIC) ubicada en la depresión central del Valle del Ebro. En el primer ensayo experimental, se evaluó el impacto del sistema de riego (aspersión vs. inundación) en la producción y transporte de dióxido de carbono (CO_2), metano (CH_4) y óxido nitroso (N_2O) a través del perfil del suelo, así como el efecto del sistema de manejo (laboreo convencional *vs* siembra directa) del suelo junto con la gestión de los restos de cultivo (mantenerlos en la superficie vs. retirarlos), y la interacción entre ambas prácticas agrícolas sobre las emisiones de CO_2, CH_4 y N_2O del suelo. En el segundo ensayo de campo se estudió el efecto del momento (día vs. noche) y la frecuencia de riego (alta vs. baja) sobre las emisiones de CO_2, CH_4 y N_2O del suelo a la atmósfera en el sistema de riego por aspersión.

El sistema de riego por aspersión mostró una mayor concentración y emisión de CO_2 del suelo frente al sistema de riego por inundación, presentando a su vez una reducción del 50 y del 42% de la concentración y la emisión de N_2O del suelo, respectivamente. Además, el sistema de riego por aspersión redujo en un 51% las emisiones de N_2O por

unidad de rendimiento. Asimismo, la aplicación nocturna del riego por aspersión resultó en una reducción de las emisiones de CO_2 del suelo, y en un aumento de las emisiones de N_2O frente al momento de aplicación diurno. Sin embargo, no se observaron diferencias entre momentos de aplicación del riego por aspersión cuando las emisiones de N_2O se expresaron por unidad de rendimiento debido al incremento en los rendimientos bajo el momento de aplicación nocturno. En ambos sistemas de riego y a lo largo de todo el perfil del suelo, la aplicación de compuestos fertilizantes NPK incrementó la concentración de CH_4. Sin embargo, las emisiones de CH_4 del suelo a la atmósfera no se vieron afectadas ni por el sistema de riego ni por su manejo, observándose únicamente diferencias en la concentración de CH_4 en el perfil del suelo entre sistemas de riego a 0,40 m de profundidad.

Los sistemas de siembra directa redujeron en un 30% las emisiones de CO_2 del suelo a la atmosfera respecto de los sistemas de laboreo convencional, sin dar lugar a un incremento de las emisiones de N_2O. Además, pese a que todos los sistemas de manejo del suelo mostraron un consumo neto de CH_4, los sistemas de siembra directa, especialmente manteniendo los restos de cultivo, favorecieron un mayor consumo de CH_4 frente a los sistemas de laboreo convencional.

Los resultados obtenidos en esta Tesis doctoral han demostrado que el sistema de riego por aspersión, y concretamente cuando es aplicado durante la noche, junto con el sistema de siembra directa manteniendo el rastrojo en el campo son estrategias viables para la reducción de emisiones de GEI del suelo sin penalización sobre los rendimientos de cultivo bajo condiciones mediterráneas.

Abstract

Irrigation and soil management are agricultural practices that can affect the processes of production, consumption, transport and emission of greenhouse gases (GHG) in soils. Therefore, it is necessary to assess the impact of those practices on soil GHG emissions. The general aim of this PhD Thesis was to quantify the effects of the soil management system and the irrigation system and its management on the production, transport and emission of soil GHG emissions in maize (*Zea mays* L.) monoculture systems under Mediterranean conditions. To achieve this objective, two field trials were conducted in 2015-2017 in the experimental farm of the Aula Dei Experimental Station (EEAD-CSIC) located in the central depression of the Ebro River Valley. In the first experimental trial, the impact of the irrigation system (sprinkler *vs*. flood) on the production and transport of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) through the soil profile was assessed. Moreover, in the same field trial, the effect of the irrigation system (sprinkler vs. flood) and the soil management system (conventional tillage *vs*. no tillage), together with the management of the crop stover (maintaining on the surface *vs*. removing it), and the interaction between both agricultural practices on the soil CO_2, CH_4 and N_2O emissions was also investigated. In the second field trial, the effect of irrigation time (day vs. night) and irrigation frequency (high vs. low) on soil CO_2, CH_4 and N_2O emissions under sprinkler irrigation was studied.

Sprinkler irrigation showed a higher soil CO_2 concentration and emission compared with flood irrigation, presenting at the same time a reduction of 50 and 42% in soil N_2O concentration and emission, respectively. In addition, the sprinkler irrigation system reduced by 51% the N_2O emissions per unit of yield. Likewise, nighttime sprinkler

irrigation resulted in a reduction of soil CO_2 emissions, but in an increase of N_2O emissions compared with the daytime application. However, no differences were observed between sprinkler irrigation time when soil N_2O emissions were expressed per unit of yield due to the increase in grain yields under nighttime irrigation. In both irrigation systems and along the entire soil profile, the application of NPK fertilizer compounds resulted in an increase of the soil CH_4 concentration. However, soil CH_4 emissions were not affected by the irrigation system or its management, showing only differences between irrigation systems in the soil profile CH_4 concentration at 0.40 m depth.

No tillage systems reduced soil CO_2 emissions by 30% compared with conventional tillage systems without leading to an increase in soil N_2O emissions. In addition, although all soil management systems showed a net CH_4 consumption, no tillage systems, especially when the crop stover was maintained, favored a higher consumption of CH_4 compared with the conventional tillage system.

The results obtained in this PhD Thesis have shown that sprinkler irrigation with nighttime application together with no tillage maintaining the crop stover in the field are feasible strategies to reduce soil GHG emissions without penalty on crop yields under Mediterranean conditions.

Resum

El reg i el maneig del sòl són pràctiques agrícoles que poden afectar als processos de producció, consum, transport i emissió de gasos d'efecte hivernacle (GEH) del sòl. Per tant, resulta necessari avaluar i documentar l'impacte d'aquestes pràctiques sobre les emissions d'aquests GEH. L'objectiu general d'aquesta Tesi doctoral ha sigut el de quantificar l'efecte del sistema de maneig del sòl i el sistema de reg i la seva gestió sobre la producció, transport i emissió de GEH del sòl a l'atmosfera en sistemes de monocultiu de panís sota condicions mediterrànies. Per assolir aquest objectiu, entre els anys 2015 i 2017 es van realitzar dos assajos de campo a la finca experimental de la Estación Experimental de Aula Dei (EEAD-CSIC) ubicada a la depressió central de la vall del riu Ebre. Al primer assaig experimental, es va avaluar l'impacte del sistema de reg (aspersió vs. inundació) sobre la producció i transport de diòxid de carboni (CO_2), metà (CH_4) i òxid nitrós (N_2O) a través del perfil del sòl, així com l'efecte del sistema de reg (aspersió vs. inundació) i del sistema de maneig del sòl (conreu convencional vs. sembra directa) del sòl juntament amb la gestió de les restes de collita (mantingudes en superfície vs. retirades) i la interacció entre ambdues pràctiques agrícoles sobre les emissions de CO_2, CH_4 i N_2O del sòl a l'atmosfera. Al segon assaig de camp es va estudiar l'efecte del moment del reg (dia vs. nit) i de la freqüència de reg (alta vs. baixa) sobre les emissions de CO_2, CH_4 i N_2O del sòl a l'atmosfera en un sistema de reg per aspersió.

El sistema de reg per aspersió va mostrar una major concentració i emissió de CO_2 del sòl enfront al sistema de reg per inundació, presentant a la vegada una reducció del 50 i del 42% de la concentració i la emissió de N_2O del sòl, respectivament. A més, el sistema de reg per aspersió va reduir en un 51% les emissions de N_2O per unitat de rendiment.

Així mateix, la aplicació nocturna de reg per aspersió va donar a lloc a una reducció de les emissions de CO_2 del sòl, i a un augment de les emissions de N_2O enfront a l'aplicació diürna. No obstant, no es van observar diferències entre moments d'aplicació del reg per aspersió quan les emissions de N_2O es van expressar per unitat de rendiment degut a l'increment dels rendiments sota el moment d'aplicació nocturn. En ambdós sistemes de reg i al llarg de tot el perfil del sòl, la aplicació de compostos fertilitzants NPK va incrementar la concentració de CH_4. No obstant, les emissions de CH_4 del sòl a l'atmosfera no es van veure afectades pel sistema de reg ni el seu maneig, observant-se únicament diferències de CH_4 al perfil del sòl entre sistemes de reg a 0,40 m de profunditat.

Els sistemes de sembra directa van reduir en un 30% les emissions de CO_2 del sòl a la atmosfera respecte als sistemes de conreu convencional, sense donar a lloc un increment de les emissions de N_2O. A més, tot i que tots els sistemes de maneig del sòl van mostrar un consum net de CH_4, els sistemes de sembra directa, especialment mantenint les restes de collita, van afavorir un major consum de CH_4 enfront als sistemes de conreu convencional.

Els resultats d'aquesta Tesi doctoral han demostrat que els sistema de reg per aspersió, i concretament aplicat durant la nit, juntament amb el sistema de sembra directa mantenint el rostoll al camp són estratègies viables per a la reducció de les emissions de gasos d'efecte hivernacle del sòl sense penalització sobre els rendiments de cultiu sota condicions mediterrànies.

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2015	2015 maize growing season
2016	2016 maize growing season
2017	2017 maize growing season
15-16 fallow	Fallow period 2015-2016
16-17 fallow	Fallow period 2016-2017
ANOVA	Analysis of variance
C	Carbono / carbon
$CaCO_3$	Calcium carbonate
CH_4	Metano / methane
CIR	Crop irrigation requirement
CO_2	Dióxido de carbono / carbon dioxide
CO_3^{2-}	Ión carbonato / carbonate ion
COS	Carbono orgánico del suelo
CT	Conventional tillage
DH	Daytime high frequency
DL	Daytime low frequency
D_0	Gas diffusion coefficient in free air
D_s	Soil gas diffusion coefficient
D_S/D_0	Relative gas diffusivity
ECD	Electron capture detector
ETc	Crop evapotranspiration
ETo	Grass reference crop evapotranspiration
F	Flood irrigation
FC	Field capacity
Fe^{3+}	Iron ion
FID	Flame ionization detector
FP1	Fallow period 2016-2017
FP2	Fallow period 2017-2018
GHG	Greenhouse gas
GM	Gradient method
GMT	Greenwich Mean Time
GS1	2016 maize growing season
GS2	2017 maize growing season

Mn^{4+}	Manganese ion
N	Nitrógeno / Nitrogen
NH	Nighttime high frequency
NL	Nighttime low frequency
N_2O	Óxido nitroso / nitrous oxide
NH_4^+	Ión amonio / ammonium ion
NO_2^-	Ión nitrito / nitrite ion
NO_3^-	Ión nitrato / nitrate ion
NS / ns	non-significant
NT	No-tillage removing the maize stover
NTr	No-tillage maintaining the maize stover
O_2	Oxigene
P	Precipitation
q	Gas flux
R3	Milk growth stage
S	Sprinkler irrigation
SO_4^{2-}	Ion sulfate
SOC	Soil organic carbon
STP	Standard temperature and pressure conditions
T	Air temeperature
VT	Tasselling growth stage
WDEL	Wind drift and evaporation losses
WP	Wilting point
WFPS	Water-filled pore space;
Z	Soil depth
ε	Air-filled pore space
Φ	Total soil porosity

Introducción general

Introducción general.

En la actualidad, el uso del suelo para la producción de bienes y servicios para el ser humano es una de las principales fuentes de emisión de gases de efecto invernadero (GEI), en particular dióxido de carbono (CO_2), metano (CH_4) y óxido nitroso (N_2O). Se estima que un 23% del total de las emisiones de GEI de origen antropogénico derivan del sector AFOLU (por sus siglas en inglés), a saber, agricultura, silvicultura y otros usos de la tierra (Shukla *et al*., 2019). En España, un 12% del total de las emisiones de GEI se estima que provienen del sector agrario, siendo los suelos agrícolas una de las principales fuentes de emisión (MITECO, 2019).

La producción de CO_2 en el suelo es el resultado de procesos bióticos (i.e. oxidación de la materia orgánica del suelo y respiración de las raices) y abióticos (i.e. disolución de formas inorgánicas de carbono (C) como los carbonatos (CO_3^{2-})) que tienen lugar en el suelo. Por tanto, los suelos agrícolas son una de las principales fuentes de emisión de CO_2 (Follett, 2001; Ramnarine *et al*., 2012; Rey, 2015). El CH_4 es el segundo GEI en importancia tras el CO_2, presentando un potencial de calentamiento global 25 veces superior al CO_2 (Forster *et al*., 2007). En los suelos agrícolas, el CH_4 puede producirse (metanogénesis) o consumirse (metanotrofia) por los microrganismos del suelo en función de la disponibilidad de O_2 y del potencial de óxido-reducción del suelo (Eh), pudiendo tener lugar ambos procesos simultáneamente (Peters y Conrad, 1996; Wang *et al*., 1993; Hütsch, 2001; Le Mer y Roger, 2001). El N_2O es el GEI proveniente de los suelos agrícolas que presenta un mayor potencial de calentamiento global, 298 veces superior al CO_2 (Forster *et al*., 2007). La producción de N_2O en el suelo es el resultado de la descomposición de las formas reactivas de nitrógeno presentes en el suelo (i.e. amonio (NH_4^+) y nitrato (NO_3^-)) a través de los procesos biológicos de nitrificación, desnitrifación nitrificante y desnitrificación, dependiendo la predominancia de cada uno de ellos en función de las condiciones de aireación y humedad del suelo (Firestone y Davidson, 1989; Bremner, 1997; Wrage *et al*., 2001).

La producción de estos GEI en el perfil del suelo está regulada por diversos factores como la disponibilidad de C orgánico, nitrógeno (N), la temperatura del suelo y el contenido de humedad del mismo (Linn y Doran, 1984; Lloyd y Taylor, 1994; Davidson y Janssens, 2006, Butterbach-Bahl *et al*., 2013), que a su vez pueden verse afectados por diferentes prácticas agrícolas (Smith *et al*., 2008).

De este modo, es de gran interés comprender cómo estos GEI se producen en el perfil del suelo y son posteriormente emitidos a la atmosfera y entender cómo las diversas prácticas agrícolas pueden afectar a estos procesos de producción y transporte. Hasta la fecha, diversos trabajos se han realizado bajo condiciones de campo para estudiar los factores que gobiernan la producción y transporte de GEI a través del perfil del suelo (e.g., Kusa *et al*., 2008; Wolf *et al*., 2011; Wang *et al*., 2013, 2018). Sin embargo, existe muy poca información sobre cómo diferentes prácticas agrícolas afectan a la producción y transporte de estos gases, centrándose principalmente en el efecto de la fertilización nitrogenada (Nan *et al*., 2016).

Prácticas agrícolas como el riego y el manejo del suelo juegan un papel fundamental en la producción y emisiones de GEI del suelo a la atmosfera, siendo a su vez prácticas agrícolas que pueden ayudar en la mitigación de estas emisiones procedentes de los suelos agrícolas (Sanz-Cobeña *et al*., 2017).

El riego, dada su capacidad para modificar el contenido de humedad del suelo, tiene un efecto directo sobre los ciclos del C y N del suelo. El riego de los cultivos tiende a incrementar el contenido de carbono orgánico del suelo (COS) debido a los mayores rendimientos de cultivo y, por tanto, a la mayor cantidad de biomasa de restos de cosecha que retorna al suelo (Trost *et al*., 2013). Además, los continuos ciclos de humectacióndesecación producidos por los eventos de riego pueden tener un efecto sobre las propiedades físicas del suelo tales como la estabilidad de los agregados y la densidad aparente del suelo, afectando de este modo a la estructura y, por tanto, a la aireación del suelo (Rajaram y Erbach, 1999; Smith *et al*., 2003; Ball, 2013).

La mayor productividad de los sistemas de regadío, en comparación con los sistemas de cultivo bajo condiciones de secano, está dando lugar a un aumento de la superficie regada (Matson *et at*., 1997). En particular, bajo condiciones mediterráneas, donde el agua es factor limitante para el desarrollo de los cultivos debido a las bajas y erráticas precipitaciones, el riego es fundamental para la mayoría de los cultivos de verano, como el maíz (*Zea mays* L.).

De los diferentes sistemas de riego existentes, el sistema de riego por aspersión (riego presurizado) y el sistema de riego por inundación (riego por gravedad) son los más extendidos en España para cultivos extensivos como el maíz. Bajo condiciones climáticas mediterráneas, Aguilera *et al*. (2013b) y Cayuela *et al*. (2017) señalaron la correcta elección del sistema de riego como estrategia de mitigación de GEI, especialmente para la reducción de las emisiones de N_2O del suelo. Ambos meta-análisis coinciden en que sistemas con una mayor eficiencia de riego, como los sistemas de riego localizados, y la reducción de las dosis de riego dan lugar a una reducción de las emisiones de N_2O del suelo. Si bien, ninguno de estos dos meta-análisis consideró el sistema de riego por inundación como sistema de riego para cultivos extensivos como el maíz, pese a ser el sistema de riego mayoritario en muchas zonas. Otros autores como Deng *et al*. (2018) bajo condiciones mediterráneas (California) y Yang *et al*. (2019) en condiciones semiáridas (Mongolia, China), compararon el impacto de estos dos sistemas de riego sobre las emisiones de N_2O del suelo, mostrando una reducción de las emisiones bajo el sistema de riego por aspersión. Estos autores coinciden con los resultados de Aguilera *et* *al.* (2013b) y Cayuela *et al.* (2017) en que los sistemas de riego con mayor eficiencia y menores dotaciones de agua resultan en una disminución de las emisiones de N_2O del suelo.

En la actualidad, los sistemas de riego por aspersión están aumentando frente a los sistemas de riego por inundación debido a los mayores rendimientos de cultivo y a la posibilidad de automatización, junto con la reducción de las pérdidas por escorrentía y drenaje debido a las menores dosis de agua aplicada en el riego por aspersión (Rawlins y Raats, 1975; Playán y Mateos, 2006; Lecina *et al.*, 2010). Dentro de los sistemas de riego por aspersión, los sistemas de aspersión en cobertura total fija permiten una mayor flexibilidad a la hora de elegir el momento de la aplicación (día *vs* noche) y la frecuencia de riego. Este tipo de sistemas de riego por aspersión suelen presentar una programación de riegos basada en intervalos de riego que oscilan entre uno a cinco días por semana, siendo las 08:00 y las 20:00h GMT (Greenwich Mean Time) las horas de inicio del riego más frecuentes (Salvador *et al.*, 2011a). Tanto la frecuencia como el momento de aplicación del riego por aspersión pueden afectar al rendimiento de diversos cultivos de verano como el maíz y la alfalfa (*Medicago sativa* L.) bajo condiciones mediterráneas (Cavero *et al.*, 2008, 2009, 2016, 2018; Urrego-Pereira *et al.*, 2013a, 2013b). Sin embargo, no se ha estudiado el impacto de estos factores del manejo del riego por aspersión sobre las dinámicas del C y N del suelo y, en concreto, sobre la emisión de GEI del suelo a la atmosfera.

El sistema de manejo del suelo puede tener un impacto sobre los ciclos del C yN del suelo, alterando la evolución del COS e impactando sobre las propiedades físicas del mismo (West y Post, 2002; Ball, 2013). En los agroecosistemas mediterráneos, y concretamente en el caso de España, los sistemas de laboreo tradicional y laboreo mínimo representan un 58% del total de la superficie agrícola frente a los sistemas de siembra directa que sólo representan el 11% de la superficie total (MAPAMA, 2018b). Sin embargo, los sistemas de siembra directa tienen una importante presencia en condiciones de secano, llegando a representar el 9,4% de la superficie total agrícola, frente al 1,6% de la superficie total agrícola que supone está práctica de manejo del suelo bajo condiciones de regadio (MAPAMA, 2018b). Esta mayor implantación de los sistemas de siembra directa bajo condiciones de secano se debe, principalmente, a la reducción de costes asociados y al menor número de horas de maquinaria necesarias, junto con el aumento de la disponibilidad de agua en el suelo y el aumento de los rendimientos de cultivo (Cantero-Martínez *et al*., 2003). Sin embargo, la mayor humedad del suelo junto con la mayor cantidad de restos de cultivo dificulta un uso más extensivo de la siembra directa en condiciones de regadío.

Los sistemas de siembra directa, frente a los sistemas de laboreo del suelo, favorecen el aumento del contenido del COS debido a la menor perturbación del suelo y a una mayor protección física de este C en los agregados del suelo, dando lugar al desarrollo de una mejor estructura del suelo (Paustian *et al*., 1997; Álvaro-Fuentes *et al*., 2008; Follett *et al*., 2013; Plaza-Bonilla *et al*., 2014). Del mismo modo, el mantenimiento de los restos de cosecha en la superficie del suelo reduce las pérdidas de agua del suelo por evaporación directa, frente a su retirada que implica un menor aporte de materia orgánica y, por tanto, una reducción del COS, lo que puede generar una degradación de las propiedades físicas del suelo (Sauer *et al*., 1998; Blanco-Canqui and Lal, 2008).

Diversos estudios llevados a cabo en condiciones de secano (Plaza-Bonilla *et al*., 2014, 2018) y regadío (Pareja-Sánchez *et al*., 2017, 2019, 2020) en zonas mediterráneas, han observado que los sistemas de siembra directa son una estrategia efectiva para reducir las emisiones de GEI a la atmosfera, mejorando o manteniendo los rendimientos de cultivo frente a los sistemas de laboreo convencional. No obstante, la mayoría de los trabajos y, en concreto, aquellos bajo condiciones de regadío, no evaluaron la interacción del sistema de manejo del suelo con el sistema de riego.

Tanto el sistema de riego como el sistema de manejo del suelo son prácticas agrícolas que afectan o modifican parámetros claves para los procesos de producción, consumo, transporte y emisión del CO_2, CH_4 y N_2O a través del perfil del suelo. Pese a ello, existe poca o escasa información sobre el efecto del uso de diferentes sistemas de riego y su manejo, así como la interacción de este con el sistema de laboreo del suelo, sobre la producción y emisión de GEI del suelo a la atmosfera. Por todo ello, es necesario evaluar y documentar el impacto del sistema de manejo del suelo y del sistema de riego y su manejo, así como el de la interacción entre ambas práticas, sobre las emisiones de GEI, con el fin de establecer estrategias de mitigación eficaces que no repercutan negativamente sobre los rendimientos de los cultivos en los agroecosistemas mediterráneos.

Objetivos.

El objetivo general de esta Tesis doctoral es cuantificar el efecto del sistema de manejo del suelo y del sistema de riego, y su manejo, sobre la producción, transporte y emisión de GEI del suelo a la atmósfera en sistemas de monocultivo de maíz bajo condiciones mediterráneas.

Para alcanzar este objetivo general, se plantean tres objetivos específicos:

I. Evaluar el impacto del sistema de riego (riego por aspersión *vs* riego por inundación) en la producción y transporte de CO_2, CH_4 y N_2O a través del perfil del suelo.
II. Cuantificar el efecto del sistema de riego (riego por aspersión *vs* riego por inundación) y del sistema de manejo del suelo (laboreo convencional *vs* siembra directa) junto con la gestión de los restos de cultivo (mantenimiento *vs* retirada de la superfice del suelo), sobre las emisiones de CO_2, CH_4 y N_2O del suelo.
III. Determinar el impacto del momento (día *vs* noche) y la frecuencia del riego (alta *vs* baja) sobre las emisiones de CO_2, CH_4 y N_2O del suelo en el sistema de riego por aspersión.

Esta Tesis doctoral se estructura en cuatro capítulos que pretenden responder a los objetivos planteados. A continuación, se describe brevemente cada uno de los capítulos:

Capítulo 1. The impact of irrigation system on the production and transport of carbon dioxide, methane and nitrous oxide in the soil profile in a maize monoculture

Este capítulo se centra en evaluar el impacto de dos sistemas de riego diferenciados (riego por aspersión *vs* riego por inundación) en la producción de CO_2, CH_4 y N_2O a diferentes profundidades del suelo (0.10, 0.20 y 0.40 m), así como en el transporte de estos gases a lo largo del perfil del suelo y su posterior emisión a la atmósfera.

Los contenidos de este capítulo se corresponden con los del artículo:

Franco-Luesma S., Plaza-Bonilla D., Cavero J., Cantero-Martínez C., Arrúe J.L., Maier M., Laemmel T., Álvaro-Fuentes J. The impact of irrigation system on the production and transport of carbon dioxide, methane and nitrous oxide in the soil profile in a maize monoculture. Geoderma. En revisión.

Capítulo 2. Tillage and irrigation system effects on soil carbon dioxide (CO_2) and methane (CH_4) emissions in a maize monoculture under Mediterranean conditions.

En este capítulo se evalúa el efecto del sistema de riego (riego por aspersión *vs* riego por inundación) y del manejo del suelo (laboreo convencional; siembra directa manteniendo el rastrojo; siembra directa retirando el rastrojo) y su interacción sobre las emisiones de CO_2, y CH_4 del suelo a la atmósfera.

Los contenidos de este capítulo se corresponden con los del artículo:

Franco-Luesma, S., Cavero, J., Plaza-Bonilla, D., Cantero-Martínez, C., Arrúe, J.L., Álvaro-Fuentes, J., 2020. Tillage and irrigation system effects on soil carbon dioxide (CO_2) and methane (CH_4) emissions in a maize monoculture under Mediterranean conditions. Soil and Tillage Research 196, 104488.

Capítulo 3. Irrigation and tillage effects on soil nitrous oxide emissions in maize monoculture.

En este capítulo se cuantifican las emisiones de N_2O, así como las emisiones de N_2O por unidad de rendimiento bajo dos sistemas de riego (riego por aspersión *vs* riego por inundación) y tres manejos de suelo diferenciados (laboreo convencional; siembra directa manteniendo el rastrojo; siembra directa retirando el rastrojo).

Los contenidos de este capítulo se corresponden con los del artículo:

Franco-Luesma, S., Cavero, J., Plaza-Bonilla, D., Cantero-Martínez, C., Tortosa, G., Bedmar, E.J., Álvaro-Fuentes, J., 2020. Irrigation and tillage effects on soil nitrous oxide emissions in maize monoculture. Agronomy Journal 112, 56-71.

Capítulo 4. Influence of irrigation time and frequency on greenhouse gas emissions in a solid-set sprinkler-irrigated maize under Mediterranean conditions.

En este capítulo se estudia el efecto del momento (día *vs* noche) y la frecuencia del riego (riego diario *vs* 2 riegos por semana) en un sistema de riego por aspersión sobre las emisiones de CO_2, CH_4 y N_2O del suelo a la atmósfera, así como sobre las emisiones de N_2O por unidad de rendimiento.

Los contenidos de este capítulo se corresponden con los del artículo:

Franco-Luesma, S., Álvaro-Fuentes, J., Plaza-Bonilla, D., Arrúe, J.L., Cantero-Martínez, C., Cavero, J., 2019. Influence of irrigation time and frequency on greenhouse gas emissions in a solid-set sprinkler-irrigated maize under Mediterranean conditions. Agricultural Water Management 221, 303-311.

Capítulo 1

The impact of irrigation system on the production and transport of carbon dioxide, methane and nitrous oxide in the soil profile in a maize monoculture.

Submitted to*: Geoderma*

The impact of irrigation system on the production and transport of carbon dioxide, methane and nitrous oxide in the soil profile in a maize monoculture.

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Abstract

Irrigation systems, due to their capacity to modify soil water content are very important to improve food security and production in many regions of the word, also playing an important role in the production and transport of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) in the soil profile. A field experiment was established to evaluate the impact of two different irrigation systems, flood irrigation (F) and sprinkler irrigation (S), on the production and transport of CO_2, CH_4 and N_2O at three different soil depths (0.10, 0.20 and 0.40 m) in a two-year maize (*Zea mays* L.) monoculture. Soil CO_2 concentration showed an increase with soil depth, reporting higher concentration values under S irrigation. Soil CH_4 concentration was similar to the atmospheric value expect under S irrigation at 0.40 m depth where concentration values remained below the atmospheric values for most of the experimental time due to a short-term methane uptake. Moreover, soil CH_4 concentrations at all soil depths showed a significant increase associated with pre-sowing NPK fertilizer application in both irrigation systems. In both maize growing seasons, S irrigation showed soil N_2O concentration values four to ten times lower than F irrigation due to the lower soil WFPS values found in S irrigation, especially during the top dressing application of N fertilizer. In general, when soil gas fluxes estimated by the gradient method (GM) were compared with the soil fluxes measured by the closed chamber technique, soil CO_2 fluxes presented high correlation. In contrast, soil CH_4 and N_2O fluxes showed poor or no significant correlation. This could be explained by the incapacity of diffusivity models to consider soil cracks that were observed in the field under dry conditions, as well as, soil saturation conditions in which soil gas diffusivity models also may fail. The results of this work highlight the capability of sprinkler irrigation systems to reduce soil N_2O concentration compared with flood irrigation systems.

Keywords

Soil CO_2 concentration; soil CH_4 concentration; soil N_2O concentration; soil gas fluxes; sprinkler irrigation; flood irrigation; maize monoculture; gradient method; soil diffusivity

1. Introduction

Agricultural practices, such as irrigation, are very important to improve security, quality and quantity in world food production in many regions (Bruinsma, 2017). They also play a key role in the soil greenhouse gas (GHG) exchange (Smith *et al.*, 2008). Irrigation acreage is increasing due to the higher crop yields in irrigated farming compared with rainfed farming system (Matson *et at.*, 1997). In particular, under Mediterranean climate conditions, the low and erratic precipitation characterizing this type of climate makes irrigation necessary for most summer crops like maize.

Irrigation might favour carbon storage in soils due to higher crop yields and, consequently, a higher amount of crop residues returned to the soil. However, at the same time, irrigation together with N inputs can increase soil N_2O emissions because of higher soil moisture contents. Moreover, irrigation may affect CH_4 emissions depending on the water regime (Lal, 2004; Liebig *et al.*, 2005; Zou *et al.*, 2005). Likewise, wetting–drying cycles can have an impact on soil physical properties such as aggregate stability and soil bulk density, thus affecting soil structure and soil aeration (Rajaram and Erbach, 1999; Smith *et al.*, 2003; Ball, 2013).

Soil CO_2 production is a consequence of root respiration and microbial decomposition of organic matter and is strongly affectedby soil temperature and water content (Linn and Doran, 1984; Lloyd and Taylor, 1994; Davidson and Janssens, 2006). CH_4 can be produced (methanogenesis) and consumed (methanotrophy) by soil microorganisms, being both processes driven by soil O_2 availability and soil oxidation-reduction potentials (Eh) which may occur simultaneously. Methanogenesis requires strict anaerobiosis and low Eh values, while methanotrophy needs the presence of O_2 and high Eh values (Hütsch, 2001; Le Mer and Roger, 2001). Similarly, soil microbial communities control soil N_2O production through different processes such as nitrification, denitrification and nitrifier denitrification (Bremner, 1997; Firestone and Davidson, 1989). These processes are mainly affected by soil water-filled pore space (WFPS) and soil temperature and by the availability of soil nitrate, soil ammonium and soil organic carbon (Bateman and Baggs, 2005; Davidson *et al*., 2000; Bouwman *et al*., 2002; Butterbach-Bahl *et al*., 2013).

Soil gas transport is mainly controlled by molecular diffusion in the air filled pores space of the soil. The relative soil gas diffusion coefficient or soil gas diffusivity (D_S/D_0) is related to the air-filled porosity of the soil, which depends on the total porosity and the soil water content. Then, irrigation affects directly (D_S/D_0) and soil gas transport processes (Maier and Schack-Kirchner, 2014). Many different diffusivity models have been developed to derive (D_S/D_0) from basic soil physical parameters such as total porosity and air- filled pore space e.g. Penman (1940) and Millington and Quirk (1961). Yet they have developed for more or less homogenous soils. Other soil physical aspects like the presence of macro-features like large soil cracks can have a significant impact on the estimation of soil gas diffusivity (Weisbrod *et al*., 2009), and are usually not included by soil gas diffusivty models.

Several studies have been carried out to investigate *in situ* the factors controlling GHG production and transport in the soil profile (e.g., Kusa *et al*., 2008; Wolf *et al.*, 2011; Wang *et al*., 2013, 2018; Nan *et al*., 2016). Most studies agreed that soil moisture is a key factor in the production and transport processes. However, there is no information about how different irrigation systems affect soil GHG production and transport processes. The aim of this study was to assess the impact of two irrigation system (sprinkler irrigation *vs* flood irrigation) on soil GHG production and transport through the soil profile in a maize monoculture system. We hypothesized that different irrigation systems would result in different soil water contents, especially during the growing season, which would affect the production and transport of CO_2, CH_4 and N_2O in the soil.

2. Material and Methods

2.1 Site description and experimental design

The field experiment was conducted at the irrigated farm of the Aula Dei Experimental Station, Zaragoza, Spain (41º 42´ N, 0º 49´ W, 225 m altitude), during two maize growing seasons and two fallow periods (June 2016 – March 2018). The area is characterized by a Mediterranean semiarid climate with an annual mean air temperature of 14.1 ºC, an annual precipitation of 298 mm and a grass reference crop evapotranspiration (ETo) of 1243 mm. The soil is classified as Typic Xerofluvent (Soil Survey Staff, 2015). Texture is silty loam (21% sand, 63% silt and 16% clay) with a mean pH value of 8.04 in the upper 0.00–0.50 m soil layer (Table 1.1).

Table 1.1. Soil characteristics of the experimental field.

Depth (m)	pH	SOC† (%)	$CaCO_3$ (%)	Sand (%)	Silt (%)	Clay (%)	FC‡ (m^3 m^{-3})	WP§ (m^3 m^{-3})
0.00−0.05	7.98	1.93	34.9	15.8	61.9	22.3	0.26	0.14
0.05−0.10	8.20	1.85	34.9	15.4	62.9	21.7	0.26	0.14
0.10−0.25	8.03	1.75	35.1	15.9	62.1	22.0	0.25	0.16
0.25−0.50	7.95	1.51	35.3	16.0	63.6	20.4	0.25	0.16

† SOC, Soil organic carbon. ‡ FC, Field capacity (–0.033 MPa). § WP, Wilting point (–1.5 MPa).

In 2016, two plots (6 x 18 m) were established under no-tillage to study the effect of flood irrigation (F) and sprinkler irrigation (S), on the production and transport of CO_2, CH_4 and N_2O in the soil. These plots were part of an experiment where the effect of irrigation systems and tillage were studied (Franco-Luesma *et al*., 2020). In each plot, three passive soil gas samplers were installed. Before the experiment, plots were under bare fallow and conventional tillage, which consisted in one pass of a subsoiler to 0.30 m depth followed by one pass of a disk harrow in winter.

No-tillage management consisted of an application of glyphosate (36% at 5L ha^{-1}) to control weeds before planting. For both irrigation systems, maize cv. Pioneer P1785 was planted in rows 0.75 m apart at a planting density of 89,500 plants ha^{-1} on 12 April 2016 and 17 April 2017. Fertilization was the same in all treatments and consisted of two different applications per growing season. The first application was 800 kg ha^{-1} of NPK 8-15-15 (8% (ammonium N (N-NH_4^+))-15%-15%) compound fertilizer before planting, on 12 April 2016 and 17 April 2017, respectively. The second N fertilizer application was a top dressing application of 740 kg ha^{-1} of calcium ammonium nitrate 27% N (13.5% ammonium N (N-NH_4) – 13.5% nitrate N (N-NO_3)) at V6-V8 maize growth stage on 13 June 2016 and 7 June 2017, respectively. Harvest was done with a commercial combine on 5 October 2016 and 17 October 2017, respectively. Afterwards, the stover was chopped and removed manually.

Irrigation was applied according to the crop irrigation requirements (CIR), which were determined weekly by subtracting the effective precipitation (75% of total weekly precipitation) from maize crop evapotranspiration (ETc) (Dastane, 1978). ETc was calculated by the daily reference evapotranspiration (ETo), obtained using the FAO Penman-Monteith method (Allen *et al*., 1998) and meteorological data from a weather station located 1 km away from the field experiment, multiplied by the crop coefficient (Kc) for maize, calculated as a function of thermal time (Allen *et al*., 1998; Martínez-Cob *et al*., 2008). Under the S system, two irrigation events per week were performed (i.e. on Monday and Wednesday), while under the F system irrigation occurred every 10-14 days. In order to favour plant emergence, irrigation water was applied by sprinkler irrigation to all the plots until V6 growth stage.

2.2 Gas measurements

Soil surface CO_2, CH_4 and N_2O emissions were measured from June 2016 to March 2018 using the closed chamber technique (Hutchinson and Moiser, 1981). Six polyvinyl chloride (PVC) rings (31.5 cm internal diameter) per plot were inserted 10 cm into the soil on April 2015 and were only removed at tillage, sowing and harvesting operations. To compute soil gas fluxes, 20 mL of gas were collected at 0, 20 and 40 min after chamber closure and transferred to an evacuated 12-mL Exetainer ® borosilicate glass vial (model 038W, Labco, High Wycombe, UK). The concentration of each gas at 0 min was used as the concentration at the soil surface (0.00 m depth). At every sampling date, a total of 18 gas samples were collected from each irrigation system (6 observations per treatment x 3 sampling times per chamber).

At the same sampling dates, soil profile CO_2, CH_4 and N_2O concentrations were measured by using a passive soil gas sampler based on the design proposed by Kammann *et al* (2001). Each passive gas sampler consisted of a silicone tube 15 cm long and 3 cm internal diameter (yielding an inner volume of 106 cm^3) sealed with silicone septa at both ends. The silicone tube was encapsulated in a pre-drilled aluminium tube to protect it to any mechanical processes that could affect the sampler volume. At one end, a stainless steel tube was inserted to connect the sampler with the soil surface. The end of the steel tube was closed with a three-way stopcock, from which 10 mL air samples were taken and transferred to evacuated 4.5-mL Exetainer ® borosilicate glass vial (model 048W, Labco, High Wycombe, UK). Soil surface temperature (at 0.05 m depth) and soil surface water content (0.00-0.05 m) were measured using a TM 65 probe (Crison, Carpi, Italy) and a GS3 probe (Decagon Devices, Pullman, WA), respectively.

Passive soil gas samplers were installed in May 2016 and the first sampling was carried out 45 days after, in June 2016, to avoid any perturbation associated with the installation of the samplers. To install the passive soil gas samplers, six trenches (0.50 x 0.50 x 0.50 m) were dug, three per irrigation treatment. Then, a soil core 30 cm length and 5 cm external diameter, similar to the passive soil gas samplers' external diameter, was extracted from one of the lateral walls of the trench to insert the sampler and the remnant hole was filled with soil from the soil core. Samplers were installed at three soil depths: 0.10, 0.20 and 0.40 m. Soil moisture and temperature were monitored using 5TM probes (Decagon Devices, Pullman, WA) connected to data loggers installed close to each soil gas sampler. At each sampling date, a total of 9 gas samples were collected from each irrigation system (3 observations per treatment x 3 sampling depths).

Soil gas sampling frequency was weekly from planting (April) until maize milk stage (R3) (mid-August), every two weeks from mid-August until harvest (late September) and every three weeks during the fallow period (November-March). Moreover, soil gas sampling frequency increased during fertilization events. During these events, soil gas samples were taken 24 h before and 24, 48, 72, 96, 144 and 192 h after fertilization. Furthermore, under F irrigation, soil gas sampling frequency was increased within the five days after each irrigation event.

The concentrations of CO_2, CH_4 and N_2O in the air gas samples were measured with a gas chromatograph system (Agilent 7890B, Agilent, Santa Clara, CA, United States) equipped with a flame ionization detector (FID) coupled to a methanizer and with an electron capture detector (ECD). Further details of the analysis method are described in Franco-Luesma *et al*. (2019).

2.3 Soil gas flux calculation

Soil gas flux (i.e. chamber flux) of each gas was calculated by the linear increase of the gas mass concentration inside the chamber during the enclosure time and corrected by the air temperature in the chamber.

Soil gas flux through each soil layer was calculated by the gradient method (i.e. GM flux) using Fick's first law (Eq. 1), where q is the gas flux (mol m^{-2} s^{-1}), D_s is the soil gas diffusion coefficient (m^2 s^{-1}), C is the gas concentration (mol m^{-3}) and z is the soil depth (m).

$$q = -D_s \frac{\partial C}{\partial z} \tag{1}$$

The soil gas diffusion coefficient (D_s) can be measured *in situ* or can be estimated by a mathematical expression. In this work, soil diffusion coefficient for each gas was estimated by using a mathematical expression (Eq. 2), where D_0 is the gas diffusion coefficient in free air for each gas species and DS/D0 is the relative gas diffusivity.

$$D_s = D_0 \; x DS/D0 \tag{2}$$

The gas diffusion coefficient of a gas species in free air (D_0) may be represented as a function of pressure and temperature near to the standard temperature and pressure conditions (STP conditions: temperature 273.15 K; pressure 1 bar) (Eq. 3):

$$D_{0i}(p,T) = D_{0i}^{SPT} \left(\frac{p_{STP}}{p}\right) \left(\frac{T}{T_{STP}}\right)^{\alpha} \tag{3}$$

where D_{0i}^{STP} is the gas diffusion coefficient in free air at STP conditions, p and T are the pressure and temperature of the specific experiment conditions and α is a gas specific exponent between1.5 and 2.

Moreover, considering soil as an isobaric system, Eq. 3 can be simplified resulting in the following expression (Eq. 4), where D_{0i}^{STP} depends only on temperature fluctuations.

$$D_{0i}(1,T)= D_{0i}^{STP} \left(\frac{T}{T_{STP}}\right)^{\alpha} \tag{4}$$

In this study, D_0^{STP} values of $1.381 \cdot 10^{-5}$, $1.952 \cdot 10^{-5}$ and $1.436 \cdot 10^{-5}$ $m^2 s^{-1}$ for CO_2, CH_4 and N_2O were used, respectively, and a constant α value of 1.81 as recommended in Massman (1998).

The relative gas diffusivity coefficient (D) was calculated by a mathematical approach, using the diffusivity model proposed by Moldrup *et al.* (1996) (Eq. 5).

$$D= \phi^{4/3} \left(\frac{\varepsilon}{\phi}\right)^{1.5+3/b} \tag{5}$$

This diffusivity model is a function of total soil porosity (ϕ), air-filled pore space (ε) and an empirical constant predicted from soil texture (b) proposed by Saxton *et al.* (1986). Total soil porosity was calculated from the soil bulk density considering a soil particle density of 2.65 Mg m^{-3}. Air-filled pore space was estimated by subtracting the soil volumetric water content from the total porosity.

Soil gas fluxes between soil depths were estimated by the discrete difference in the soil gas concentration between soil layers as describe by De Jong and Schappert (1972) by using Eq. 6.

$$q_{z_n\text{-}z_{n-1}} = -D_{s_{z_n\text{-}z_{n-1}}} \frac{C_{z_n}\text{-}C_{z_{n-1}}}{z_n\text{-}z_{n-1}} \tag{6}$$

where $D_{s_{z_n - z_{n-1}}}$ is the average value of the soil diffusion coefficient of the two considered soil depths (i.e. z_n and z_{n-1}) , C_{z_n} and $C_{z_{n-1}}$ are the gas concentration in each of the soil depths and z_n and z_{n-1} are the depths from the soil surface.

Soil gas fluxes between 0.00–0.20 and 0.00–0.40 m soil layers were calculated by adding the partial soil gas fluxes of the different soil layers, 0.00–0.10, 0.10–0.20 and 0.20–0.40 m, obtained in Eq.6. Thus, the soil gas flux between 0.00–0.20 m was the result of adding the soil gas fluxes between 0.00–0.10 and 0.10–0.20 m soil layers. Similarly, soil gas flux between 0.00–0.40 m was obtained by adding the soil gas fluxes between 0.00–0.10, 0.10–0.20 and 0.20–0.40 m soil layers.

2.4 Soil measurements

Soil bulk density was determined using the cylinder method (Grossman and Reinsch, 2002). Soil bulk density of the first 0.05 m was determined monthly. Measurement of the soil bulk density at different soil depths (0.10, 0.20 and 0.40 m depth) was only done at certain occasions One sampling was performed for the 2016 maize growing season, hereafter GS1, in June 2016 and in November 2016 for the fallow period 2016-2017, hereafter FP1. During the 2017 maize growing season, hereafter GS2, and for the fallow period 2017-2018, hereafter FP2, soil bulk density of the soil profile was determined monthly. To determine soil bulk density in the soil profile an auger, 1 m length, and a stainless steel cylinder 5 cm in length and 8 cm in diameter was used to collect undisturbed soil samples and minimize the soil profile perturbation. Soil WFPS was calculated by dividing the volumetric soil water content by the total soil porosity, so it can range from 0 (completely dry) to 100% (completely saturated).

2.5 Data analysis

Data normality of all data was checked by the Shapiro-Wilk test, transforming the data when it was necessary to comply with normality. Soil CO_2 and N_2O concentrations needed a reciprocal transformation. Analysis of variance (ANOVA) for soil CO_2, CH_4 and N_2O concentrations was performed separately for the different measurement periods with irrigation system, soil depth and their interaction as a source of variation. Different ANOVA analyses for each measurement period were performed for soil temperature, soil WFPS, soil bulk density and soil diffusivity with irrigation system and soil depth as a source of variation. When significant, differences between treatments were identified at 0.05 probability level using the Tukey test. Simple regressions between soil CO_2, CH_4 and N_2O concentrations, soil temperature and soil WFPS were performed to test the presence of significant relationships. In addition, the relationship between soil CO_2, CH_4, N_2O fluxes measured by the chamber method and soil CO_2, CH_4, N_2O fluxes estimated by the GM method were checked by simple regressions. All statistical analyses were performed with JMP 10 statistical package (SAS Institute Inc., 2012).

3. Results

3.1 Weather conditions and soil variables

Mean air temperature, total precipitation and total ETo of each month were recorded for the entire measurement period (Table 1.2). Air temperature showed the typical pattern of Mediterranean climate, with the highest temperatures during the summer months (i.e. June – August) and the lowest during the winter months (December – February). Average monthly air temperature was 19.9 and 20.5ºC for GS1 and GS2 growing seasons, respectively, while during FP1 and FP2 periods, monthly air temperature was 9.1 and 8.9ºC, respectively. Precipitation presented the greatest values in spring (i.e. March – May) and autumn (i.e. September – November). In both maize growing seasons, total precipitation was 168 and 152 mm for GS1 and GS2, respectively, while over the two fallow periods total precipitation was 194 and 152 mm for the FP1 and FP2 periods, respectively (Table 1.2).

Table 1.2. Mean monthly air temperature (T), monthly precipitation (P) and monthly reference evapotranspiration (ETo) during 2016 maize growing season, GS1, 2016-2017 fallow period, FP1, 2017 maize growing season, GS2 and 2017-2018 fallow period, FP2.

	GS1			FP1			GS2			FP2		
	T (ºC)	P (mm)	ETo (mm)	T (ºC)	P (mm)	ETo (mm)	T (ºC)	P (mm)	ETo (mm)	T (ºC)	P (mm)	ETo (mm)
April	12.7	56	106				13.7	12	123			
May	16.6	47	145				18.7	25	153			
June	21.5	8	184				23.7	89	180			
July	24.0	43	198				24.4	6	198			
August	23.7	1	179				23.8	8	168			
September	20.8	13	119				18.5	12	115			
October				15.0	22	60				16.3	10	82
November				8.8	87	33				8.7	4	54
December				5.4	4	13				5.4	9	34
January				5.2	5	43				7.5	51	37
February				8.4	25	46				6.2	35	54
March				11.3	51	84				9.6	43	77

Over the entire measurement period, soil bulk density always increased with depth (Fig.1.1a, b, c, d). For GS1 and FP1 periods, the lower soil bulk density values were observed in the upper soil depths (0.05 and 0.10 m) compared with 0.20 and 0.40 m soil depths, which presented the higher soil bulk density values in both irrigation systems (Fig. 1.1a, b). Moreover, during GS2 and FP2 periods, differences in soil bulk density values were observed between the soil surface layer (0.00-0.05 m) and the other three soil layers, with the lowest values at the soil surface in both irrigation systems (Fig. 1.1c, d).

For both irrigation systems, soil temperature only showed significant differences between soil depths during the maize growing seasons (GS1, GS2) and FP2 but not during FP1 fallow period (Fig. 1.1e, f, g, h). Over the GS1, GS2 and FP2 periods and for both irrigation systems, soil temperature presented the same pattern, showing the lowest values at the upper depths and increasing with depth (Fig. 1.1e, g, h). Moreover, during the GS2 period, soil temperature was significantly greater in F irrigation than in S irrigation system (Fig. 1.1g).

During the entire experimental time, soil WFPS was higher under F irrigation compared with S irrigation (Fig. 1.1i, j, k l). Besides, significant differences in WFPS between soil depths were observed for both irrigation systems in all the measurement periods except for FP2. In both growing seasons, GS1 and GS2, and during the FP1 period, soil WFPS showed an increase with soil depth under S and F irrigation systems, with the greatest values at 0.40 m depth and the lowest at the upper soil depths (Fig. 1.1i, k, l). Over the four measurement periods (GS1, FP1, GS2 and FP2), soil diffusivity was significantly affected by the irrigation system and by soil depth. In both irrigation systems, soil diffusivity values showed a reduction along the soil profile, with greater values under S irrigation compared with F irrigation (Fig.1.1m, n, o, p).

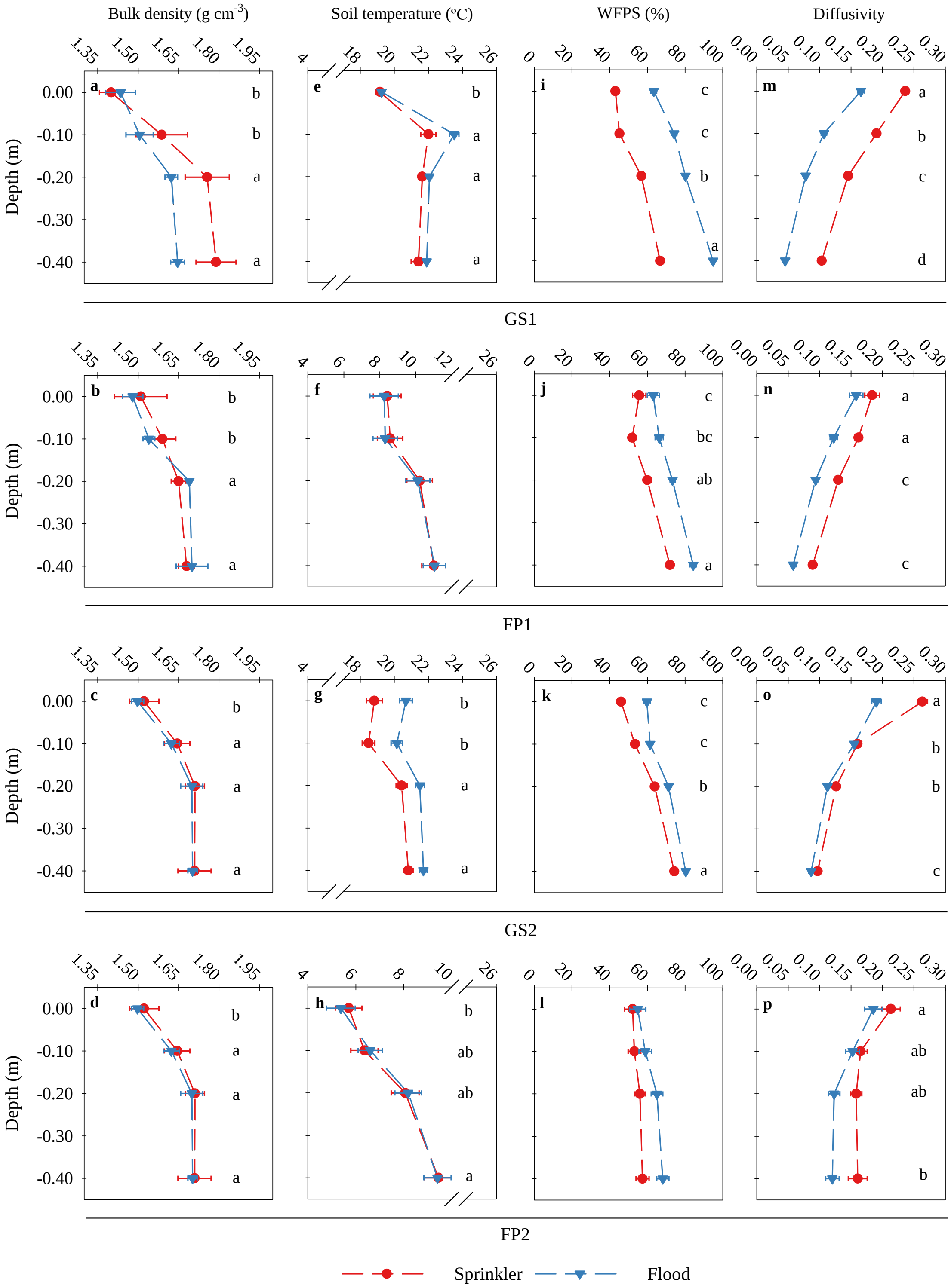

Figure 1.1. Soil bulk density (a, b, c, d), soil temperature (e, f, g, h), soil water-filled pore space (WFPS) (i, j, k, l) and soil diffusivity (m, n, o, p) for GS1, FP1, GS2 and FP2 measurement period as affected by soil depth and irrigation system. For each measurement period and soil variable, different letters indicate significant differences between treatments at $p<0.05$. Error bars represent standard error.

3.2 Carbon dioxide, methane and nitrous oxide soil concentration

Throughout the entire measurement period, soil CO_2 concentration was affected by the interaction between irrigation system and soil depth (Table 1.3). In all of the four measurement periods (GS1, FP1, GS2 and FP2), and for the both irrigation systems (S and F), the lowest soil CO_2 concentration was found at the soil surface, while the greatest soil CO_2 concentration was always observed at 0.40 m depth under S irrigation (Fig. 1.2). Moreover, soil CO_2 concentrations at 0.10, 0.20 and 0.40 m depth were greatest in summer during the maize tasselling growth stage (VT) (Fig. 1.2b, c, d).

During the GS2 and FP2 periods, significant differences for the interaction between the irrigation system and soil depth were observed for soil CH_4 concentrations, showing lower CH_4 concentration under S irrigation compared with F irrigation, especially at 40 cm depth under S irrigation. Soil CH_4 concentrations increased at all depths following de NPK fertilizer application on April 2017 (Fig. 1.3b, c, d). Moreover, in both irrigation systems, the highest soil CH_4 concentrations were measured at 0.10 and 0.20 m depths (Table 1.3). Likewise, over the GS1 period, significant differences in soil CH_4 concentration were observed between irrigation systems and soil depths, with lower soil CH_4 concentrations under S compared with F irrigation and greater CH_4 concentrations at 0.10 and 0.20 m depths compared with 0.40 m depth (Table 1.3).

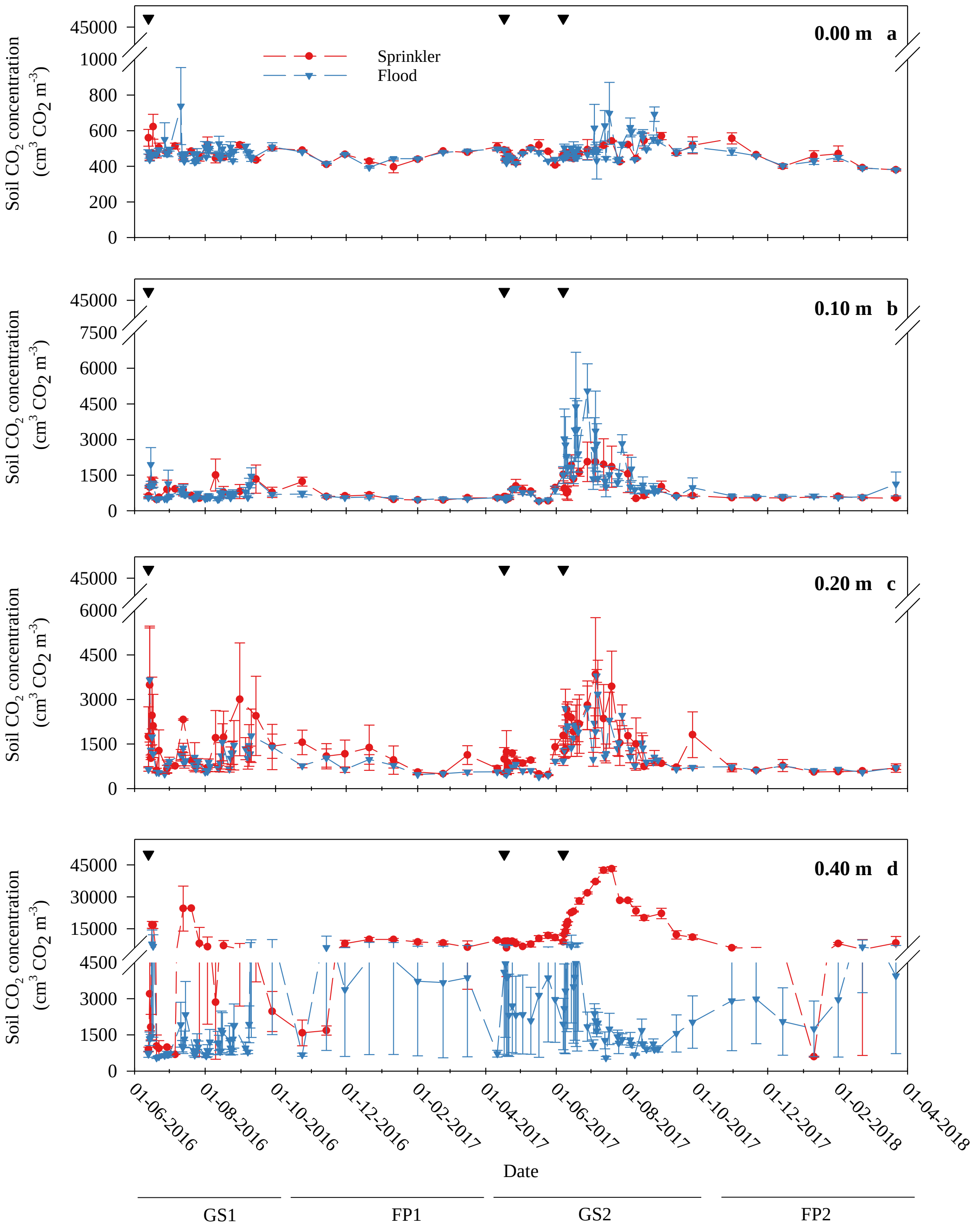

Figure 1.2. Soil CO_2 concentration for 0.00 (a), 0.10 (b), 0.20 (c) and 0.40 m (d) soil depth as affected by irrigation system. Black triangles indicate N fertilizer application. Error bars represent standard error.

Table 1.3. Analysis of the variance of soil CO_2, soil CH_4 and soil N_2O concentration for GS1 and GS2 maize growing seasons and FP1 and FP2 fallow periods as affected by irrigation system, soil depth and their interactions.

Effects and levels[†]	CO_2				CH_4				N_2O			
	cm^3 CO_2 m^{-3}				cm^3 CH_4 m^{-3}				cm^3 N_2O m^{-3}			
	GS1	FP1	GS2	FP2	GS1	FP1	GS2	FP2	GS1	FP1	GS2	FP2
Irrigation system	*<0.001*	*<0.001*	*<0.001*	*0.049*	*<0.001*	n.s.	*<0.001*	*0.039*	*0.004*	n.s.	*<0.001*	n.s.
Sprinkler (S)	2,493 a	2,240 a	5,078 a	1,893 a	1.95 b	1.77	1.88 b	1.89 b	0.86 b	0.36	1.01 b	0.33
Flood (F)	993 b	1,394 b	1,431 b	1,262 b	2.01 a	1.98	2.05 a	2.03 a	1.94 a	0.35	2.21 a	0.34
Depth	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	n.s.	*<0.001*	n.s.
0	482 d	451 d	493 d	435 c	1.95 b	2.04 a	1.99 b	2.00 a	0.36 c	0.36	0.38 c	0.33
10	773 c	590 c	1,491 b	765 b	2.03 a	1.96 a	2.11 a	2.03 a	1.83 b	0.35	3.64 a	0.35
20	1,268 b	845 b	1,390 c	651 b	2.02 a	1.94 a	2.11 a	2.02 a	2.81 a	0.36	1.47 b	0.34
40	2,783 a	5,043 a	6,580 a	4,260 a	1.93 b	1.56 b	1.81 c	1.78 b	1.82 b	0.35	1.97 b	0.33
Irrigation x Depth	*0.001*	*<0.001*	*<0.001*	*0.015*	n.s.*	n.s.	*<0.001*	*0.002*	n.s.	n.s.	*<0.001*	n.s.
S-0	488 e	450 f	477 e	446 c	1.94	2.07	1.97 b	1.98 a	0.36	0.36	0.36 e	0.33
S-10	878 cd	633 cde	1,437 d	880 c	1.99	1.92	2.14 a	2.02 a	0.57	0.36	0.49 d	0.36
S-20	2,031 b	1,040 bc	1,529 bc	639 c	2.01	1.91	2.15 a	2.03 a	0.67	0.36	0.54 d	0.34
S-40	6,692 a	6836 a	17,051 a	5,609 a	1.88	1.18	1.26 c	1.53 b	1.86	0.35	2.65 b	0.34
F-0	480 e	451 f	499 e	428 c	1.96	2.01	1.99 b	2.03 a	0.36	0.36	0.38 e	0.34
F-10	743 d	561 def	1,514 bcd	685 c	2.05	1.99	2.11 a	2.04 a	2.19	0.34	4.93 a	0.35
F-20	1,050 c	715 bcd	1,334 cd	660 c	2.01	1.96	2.09 a	2.04 a	3.41	0.37	1.85 bc	0.34
F-40	1,697 bc	3848 b	2,379 b	3,316 b	1.99	1.97	2.03 ab	2.03 a	1.81	0.35	1.69 c	0.35

[†] For each variable, measurement period and effect, values followed by different letters are significantly different according to Tukey test at $p=0.05$ level. * n.s., non-significant.

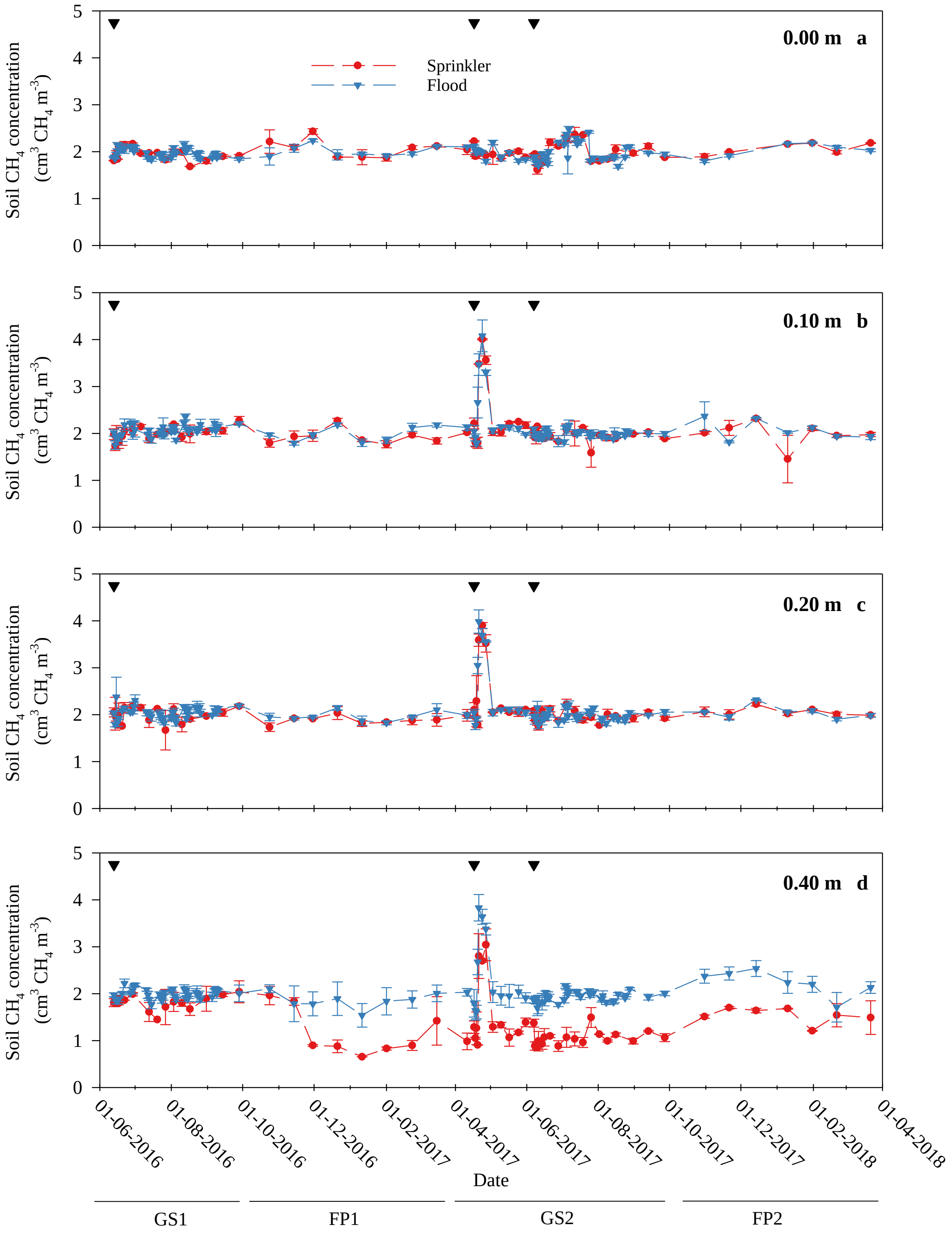

Figure 1.3. Soil CH$_4$ concentration for 0.00 (a), 0.10 (b), 0.20 (c) and 0.40 m (d) soil depth as affected by irrigation system. Black triangles indicate N fertilizer application. Error bars represent standard error.

Soil N_2O always concentrations remained low and close to the atmospheric value for all the soil depths (Fig. 1.4). However, a marked increase in soil N_2O concentrations was observed after the dressing application of N fertilizer at the three soil depths (0.10, 0.20 and 0.40 m) (Fig 4b, c, d). Soil N_2O concentration was affected by the irrigation system and the soil depth during the GS2 measurement period, presenting the maximum concentration values at 0.10 m depth under the F irrigation system (Table 1.3). Moreover, during the GS1 period, the irrigation system and soil depth affected soil N_2O concentration, showing greater soil concentration values under F than under S irrigation and the highest soil N_2O concentration values at 0.20 m depth (Table 1.3). In contrast, no significant differences in soil N_2O concentration were observed between irrigation system or soil depths over the two fallow periods (Table 1.3).

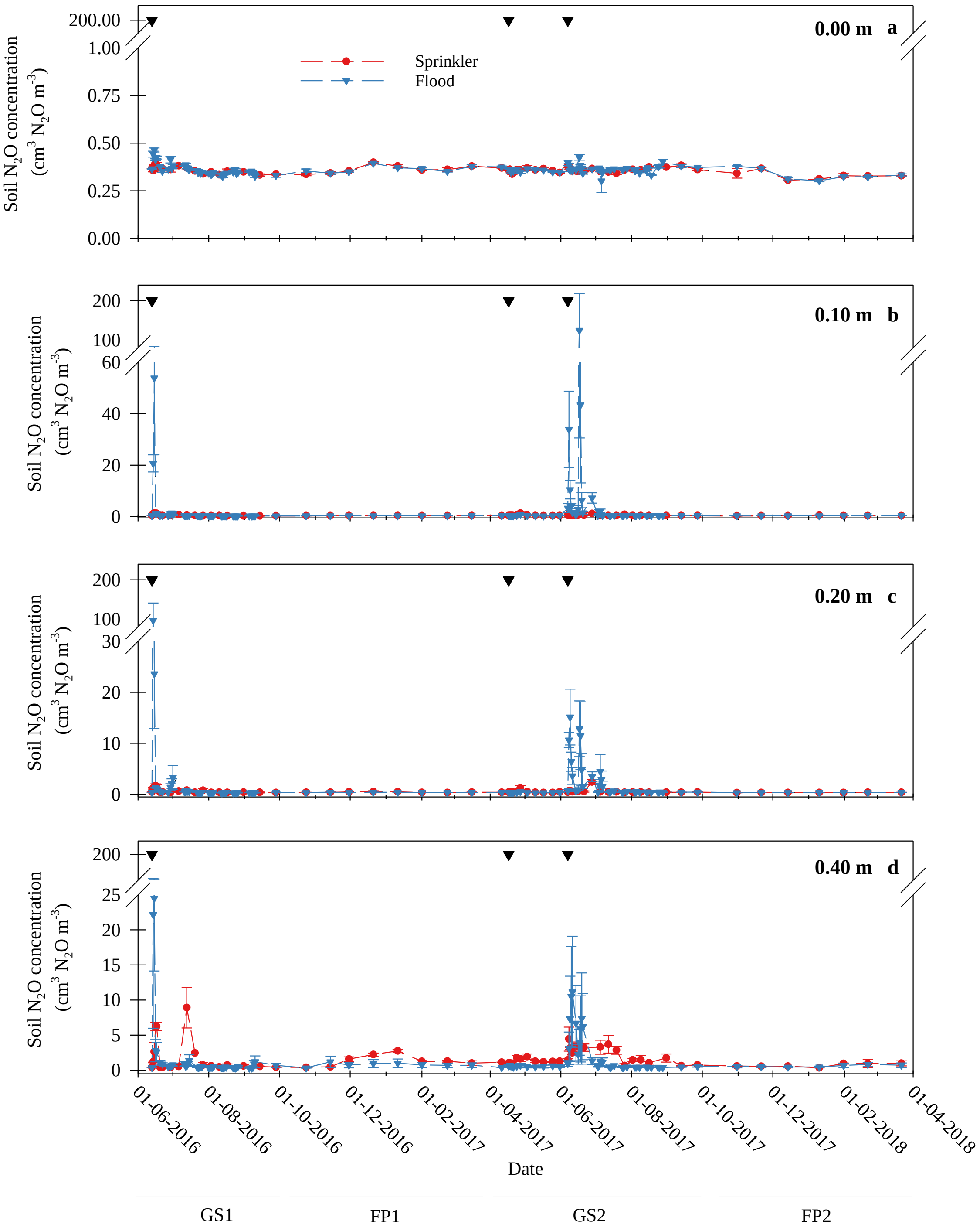

Figure 1.4. Soil N$_2$O concentration for 0.00 (a), .010 (b), 0.20 (c) and 0.40 m (d) soil depth as affected by irrigation system. Black triangles indicate N fertilizer application. Error bars represent standard error.

Along the whole measurement period, soil CO_2 concentrations showed a positive significant relationship with soil temperature in both irrigation systems and for all soil depths except for the 0.40 m depth under F irrigation. Similarly, a positive correlation between soil CO_2 and soil N_2O concentrations was observed in both irrigation systems for all depths except for the 0.40 m depth under F irrigation. Besides, soil CO_2 and CH_4 concentrations showed a negative significant relationship at 0.40 m depth under the S irrigation system. Soil WFPS presented a significant positive relationships with soil CO_2 and N_2O concentrations at 0.10 and 0.40 m depths, respectively, under the S irrigation system. However, no significant relationship was observed between soil WFPS and soil CO_2, CH_4 and N_2O concentrations under F irrigation (Table 1.4).

Table 1.4. Pearson's correlation coefficient for the linear relationships between soil temperature, soil WFPS and soil CO_2, CH_4 and N_2O concentration for sprinkler and flood irrigation systems and for 10, 20 and 40 cm soil depth.

	Sprinkler					Flood				
	Temperature	WFPS	CO_2	CH_4	N_2O	Temperature	WFPS	CO_2	CH_4	N_2O
10 cm depth										
Temperature	1					1				
WFPS	-0.11	1				0.38	1			
CO_2	0.42**	0.26*	1			0.17*	0.04	1		
CH_4	-0.38	0.03	-0.17	1		-0.29	-0.14	-0.11	1	
N_2O	0.10	0.05	0.36**	0.01	1	0.04	0.09	0.47**	-0.05	1
20 cm depth										
Temperature	1					1				
WFPS	0.09	1				0.24	1			
CO_2	0.50***	0.03	1			0.38***	0.10	1		
CH_4	-0.35	0.05	-0.24	1		-0.34	-0.13	-0.15	1	
N_2O	0.22	0.08	0.39**	-0.05	1	0.10	0.10	0.47***	-0.07	1
40 cm depth										
Temperature	1					1				
WFPS	0.23	1				0.29	1			
CO_2	0.39**	0.24	1			-0.32	-0.11	1		
CH_4	-0.13	-0.17	-0.44**	1		-0.17	-0.11	-0.07	1	
N_2O	0.21	0.31*	0.53***	-0.17	1	0.18	0.14	0.20	-0.13	1

*, **, *** indicate significant level at, $p<0.05$, $p<0.01$ $p<0.001$, respectively.

3.3 Carbon dioxide, methane and nitrous oxide soil fluxes

Soil CO_2, CH_4 and N_2O fluxes estimated by the GM method were compared with the soil fluxes measured at the soil surface using the chamber method (Fig. 1.5). Throughout the entire measurement period, CO_2 fluxes showed a positive significant relationship between GM soil fluxes and chamber method soil fluxes (Fig. 1.5a, b, c). Under S irrigation, GM CO_2 fluxes considering both the 0.00-0.10 and the 0.00-0.20 m soil layers showed a good correlation with chamber method soil CO_2 fluxes, presenting a slope of 0.82 and 1.13 for 0.00-0.10 and 0.00-0.20 m soil layers, respectively (Fig. 1.5a, b). In contrast, GM CO_2 fluxes between 0.00–0.40 m soil layer overestimated soil chamber CO_2 fluxes with a slope of 5.73 (Fig. 1.5c). Under F irrigation, GM CO_2 fluxes for the three soil depth layers underestimated soil CO_2 chamber fluxes, showing similar slopes values of 0.49, 0.51 and 0.44 for 0.00-0.10, 0.00-0.20 and 0.0-0.40 m soil layers, respectively (Fig. 1.5a, b, c).

For soil N_2O, significant relationships, despite low coefficient of determination (r^2), between measured and estimated fluxes by the gradient method were observed over the entire measurement period in both irrigation systems (Fig. 1.5g, h, i). No significant relationship between measured and estimated soil fluxes was observed for CH_4 (Fig. 1.5d, e, f).

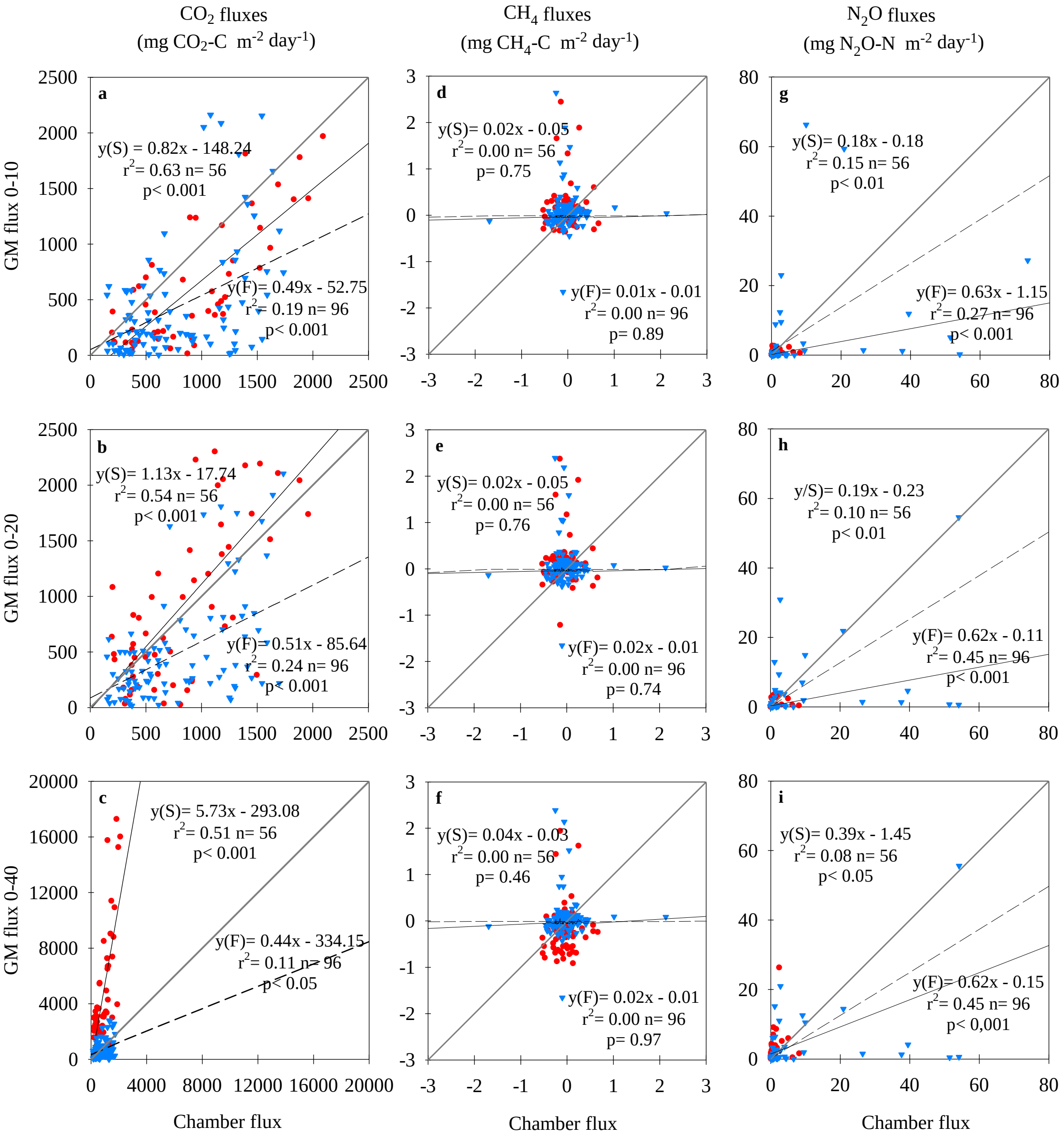

Figure 1.5. Regression analysis between soil fluxes measured by the chamber method and soil fluxes estimated by the GM method for CO_2 (a, b, c), CH_4 (d, e, f) and N_2O (g, h, i). Sprinkler irrigation (S; red circles and black line) and flood irrigation (F; blue triangles and dotted black line). Grey line represents 1:1 line. Each point represents the average value for each sampling date.

4. Discussion

The results obtained in this two-year field experiment show that irrigation system has a significant impact on the production and transport of CO_2 CH_4 and N_2O within the soil profile.

Soil CO_2 concentration at 0.10, 0.20 and 0.40 m depth presented a seasonal pattern similar to that observed by Pumpanen *et al.* (2003). This pattern, characterized by an increase of CO_2 concentration during the growing season periods (spring-summer months) with the lowest concentration values during the fallow periods (autumn-winter months), was explained by the effect of soil temperature and the presence of a crop on soil CO_2 production (Davidson and Janssens, 2006). The positive effect of soil temperature on soil CO_2 concentration observed together with the root-derived CO_2 could explain the greatest soil CO_2 concentration measured during the maize growing seasons. In contrast, the absence of crop and lower soil temperatures during the fallow periods (November-March) resulted in less favourable conditions for soil CO_2 production (Lloyd and Taylor, 1994; Rochette and Flanagan, 1997).

Moreover, over the entire measurement period, an increase in the soil CO_2 concentration along the soil profile was showed under both irrigation systems, similar to the pattern observed by Wang *et al.* (2018) for a rainfed maize crop. This concentration pattern was related to the observed increase in soil bulk density and soil WFPS with soil depth, resulting in a reduction of soil gas diffusivity. Soil gas diffusivity is strongly influenced by soil bulk density and soil water content, since it is a function of air-filled porosity and total soil porosity. Besides, soil gas diffusivity is greatly reduced in aqueous phase, being 10^4-10^5 times lower compared with the gas phase (Maier and Schack-Kirchner, 2014). Then, the increase of WFPS and soil bulk density observed along the soil profile could affect diffusion processes (Smith *et al.*, 2003; Ball *et al.*, 2008) and it could explain the greatest CO_2 concentration values found at 0.40 m depth in both irrigation systems.

Greater soil CO_2 concentration under S irrigation compared to F irrigation was related to the differences in soil WFPS between irrigation systems. Under F irrigation, 80 to 100 mm of water was applied in each irrigation event (every 10 to 15 days), while in S irrigation water rates ranged between 20 and 25 mm per irrigation event (2 events per week). The difference in the water application rate resulted in soil WFPS values between 40 and 60% under S irrigation at all soil depths, a range that it is considered as optimum for microorganism activity (Linn and Doran, 1984). In contrast, under F irrigation, WFPS values shifted from 20% to 100% in less than ten days during the growing season period, with an average value above 60%. Soil WFPS values above 60% limit soil CO_2 production by a reduction in the soil O_2 availability for soil microorganisms and root plants because most of the soil pores are filled with water (Linn and Doran, 1984).

Soil CH_4 concentration values found in this work were in the range of values reported by Nan *et al.* (2016) in a maize field experiment. Soil CH_4 concentration showed values closed to the atmospheric concentration for most of the measurement period in both irrigation systems. However, at 0.40 m depth in S irrigation, soil CH_4 concentration decreased drastically from mid-November 2016, maintaining concentration values close to 1 ppm during FP2 and GS1 and GS2 periods. This reduction in soil CH_4 concentration could be explained by a short-term methanotrophic activity occurred after an intense rainfall event of 57 mm recorded between 22 and 23 of November 2016. This rainfall event could result in a movement of soil nitrate from soil surface to deeper soil layers, resulting in more favourable conditions for methanotrophic activity. Under S irrigation, soil nitrate content after harvest was about 70% greater than under F irrigation, with a mean soil nitrate content value of 100 kg ha^{-1} for the first 1m soil depth. The high soil nitrate content measured in S irrigation could favour methanotrophic activity similarly to Hu and Lu (2015) who observed an increase in methanotrophic activity associated with the increase of soil nitrate content. Moreover, during the same time period, in S irrigation soil N_2O concentrations at 0.40 m depth increased rapidly from 0.43 to 1.5 cm^3 m^{-3} for soil CO_2 and N_2O concentration. This fact would also explain an increase of soil nitrate content in deeper soil layers.

In both irrigation systems, soil CH_4 concentration showed a concentration peak at all soil depths following the pre-sowing NPK fertilizer application based on ammonium nitrogen (N-NH_4^+). NH_4^+ inhibits methanotrophic activity since monooxygenase (enzyme responsible of CH_4 oxidation) can use NH_4^+ instead of CH_4 as a substrate (King and Schnell, 1994; Mancinelli, 1995). Thus, the increase of soil NH_4^+ content coming from N fertilizers could explain the CH_4 concentration peak due to a reduction of soil methanotrophic activity.

Soil N_2O concentration under both irrigation systems was similar to the pattern observed by Wang *et al.* (2013). During most of the experimental period, soil N_2O concentration values were similar to the atmospheric concentration (i.e. 0.30 cm^3 m^{-3}) at all soil depths. However, a quick increase on the soil N_2O concentration was observed at all soil depths in both growing season periods following the top-dressing applications of N fertilizer. This large increment on soil N_2O concentration could be related with a “pulse effect” consequence of the combined effect of N fertilizer application and irrigation during the warmest months (June and July) of the year (Sanchéz-Martín *et al*., 2008). The application of N fertilizers could result in an increase of the total available soil nitrogen, which together with the effect of soil temperature and soil water content on soil microorganism activity could explain these soil N_2O concentration peaks (Bouwman *et al*., 2002; Dobbie and Smith, 2003; Vallejo *et al*., 2005; Butterbach-Bahl *et al*., 2013).

Moreover, the optimum values of WFPS (70-80%) for the denitrification process observed under F irrigation during N top-dressing application, explained the greater soil N_2O concentration compared with S irrigation at 0.10 and 0.20 m depth (Davidson, 1991). Considering these results, our initial hypothesis that the irrigation system can affect the production of soil gas in the soil profile was confirmed for CO_2 and N_2O but not for CH_4.

Similar to the results reported by Kusa *et al.* (2008) and Wolf *et al.* (2011), soil CO_2 showed a good fit between measured and estimated soil fluxes. However, soil N_2O fluxes presented a poor correlation between the values estimated with the GM method and the closed chamber measured fluxes. Similarly, CH_4 did not show any relationship between measured and estimated soil CH_4 fluxes. Under S irrigation, soil GM fluxes for the 0.00–0.10 and 0.00–0.20 m soil layers provided a good estimation of the measured soil CO_2 fluxes, while GM fluxes for the 0.00–0.40 m soil layer overestimated the measured soil CO_2 fluxes. This fact may be related with the reduction of the soil diffusivity due to the increase of soil WFPS and soil bulk density with depth, resulting in an accumulation of the CO_2 in the soil profile, and then in the overestimation of the soil surface fluxes by the GM method (Maier and Schack-Kirchner, 2014). In contrast, under F irrigation, soil CO_2 fluxes estimated by the GM for the three soil depth intervals presented an underestimation of the 50 % compared with the soil CO_2 fluxes measured. This underestimation could be related with the limitation of soil diffusivity when soil presented high WFPS, exceeding 80-90% in several moments, because gas diffusion in aqueous phase is 10^4-10^5 times lower than in the gas phase (Smith *et al*., 2003; Ball *et al*., 2008; Maier and Schack-Kirchner, 2014). In addition, at high soil WFPS the dissolution of CO_2 into the soil solution may increase resulting in a reduction of the soil CO_2 concentration that diffusion models do not take into account (Schlotter and Schack-Kirchner, 2013). Moreover, wetting-drying cycles could favour the presence of soil cracks, observed at the field when soil WFPS was lower than 20% (Rajaram and Erbach, 1999). Soil cracks enhance soil gas mixing between soil and the atmosphere adding an error that is not considered by the diffusivity models (McIntyre and Philip, 1964). These results support our initial hypothesis that different irrigation systems could affect differently gas transport and diffusion processes for soil CO_2 but not for soil CH_4 and N_2O.

The poor estimation of soil CH_4 and N_2O fluxes by the GM method compared with soil fluxes measured by the closed chamber technique could be explained by the fact that both gases are produced and consumed within the soil profile (Le Mer and Roger, 2001; Butterbach-Bahl *et al*., 2013). These processes can occur simultaneously throughout the entire soil profile, difficulting the estimation of soil CH_4 and N_2O fluxes by the GM method (Maier and Schack-Kirchner, 2014).

5. Conclusions

The irrigation system showed a significant impact on the production and transport of soil CO_2, N_2O and CH_4 concentrations in the soil due to its capability to modify soil water content and its effects on the soil physical properties. Soil CO_2 concentration increased with soil depth due to the decrease of soil diffusivity as a result of higher soil bulk density and soil WFPS with soil depth. Under F irrigation, the higher WFPS values under F irrigation favoured the production of soil N_2O by denitrification process, resulting in higher soil N_2O concentrations compared with the S irrigation system. Likewise, the greater fluctuation in WFPS values under F irrigation affected soil CO_2 production and transport processes, leading to a poor estimation of soil CO_2 fluxes by the gradient method. Moreover, the inability of diffusivity models to consider the presence of soil cracks and biological processes such as CH_4 and N_2O consumption in the soil profile resulted in a poor estimation of soil gas fluxes by the gradient method.

The results of this work highlight that the type of irrigation system affects differently to the production and transport processes of CO_2, CH_4 and N_2O along the soil profile. However, further research needs to be conducted to improve our knowledge about the degree of impact that soil physical properties such as, aggregation, bulk density or the presence of soil cracks have on soil gas diffusion processes through the soil profile.

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Capítulo 2

Tillage and irrigation system effects on soil carbon dioxide (CO_2) and methane (CH_4) emissions in a maize monoculture under Mediterranean conditions

S. Franco-Luesma, J. Cavero, D. Plaza-Bonilla, C. Cantero-Martínez, J. L. Arrúe, J. Álvaro-Fuentes. 2020, *Soil & Tillage Research* 196, 104488

Tillage and irrigation system effects on soil carbon dioxide (CO_2) and methane (CH_4) emissions in a maize monoculture under Mediterranean conditions

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Abstract

Irrigation as well as soil tillage management are considered two possible strategies to reduce carbon dioxide (CO_2) and methane (CH_4) emissions from the soil in Mediterranean agroecosystems. The objective of this work was to assess the impact of the irrigation system (i.e. flood, F; and sprinkler, S) and the soil tillage system (i.e. conventional tillage, CT; no-tillage maintaining the maize stover, NTr; and no-tillage removing the maize stover, NT) on CO_2 and CH_4 emissions from the soil during three growing seasons (2015, 2016 and 2017) and two fallow periods between growing seasons (15-16 fallow and 16-17 fallow) in a maize (*Zea mays* L.) monoculture system. Soil temperature and water-filled pore space (WFPS) had a great influence on daily soil CO_2 fluxes but not on daily soil CH_4 fluxes. Daily soil CO_2 fluxes showed an increase with soil temperature in all tillage-irrigation treatments, especially when soil temperature was above 15ºC, in coincidence with the maize plant growth. In contrast, soil WFPS differently affected daily soil CO_2 fluxes depending on the irrigation system. Under S irrigation, daily soil CO_2 fluxes increased with soil WFPS, whereas under F irrigation a threshold value of 60% WFPS was found, with a positive or negative effect on CO_2 fluxes for values below or above this threshold value, respectively. Over the three maize growing seasons, CT-S presented the greatest cumulative soil CO_2 emissions with a seasonal average value of 3.28 Mg CO_2-C ha^{-1}. In contrast, for the same period, NTr-S cumulative soil CO_2 emissions were up to 42% lower than the CT-S cumulative soil CO_2 emissions. Cumulative CH_4 emissions were only affected by soil tillage during the 16-17 fallow period, observing greater net CH_4 uptake under NTr and NT compared with CT. This work highlights the importance of irrigation and soil tillage systems as key agricultural practices to minimize soil CO_2 and CH_4 emissions under Mediterranean conditions.

Keywords

Soil CO_2 emissions; soil CH_4 emissions; sprinkler irrigation; flood irrigation; conventional tillage; no-tillage; maize monoculture; maize stover

1. Introduction

Mediterranean climate is characterized by low and erratic precipitations, mainly occurring during autumn and spring, being irrigation water supplies necessary for most summer crops. On the other hand, in Mediterranean areas, adequate selection and performance of agricultural management practices such as irrigation and tillage may help to mitigate greenhouse gas (GHG) emissions from agricultural soils (Sanz-Cobeña *et al.*, 2017).

In Mediterranean agriculture, irrigation acreage is increasing due to the higher crop yields in irrigated cropping systems compared with rainfed farming systems. Sprinkler and flood irrigation systems are the most used worldwide. In turn, the acreage under sprinkler irrigation is increasing compared with flood irrigation due not only to higher crop yields but also to better automation of the irrigation process and to a reduction of runoff and drainage since irrigation water is applied at low rates (Rawlins and Raats, 1975; Playán and Mateos, 2006; Lecina *et al.*, 2010). Moreover, irrigation systems, given their capacity to modify the soil water content, directly affect the soil carbon cycle through an increase of net primary productivity and soil microbial activity, which usually results in an increase of soil organic carbon (SOC) content and an impact on the factors controlling the production and transport of CO_2 and CH_4 in the soil (Wu *et al.*, 2008; Aguilera *et al.*, 2013a; Trost *et al.*, 2013).

Likewise, soil tillage can have an impact on soil CO_2 and CH_4 emissions by affecting the SOC evolution and soil physical properties like soil structure involved in the production/consumption and transport of these gases through the soil profile (West and Post, 2002; Ball, 2013). In Mediterranean areas, no-tillage leads to an increase of SOC levels due to the physical protection of carbon within soil aggregates, which, at the same time, results in a better soil structure (Álvaro-Fuentes *et al.*, 2008; Follett *et al.*, 2013; Plaza-Bonilla *et al.*, 2014). In contrast, tillage promotes the oxidation of soil organic matter by microbial activity due to the direct incorporation of the crop stover, the disturbing and mixing of the soil profile and the breakdown of soil aggregates, which results in more favourable conditions for decomposition of the soil organic matter by soil microorganism (Paustian *et al.*, 1997). Moreover, crop stover management can influence CO_2 and CH_4 emissions from the soil. Thus, maintaining the crop stover on the soil surface can reduce soil water losses by evaporation, while removing it can lead to a reduction in the SOC content, thus resulting in a degradation of soil physical properties (Sauer *et al.*, 1998; Blanco-Canqui and Lal, 2008).

Soil CO_2 production is driven by abiotic and biotic processes. The main abiotic processes involved in the soil CO_2 production is the dissolution of inorganic forms of carbon like carbonates (CO_3^{2-}) (Ramnarine *et al.*, 2012; Rey, 2015). The soil CO_2 coming from biotic processes is a consequence of root respiration and microbial decomposition of organic matter and is regulated by soil temperature and water content (Linn and Doran, 1984; Lloyd and Taylor, 1994; Davidson and Janssens, 2006). Moreover, soil may act as a sink or as a source of CH_4, depending on the O_2 availability for microbial activity. Hence, soil methanogenesis (production of CH_4) requires strict anaerobiosis and low oxidation-reduction potentials (Eh). In contrast, soil methanotrophy (consumption of CH_4) need high Eh values and the presence of O_2, being the latter the main limiting factor for soil methanotrophy (Hütsch, 2001; Le Mer and Roger, 2001). Accordingly, irrigation and tillage practices may affect the production and dynamics of CO_2 and CH_4 in the soil by modifying the soil water-filled pore space (WFPS), soil temperature and soil structure. These variables control the microbial activity, influence the crop development and affect the diffusivity and transport of gases throughout the soil profile (Linn and Doran, 1984; Wang *et al*., 1993; Ball *et al*, 1999; Smith *et al*., 2003; Ball *et al*., 2008).

Currently, the available information about the effects of different irrigation systems and the interaction between tillage and irrigation on soil CO_2 and CH_4 emissions under Mediterranean conditions is scarce. Several studies have been carried out under Mediterranean conditions to assess the influence of different tillage practices, different types and doses of N fertilizers or the use of cover crops on CO_2 and CH_4 emissions from the soil (Álvaro-Fuentes *et al*., 2008; Menéndez *et al*., 2008; Meijide *et al*., 2010; Morell *et al*., 2011; Plaza-Bonilla *et al*., 2014; Sanz-Cobeña *et al*., 2014). All these studies, however, were carried out under rainfed conditions. In irrigated conditions, some researches have been conducted to find out the effect of different tillage systems and irrigation management on soil CO_2 and CH_4 emissions (Zornoza *et al*., 2016; Forte *et al*., 2017; Maris *et al*., 2018; Pareja-Sánchez *et al*., 2019), but none of them took into consideration the interaction between tillage and irrigation systems.

The present study was aimed to evaluate the effects of soil tillage systems (conventional tillage vs. no-tillage) and irrigation systems (sprinkler vs. flood irrigation) on soil CO_2 and CH_4 emissions under maize cultivation in a Mediterranean agroecosystem. We hypothesize that irrigation system and soil tillage management would impact on the soil carbon cycle by modifying soil physical properties, soil moisture content and SOC contents, which would also affect the soil CO_2 and CH_4 emissions. In particular, we hypothesize that conventional tillage under sprinkler irrigation would result in greater CO_2 emissions due to the expected higher crop productivity of this irrigation system and the higher soil aeration associated with tillage. Likewise, we hypothesize that flood irrigation would enhance soil CH_4 production since, under this irrigation system, anaerobic conditions would occur after each irrigation event.

2. Material and Methods

2.1 Site description and experimental design

The experiment was established in 2015 at Zaragoza, Spain (41º 42´ N, 0º 49´ W, 225 m altitude). The climate in the area is Mediterranean semiarid with an annual mean air temperature of 14.1 ºC, an annual precipitation of 298 mm and a grass reference crop evapotranspiration (ETo) of 1243 mm. The soil is a Typic Xerofluvent (Soil Survey Staff, 2015). The main properties of the experimental soil are given in Table 2.1.

Table 2.1. Soil characteristics at the beginning of the experiment.

Depth	pH	SOC[a]	$CaCO_3$	Sand	Silt	Clay	FC[b]	WP[c]
(m)				(%)			(m^3 m^{-3})	
0.00−0.05	7.98	1.93	34.9	15.7	61.9	22.4	0.26	0.14
0.05−0.10	8.20	1.85	34.9	15.4	62.9	21.7	0.26	0.14
0.10−0.25	8.03	1.75	35.1	15.9	62.1	22.0	0.25	0.16
0.25−0.50	7.95	1.51	35.3	16.1	63.6	20.3	0.25	0.16

[a] Soil organic carbon. [b] Water content at field capacity (-0.033 MPa). [c] Water content at wilting point (-1.5 MPa).

On the experimental site, winter wheat (*Triticum aestivum* L.) followed by maize (*Zea mays* L.) as second crop was grown under conventional tillage and flood irrigation during the last ten years prior to the establishment of the experiment. Accordingly, winter wheat was the precedent crop in the experimental field. In 2015, the experimental field (0.83 ha) was divided in two identical areas, one for flood irrigation (F) and the other for a hand-move sprinkler irrigation system (S). At the same time, three soil tillage systems (i.e. conventional tillage, CT; no-tillage maintaining the maize stover, NTr; and no-tillage removing the maize stover, NT) were also established in each of the two areas with different irrigation system. The experimental design was a split-block with three replications and a plot size of 6 x 18 m.

One pass of a subsoiler to 30 cm depth followed by one pass of a disk harrow in winter and one pass of a rotary tiller just before sowing were performed in the CT treatment. No-tillage treatments consisted of an application of glyphosate (36% at 5L ha^{-1}) to control weeds before sowing. Maize cv. Pioneer P1785 was sown in rows 75 cm apart at a planting density of 89,500 plants ha^{-1} (Table 2.2).

Table 2.2. Schedule of field operations during the 2015, 2016 and 2017 maize growing seasons.

Field operation	2015	2016	2017
Stover management			
Stover removal		23/12/2015	11/11/2016
Tillage operation			
Subsoiler and disk harrow	11/03/2015	15/12/2016	31/01/2017
Rotary tiller	08/04/2015	12/04/2016	17/04/2017
No-tillage weed control			
Herbicide application	21/11/2014	11/04/2016	07/02/2017
Planting	09/04/2015	12/04/2016	17/04/2017
N Fertilization			
Preplanting application	08/04/2015	11/04/2016	17/04/2017
Top dressing application	02/06/2015	13/06/2016	07/06/2017
Harvest	30/09/2015	05/10/2016	17/10/2017

Fertilization was the same in all treatments and consisted of one application of 800 kg ha^{-1} of NPK 8-15-15 compound fertilizer (ammonium N ($N\text{-}NH_4$); phosphorus P($P\text{-}P_2O_5$); potassium K ($K\text{-}K_2O$)) before planting and one top dressing application of 740 kg ha^{-1} of calcium ammonium nitrate 27% N (13.5% ammonium N ($N\text{-}NH_4$) – 13.5% nitrate N ($N\text{-}NO_3$)) at V6-V8 maize growth stage. Harvest was done with a commercial combine (Table 2.2). Afterwards, the stover was chopped and spread over the soil by a chopper machine. After harvest of the first maize growing season (2015), maize stover was manually removed from the NT treatment plots. Therefore, the NT treatment started the second growing season (2016) after the first fallow period (15-16 fallow).

It is important to state that during the two fallow periods between the three maize growing seasons no crop was grown. Weed and pest control was done according to best management practices in the area.

Meteorological data from a weather station 1km far from the field experiment was used to obtain daily reference evapotranspiration (ETo) using the FAO Penman-Monteith method (Allen *et al*., 1998). The crop coefficient (Kc) for maize was calculated as a function of thermal time using an equation developed at the same location of the experiment (Martínez-Cob *et al*., 2008). Daily maize crop evapotranspiration (ETc) was then obtained by multiplying ETo by Kc (Allen *et al*., 1998). Crop irrigation requirements (CIR) were determined weekly by subtracting the effective precipitation (75% of total weekly precipitation) from ETc and considering an irrigation efficiency of 85% (Dastane, 1978) (Table 2.3). Irrigation frequency differed between irrigation systems. Hence, in the S system, two irrigation events per week were performed (i.e. on Monday and Wednesday). In the F system irrigation occurred every 10-14 days. In order to favour plant emergence and to avoid differences in plant density among treatments, irrigation water was applied by sprinkler irrigation to all the plots until V6 growth stage. For each irrigation system, the same amount of irrigation water was applied to all tillage treatments.

Table 2.3. Calculated crop evapotranspiration (ETc), precipitation, crop irrigation requirement (CIR) and irrigation water applied in both irrigation systems (sprinkler and flood) in 2015, 2016 and 2017 maize growing seasons.

Growing season	ETc	Precipitation	CIR	Irrigation	
				Sprinkler	Flood
	mm				
2015	719	115	712	729	950
2016	763	130	722	708	824
2017	744	136	693	686	874

2.2 Gas measurements

Soil CO_2 and CH_4 emissions were measured from April 2015 to October 2017 using the closed chamber technique (Hutchinson and Moiser, 1981). Two polyvinyl chloride (PVC) rings (31.5 cm internal diameter) per plot were inserted 10 cm into the soil on April 2015 and were only removed at tillage, planting and harvesting operations. Each PVC chamber (20 cm height) was covered with a reflective layer of aluminium film to avoid increases of the internal temperature, which was measured by introducing thermometers before the chambers were closed.

Soil gas sampling frequency was weekly from planting (April) until maize milk stage (R3) (mid-August), every two weeks from mid-August until harvest (late September) and every three weeks during the fallow period (November-March). Moreover, soil gas sampling frequency was increased for tillage, fertilization and flood irrigation events. During tillage operations, soil gas samplings were performed 24 h before and 24 and 96 h after tillage, while for fertilization operations soil gas samples were taken 24 h before and 24, 48, 72, 96, 144 and 192 h after fertilization. Finally, for every flood irrigation event soil gas sampling frequency consisted of one sampling just before applying the irrigation water and several samplings (3-4) during the five days following the irrigation event. In the case of S irrigation, gas sampling was performed between the two weekly irrigation events.

In each soil gas sampling, 20 mL of gas were collected at 0, 20 and 40 min after chamber closure and transferred to an evacuated 12-mL Exetainer ® borosilicate glass vial (model 038W, Labco, High Wycombe, UK). On every sampling date, a total of 54 gas samples were collected for each irrigation system (9 plots x 2 observations per plot x 3 sampling times per chamber).

The concentration of CO_2 and CH_4 were measured with a gas chromatograph system (Agilent 7890B, Agilent, Santa Clara, CA, United States) equipped with a flame ionization detector (FID) coupled to a methanizer for determining CO_2. The system was calibrated using ultra-high purity CO_2 and CH_4 standards (Carburos Metálicos, Barcelona, Spain). Further details of the analysis method are described elsewhere (Franco-Luesma *et al*., 2019). Mass-based emission rates of each gas were calculated by the linear increase of the particular gas concentration inside the chamber during the enclosure time and correcting it by the internal air chamber temperature.

2.3 Soil and crop aboveground biomass measurements

Soil temperature (at 5 cm depth) and soil water content (0-5 cm) were measured using a TM 65 probe (Crison, Carpi, Italy) and a GS3 probe (Decagon Devices, Pullman, WA), respectively. Soil bulk density (0-5 cm) was determined once per month using the cylinder method (Grossman and Reinsch, 2002); stainless steel cylinders 5 cm in length and 8 cm in diameter were used to collect undisturbed soil samples. Soil water filled pore space (WFPS) was calculated from the volumetric soil water content and the soil bulk density measurements, assuming a soil particle density of 2.65 Mg m^{-3}.

Maize aboveground biomass was determined manually before the combine harvest by cutting the maize plants of three 2-m maize rows, at the soil surface level, at two randomly selected locations per plot. A sub-sample of four entire plants was taken. The cobs were separated, and both cobs and the rest of the plant were oven-dried at 60° C for 48 h and weighed. Afterwards, the dry weight of the plant and the cob were summed to obtain the total maize aboveground biomass.

2.4 Data analysis

Cumulative soil CO_2 and CH_4 emissions for each treatment and measurement period: 2015, 2016 and 2017 maize growing seasons (April – October) and 15–16 and 16–17 fallow periods (November – March) were expressed on a mass basis (i.e., Mg C-CO_2 ha^{-1}; g C-CH_4 ha^{-1}) using the trapezoid rule (Levy et al., 2017). Data normality was checked by the Shapiro-Wilk test and when necessary, data were transformed to get a normal distribution. Sqrt-transformation for daily soil CO_2 fluxes and logarithm transformation for cumulative soil CO_2 emissions were needed to comply with normality. Repeated measures analysis of variance (ANOVA) with the REML (Restricted Maximum Likelihood) approach were performed for transformed daily soil CO_2 fluxes, daily soil CH_4 fluxes, WFPS, and soil temperature. Analyses were done separately for each measurement period (i.e. 2015, 2016, 2017 maize growing seasons and 15-16, 16-17 fallow periods) and each irrigation system, sprinkler and flood irrigation.

In addition, different ANOVA analyses for each measurement period were performed for transformed cumulative soil CO_2 emission values, cumulative soil CH_4 emissions and maize aboveground biomass, with irrigation system, soil tillage system and their interactions as sources of variation. When significant, differences between treatments were identified at 0.05 probability level using the Tukey test. Simple regressions between CO_2 fluxes, CH4 fluxes, WFPS and soil temperature were performed to test the presence of significant relationships. All statistical analyses were performed with JMP 10 statistical package (SAS Institute Inc., 2012).

3. Results

3.1 Weather conditions, soil WFPS and soil temperature

Daily mean air temperature, precipitation and ETo were recorded for the entire measurement period. Air temperature and ETo values showed an increase from April until maximum values in July and August and then a decrease reaching the lowest values in January and February (Figure 2.1). Over the three maize growing seasons, average daily air temperature was 20.6, 19.9 and 20.5ºC for 2015, 2016 and 2017, respectively, while during the 15-16 and 16-17 fallow periods, daily air temperature was 9.2 and 9.1ºC, respectively. Likewise, a total precipitation of 116, 167 and 151 mm was recorded in 2015, 2016 and 2017 maize growing seasons, respectively, while total precipitation during fallow was 180 and 272 mm for the 15-16 and 16-17 fallow periods, respectively.

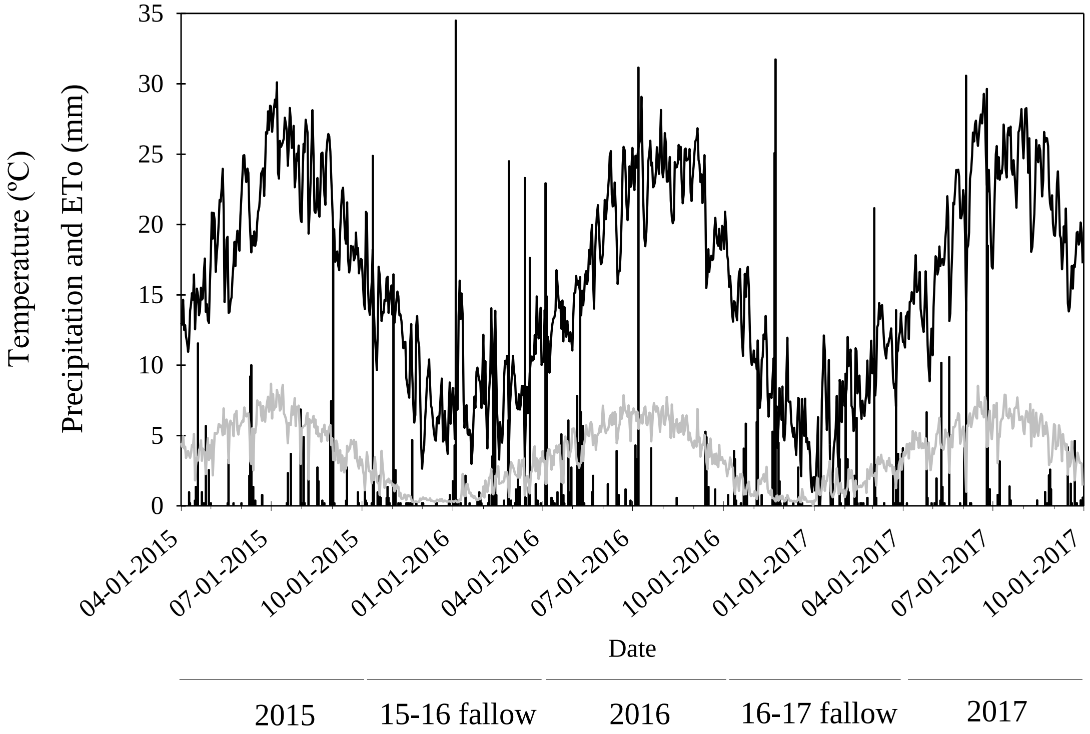

Figure 2.1. Daily mean air temperature (black continuous line), precipitation (vertical bars) and reference evapotranspiration (ETo) (grey continuous line) throughout the entire experimental period.

For both irrigation systems and throughout the entire measurement period, the WFPS was significantly affected by the interaction between tillage and sampling date (Table 2.4). In addition, during the irrigation period (June – September), F irrigation presented large fluctuations of WFPS, with increases from 30 to 100% WFPS in less than 24h, which returned to values close to 30% WFPS in less than 5 days after the irrigation event. However, S irrigation presented a lower temporal variation of WFPS, with values ranging from 30 to 60% through the irrigation period (Figure 2.2). On average, for the three maize growing seasons, mean CT-WFPS values were 38 and 55% for S and F irrigation, respectively, whereas, mean NTr- and NT-WFPS values were 58 and 64%, and 50 and 58% for S and F irrigation, respectively.

Table 2.4. Analysis of variance *F* (F-value) and *P* (*p*-values) of soil water-filled pore space (WPFS) (0-5 cm) and soil temperature at 5 cm depth for sprinkler and flood irrigation and for 2015, 2016 and 2017 growing seasons and 15-16 and 16-17 fallow periods as affected by soil tillage, sampling date and their interactions.

Sprinkler irrigation

	2015		15-16 fallow		2016		16-17 fallow		2017	
Effects	*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*
					WFPS (%)					
Tillage	16.81	*0.049*	23.43	*0.001*	71.84	*<0.001*	7.45	*0.047*	64.16	*<0.001*
Date	32.80	*<0.001*	50.84	*<0.001*	22.68	*<0.001*	85.84	*<0.001*	102.4	*<0.001*
Tillage x Date	6.44	*<0.001*	2.97	*<0.003*	2.00	*<0.001*	3.61	*<0.001*	2.50	*<0.001*
					Soil temperature (ºC)					
Tillage	28.08	*0.024*	2.01	ns*	19.45	*<0.001*	1.02	ns	9.15	*0.032*
Date	186.5	*<0.001*	355.4	*<0.001*	661.9	*<0.001*	1136	*<0.001*	636.6	*<0.001*
Tillage x Date	8.78	*<0.001*	0.89	ns	2.18	*<0.001*	2.49	*0.008*	2.25	*<0.001*

Flood irrigation

	2015		15-16 fallow		2016		16-17 fallow		2017	
Effects	*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*
					WFPS (%)					
Tillage	14.76	ns	73.33	*<0.001*	38.85	*0.002*	17.77	*0.01*	76.15	*<0.001*
Date	22.59	*<0.001*	124.33	*<0.001*	106.9	*<0.001*	92.75	*<0.001*	184.9	*<0.001*
Tillage x Date	3.64	*<0.001*	6.58	*<0.001*	5.82	*<0.001*	2.45	*0.008*	2.07	*<0.001*
					Soil temperature (ºC)					
Tillage	0.25	ns	70.44	*0.014*	12.02	*<0.001*	19.79	*<0.001*	2.23	ns
Date	144.8	*<0.001*	1086	*<0.001*	230.6	*0.021*	1644	*0.008*	160.6	*<0.001*
Tillage x Date	4.19	*<0.001*	2.51	*0.009*	2.84	*<0.001*	2.83	*0.003*	2.63	*<0.001*

* ns, non-significant.

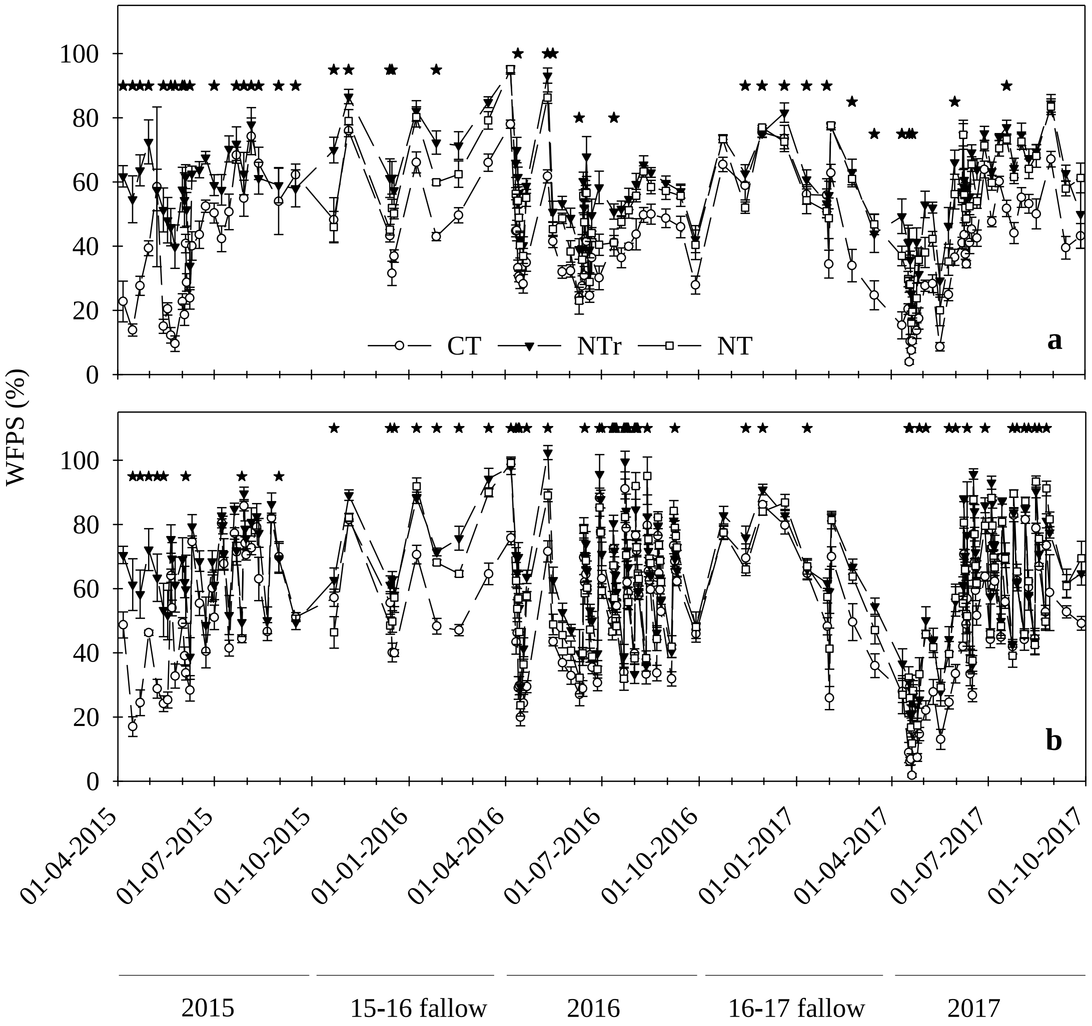

Figure 2.2. Soil water-filled pore space (WFPS) in the 0-5 cm depth for sprinkler (a) and flood (b) irrigation systems as affected by soil tillage systems: CT (conventional tillage), NTr (no-tillage maintaining the maize stover), NT (no-tillage removing the maize stover). * Indicates significant differences between tillage treatments for a given date at *p*<0.05. Error bars represent standard error.

Soil temperature was significantly affected by the interaction between tillage and sampling date during all measurement periods except during the 15-16 fallow for S irrigation (Table 2.4). Over the three maize growing seasons, mean soil temperature (at 5 cm depth) was 19.7 (2015), 17.7 (2016) and 18.2ºC (2017) in S irrigation and 19.4 (2015), 18.9 (2016) and 19.2ºC (2017) in F irrigation (Figure 2.3).

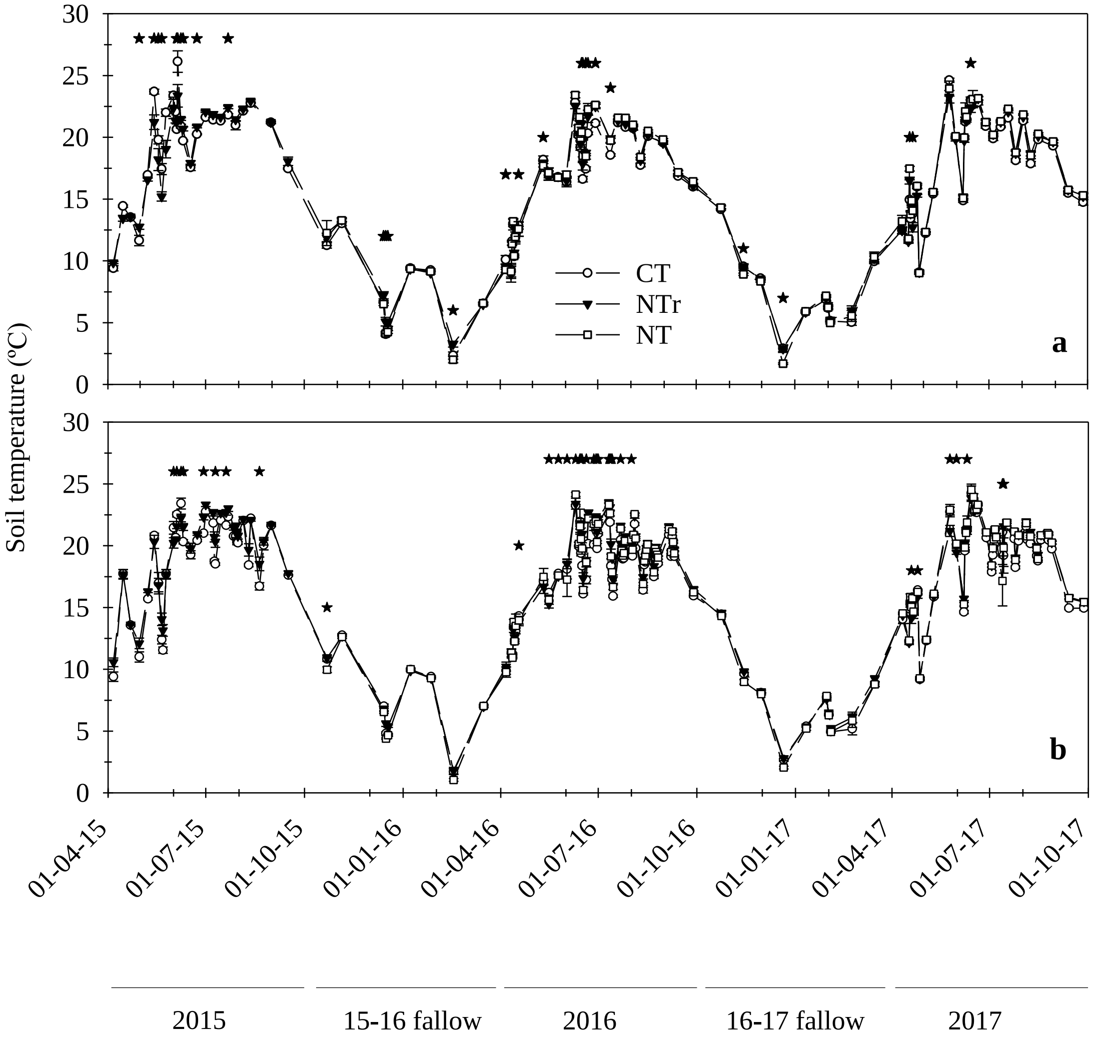

Figure 2.3. Soil temperature at 5 cm depth for sprinkler (a) and flood (b) irrigation systems as affected by soil tillage systems: CT (conventional tillage), NTr (no-tillage maintaining the maize stover), NT (no-tillage removing the maize stover). *Indicates significant differences between tillage treatments for a given date at *p*<0.05. Error bars represent standard error.

3.2 Carbon dioxide emissions

For both irrigation systems, daily soil CO_2 fluxes were affected by tillage, sampling date and their interaction (Table 2.5). During the three maize growing seasons and under both irrigation systems, soil CO_2 fluxes showed a similar pattern, with an increase in the emission rates concomitant with the crop growth over the maize growing season and reaching the maximum values in July coinciding with maize tasseling stage (VT) (Figure 2.4). Once soil CO_2 fluxes reached this peak, they started to decrease presenting the lowest values during the fallow periods (November – March) (Figure 2.4).

In the three growing seasons and under S irrigation, CT showed greater daily soil CO_2 fluxes than NT and NTr, with mean daily values of 2.50, 1.53 and 1.75 g CO_2-C m^{-2} day^{-1} for 2015, 2016 and 2017, respectively. However, under F irrigation, differences among tillage systems were only found in the 2017 growing season when CO_2 fluxes were greater under CT than under NT (Table 2.5).

Table 2.5. Analysis of variance of daily soil CO$_2$ and CH$_4$ fluxes for sprinkler and flood irrigation and for 2015, 2016 and 2017 growing seasons and 15-16 and 16-17 fallow periods as affected by soil tillage, sampling date and their interactions.

Sprinkler irrigation

	2015 (n= 306)		15-16 fallow (n= 180)		2016 (n= 522)		16-17 fallow (n=198)		2017 (n= 558)	
	Mean	*± SE*	*Mean*	*± SE*	*Mean*	*± SE*	*Mean*	*± SE*	*Mean*	*± SE*
Tillage			Soil CO$_2$ flux (g CO$_2$-C m^{-2} day^{-1})							
CT	2.50 a	0.09	0.48 ab	0.05	1.53 a	0.07	0.50 a	0.03	1.75 a	0.07
NTr	1.93 b	0.08	0.55 a	0.04	1.08 b	0.05	0.51 a	0.04	1.23 b	0.05
NT			0.32 b	0.03	1.12 b	0.05	0.35 b	0.02	1.30 b	0.06
Effects[†]					ANOVA					
Tillage	*0.009*		0.006		*<0.001*		0.042		*0.027*	
Date	*<0.001*		*<0.001*		*<0.001*		*<0.001*		*<0.001*	
Tillage x Date	*0.008*		*<0.001*		*<0.001*		*0.002*		*0.002*	
Tillage			Soil CH$_4$ flux (mg CH$_4$-C m^{-2} day^{-1})							
CT	–0.10	0.07	–0.04	0.10	–0.05	0.03	–0.16	0.15	–0.05	0.02
NTr	0.06	0.08	–0.11	0.09	–0.05	0.03	0.06	0.12	–0.05	0.03
NT			0.11	0.09	–0.01	0.02	0.19	0.15	–0.11	0.03
Effects					ANOVA					
Tillage	ns[*]		ns		ns		ns		ns	
Date	ns		ns		ns		ns		ns	
Tillage x Date	ns		ns		ns		ns		ns	

Flood irrigation

	2015 (n= 426)		15-16 fallow (n= 180)		2016 (n= 972)		16-17 fallow (n=198)		2017 (n= 826)	
	Mean	*± SE*	*Mean*	*± SE*	*Mean*	*± SE*	*Mean*	*± SE*	*Mean*	*± SE*
Tillage			Soil CO$_2$ flux (g CO$_2$-C m^{-2} day^{-1})							
CT	2.00	0.06	0.43 a	0.02	1.06	0.04	0.40 ab	0.03	1.56 a	0.05
NTr	1.55	0.05	0.45 a	0.03	0.95	0.03	0.53 a	0.03	1.36 ab	0.04
NT			0.31 b	0.02	0.84	0.02	0.33 b	0.02	1.14 b	0.03
Effects					ANOVA					
Tillage	ns		*0.011*		ns		*0.01*		0.014	
Date	*<0.001*		*<0.001*		*<0.001*		*<0.001*		*<0.001*	
Tillage x Date	*0.008*		ns		*<0.001*		*0.008*		*0.026*	
Tillage			Soil CH$_4$ flux (mg CH$_4$-C m^{-2} day^{-1})							
CT	0.02	0.07	0.02	0.09	–0.03	0.02	0.02	0.11	–0.11	0.03
NTr	–0.19	0.08	–0.11	0.08	0.02	0.03	–0.44	0.22	–0.05	0.02
NT			–0.26	0.10	0.08	0.05	–0.08	0.20	–0.06	0.03
Effects					ANOVA					
Tillage	ns		ns		ns		ns		ns	
Date	ns		ns		ns		ns		ns	
Tillage x Date	ns		ns		ns		ns		ns	

[†] For each variable, measurement period and effect, values followed by different letters are significantly different according to Tukey test at *p*=0.05 level. * ns, non-significant.

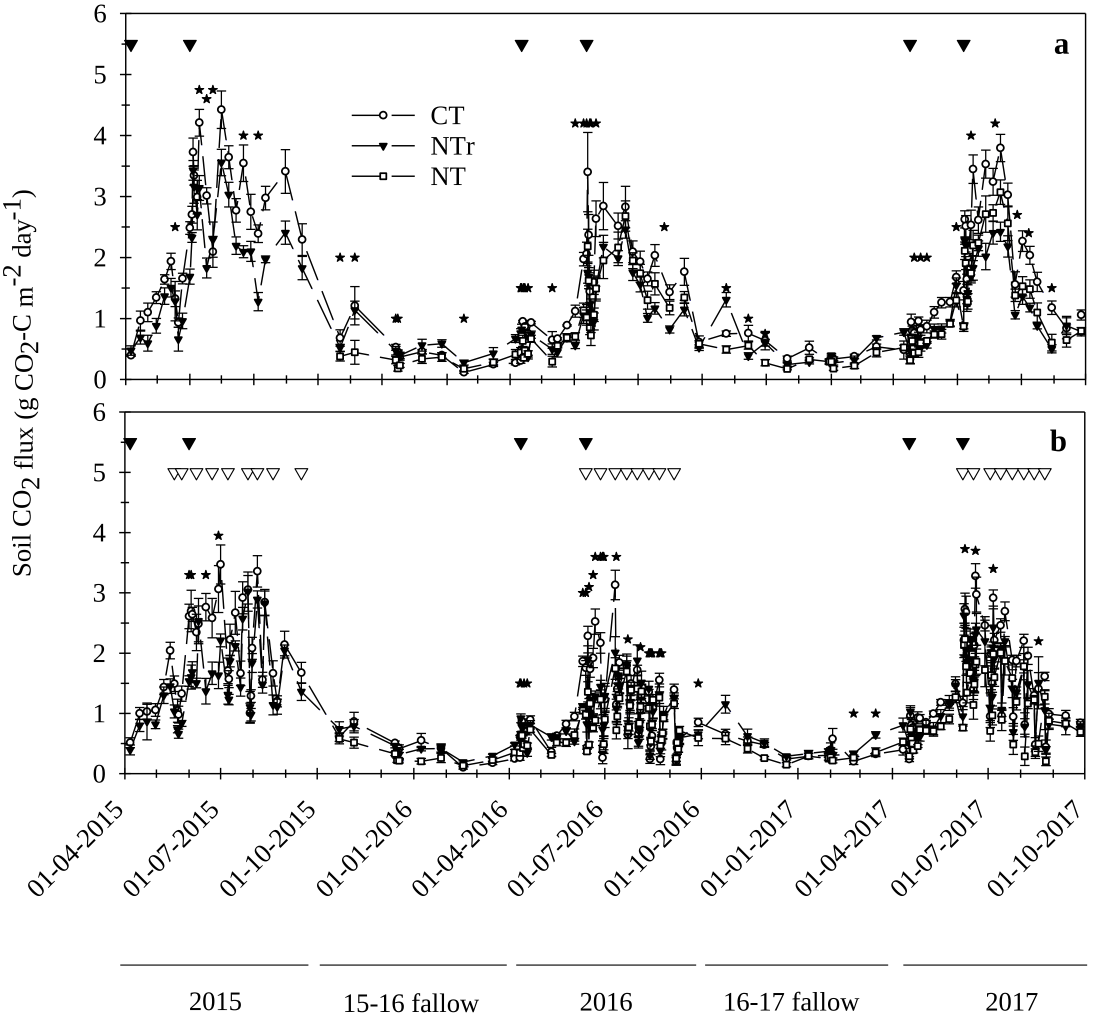

Figure 2.4. Soil CO_2 flux for sprinkler (a) and flood (b) irrigation systems as affected by soil tillage systems: CT (conventional tillage), NTr (no-tillage maintaining the maize stover), NT (no-tillage removing the maize stover). *Indicates significant differences between tillage treatments for a given date at $_p<0.05$. Black triangles indicate fertilizer applications. White triangles indicate flood irrigation events. Error bars represent standard error.

Over the entire experimental time, daily soil CO_2 fluxes and soil temperature at 5cm depth presented a significant positive exponential relationship for both irrigation systems and the three tillage systems (Figure 2.5). According to these relationships, when soil temperature was below to 15º C (mostly during the fallow periods) the response of daily soil CO_2 fluxes for the six treatments showed a linear behaviour. However, when soil temperature values were above 15º C (mostly during the growing season period) daily soil CO_2 fluxes increased rapidly with soil temperature increase. Moreover, soil temperature showed a trend to a greater impact on soil CO_2 fluxes under S irrigation than under F irrigation, with an increment in the slope value of 24, 20 and 33% for CT, NTr and NT, respectively (Figure 2.5).

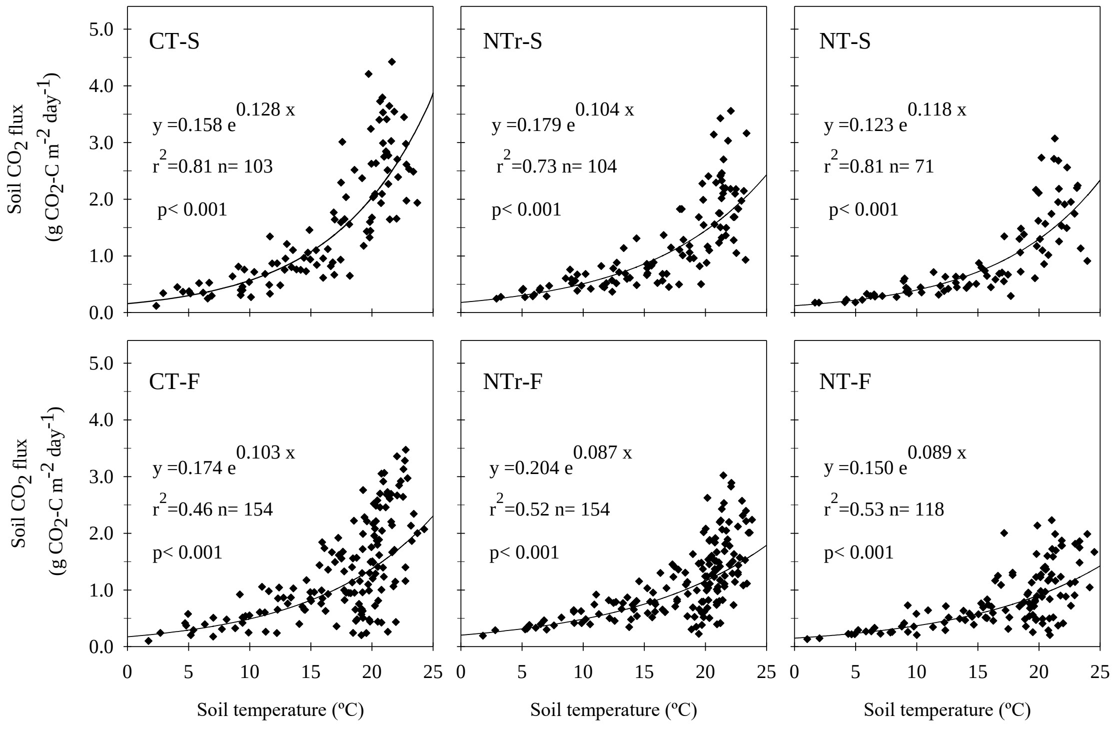

Figure 2.5. Regression analysis between soil temperature (at 5 cm depth) and soil CO_2 fluxes as affected by soil tillage (CT, conventional tillage; NTr, no-tillage maintaining the maize stover; NT, no-tillage removing the maize stover) and irrigation system (S, sprinkler irrigation; F, flood irrigation). Each point represents the average value for each sampling date.

Daily soil CO_2 fluxes presented a significant linear relationships with soil WFPS (Figure 2.6). For each irrigation system, different trends were observed, with positive increases of soil CO_2 fluxes with soil WFPS in all three tillage systems under S irrigation. Under F irrigation, all tillage systems also showed a linear positive increase of daily soil CO_2 fluxes with soil WFPS but only until a threshold value of 60% WFPS. From 60 to 100% WFPS, soil CO_2 fluxes linearly decreased as soil WFPS increased (Figure 2.6).

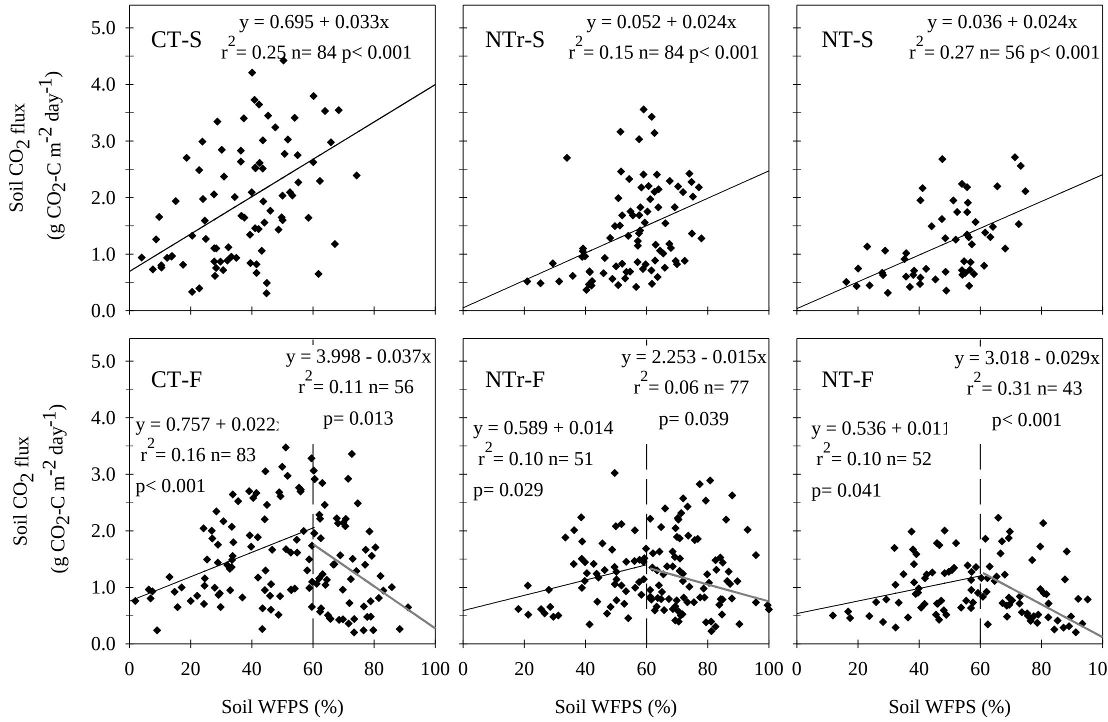

Figure 2.6. Regression analysis between soil water-filled pore space (WFPS) (0-5 cm depth) and CO_2 fluxes as affected soil tillage (CT, conventional tillage; NTr, no-tillage maintaining the maize stover; NT, no-tillage removing the maize stover) and irrigation system (S, sprinkler irrigation; F, flood irrigation). Each point represents the average value for each sampling date.

Throughout the three maize growing seasons, cumulative CO_2 emissions were significantly affected by the interaction between tillage and irrigation system (Table 2.6).

Table 2.6. Analysis of variance *F* (F-value) and *P* (*p*-values) of cumulative soil CO_2 emissions, cumulative soil CH_4 emissions and total aboveground maize biomass for 2015, 2016 and 2017 growing seasons and 15-16 and 16-17 fallow periods as affected by irrigation system, tillage system and their interactions.

	2015		15-16 fallow		2016		16-17 fallow		2017	
	F	*P*	*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*
Effects and levels	Cumulative soil CO_2 emissions									
Irrigation system	60.37	*0.004*	1.58	ns	20.07	*0.011*	9.21	ns	3.84	ns
Tillage system	50.81	*0.006*	28.16	*<0.001*	68.95	*<0.001*	20.91	*0.002*	106.5	*<0.001*
Irrigation x Tillage	22.03	*0.04*	2.07	ns	12.69	*0.003*	4.03	ns	17.65	*0.001*
	Cumulative soil CH_4 emissions									
Irrigation system	2.14	ns*	0.19	ns	1.22	ns	1.89	ns	1.05	ns
Tillage system	0.71	ns	1.39	ns	0.56	ns	1.6	*0.025*	0.65	ns
Irrigation x Tillage	4.03	ns	0.38	ns	0.32	ns	0.45	ns	0.35	ns
	Total aboveground maize biomass									
Irrigation system	18.3	*0.024*			30.74	*0.003*			33.07	*0.009*
Tillage system	2.59	ns			33.47	*<0.001*			24.03	*0.001*
Irrigation x Tillage	15.58	*0.029*			7.92	*0.013*			8.62	*0.015*

* ns, non-significant.

In all three growing seasons, cumulative soil CO_2 emissions in the CT-S treatment were greater than in the other tillage-irrigation treatments (Figure 2.7). Moreover, for both fallow periods, cumulative soil CO_2 emissions showed significant differences between tillage systems (Table 2.6). Over the two fallow periods, NT presented lower mean cumulative emissions values (0.52 and 0.54 Mg CO_2-C ha^{-1} in the 15-16 and 16-17 fallow periods, respectively) compared with CT and NTr tillage (0.77 and 0.75 Mg CO_2-C ha^{-1} in CT and 0.85 and 0.85 Mg CO_2-C ha^{-1} in NTr, for 15-16 and 16-17 fallows, respectively) (data not shown).

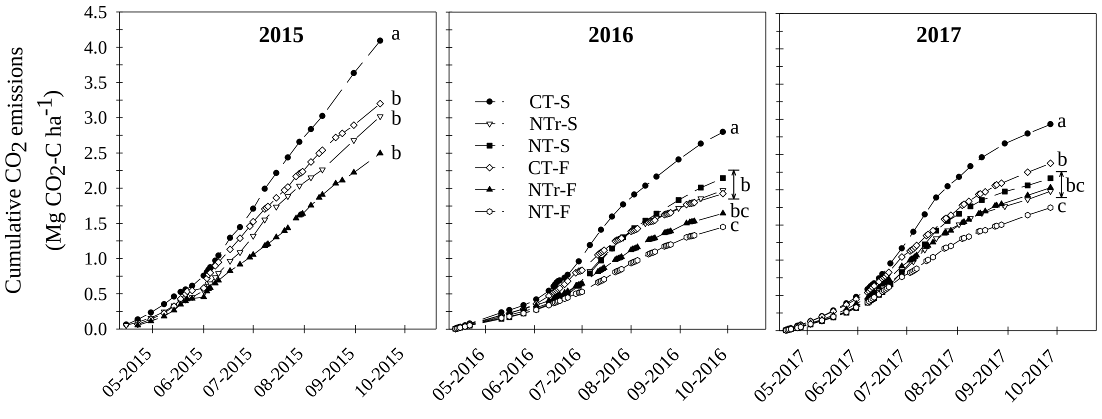

Figure 2.7. Cumulative CO_2 emissions for 2015, 2016 and 2017 growing seasons as affected by soil tillage (CT, conventional tillage; NTr, no-tillage maintaining the maize stover; NT, no-tillage removing the maize stover) and irrigation system (S, sprinkler irrigation; F, flood irrigation). For each growing season, different letters indicate significant differences between treatments at $p<0.05$.

3.3. Methane emissions

In the three maize growing seasons and the two fallow periods, no significant differences were observed for daily soil CH_4 fluxes among tillage systems (Table 2.5). Daily soil CH_4 fluxes ranged between –1.00 and 1.00 mg CH_4-C m^{-2} day^{-1} during most of the experimental time without presenting any clear pattern of CH_4 emission or consumption (Figure 2.8).

Cumulative soil CH_4 emissions were only affected by tillage during the 16-17 fallow period (Table 2.6), showing NTr lower cumulative CH_4 emissions compared with CT and NT, with mean cumulative values of -400, -91 and -106 g CH_4-C ha^{-1} for NTr, CT and NT, respectively (data not shown).

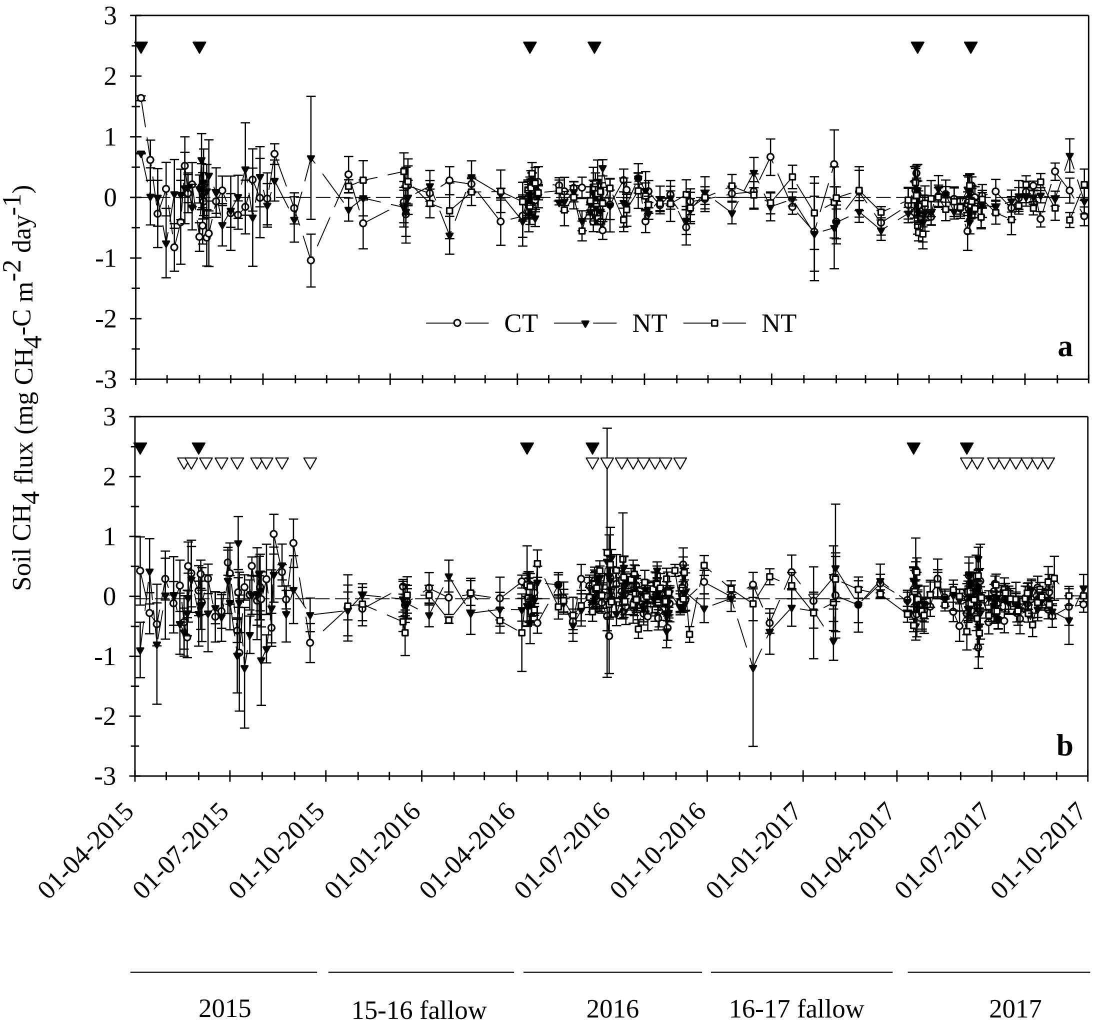

Figure 2. 8. Soil CH_4 flux for sprinkler (a) and flood (b) irrigation systems as affected by soil tillage systems: CT (conventional tillage), NTr (no-tillage maintaining the maize stover), NT (no-tillage removing the maize stover). Black triangles indicate fertilizer applications. White triangles indicate flood irrigation events. Error bars represent standard error.

3.4. Maize aboveground biomass

Over the three growing seasons, maize aboveground biomass was significantly affected by the interaction between irrigation system and tillage (Table 6). Thus, while the NTr-S treatment showed greater maize aboveground biomass values than NTr-F in 2015, in 2017 the same treatment presented greater maize aboveground biomass compared with NT-S and with NTr and NT under F irrigation. In 2016, CT resulted in higher maize aboveground biomass values compared with NT and NTr under both irrigation systems (Figure 9).

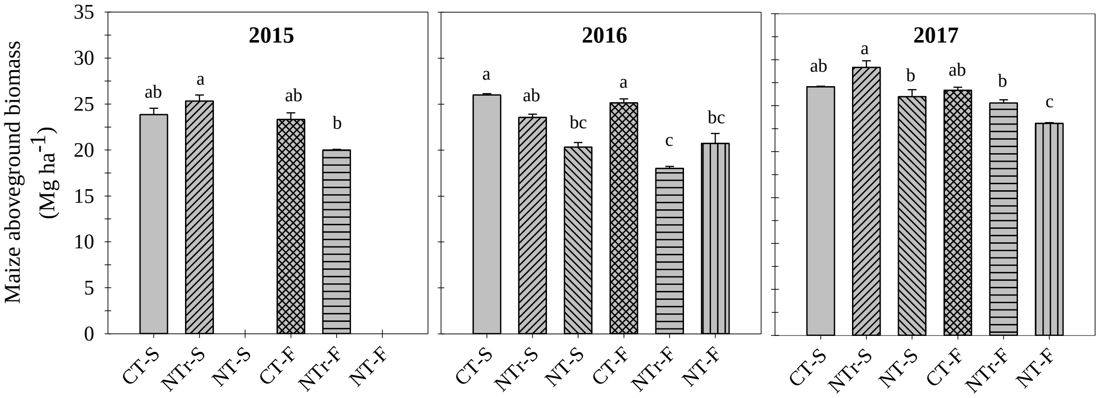

Figure 2.9. Maize aboveground biomass for 2015, 2016 and 2017 growing seasons as affected by soil tillage (CT, conventional tillage; NTr, no-tillage maintaining the maize stover; NT, no-tillage removing the maize stover) and irrigation system (S, sprinkler irrigation; F, flood irrigation). For each growing season, different letters indicate significant differences between treatments at p<0.05. Error bars represent standard error.

In addition, a positive linear relationship was observed between cumulative soil CO_2 emissions and total maize aboveground biomass for each of the three maize growing seasons (Figure 10).

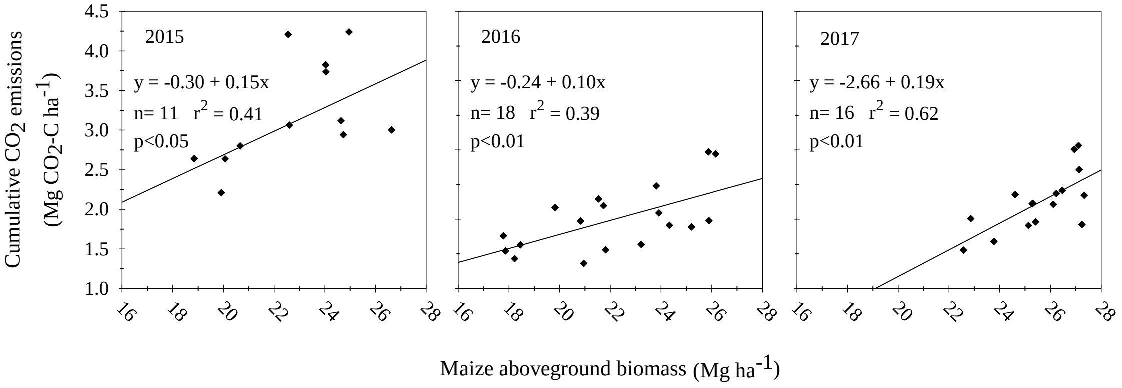

Figure 2.10. Regression analysis between cumulative soil CO_2 emissions and maize aboveground maize biomass. Each point represents the value of each tillage-irrigation treatments.

4. Discussion

Overall, the results obtained in our three maize growing seasons field experiment showed that tillage and irrigation system due to their capacity to modify soil water content and soil temperature had a significant impact on soil CO_2 emissions but not on CH_4 emissions. Likewise, carbonate dissolution is one of the main abiotic processes that can contribute to the CO_2 emissions from the soil in this semiarid climate. However, our study was focused on the biologically-derived C emissions.

Daily soil CO_2 fluxes presented a temporal pattern similar to that observed by Franco-Luesma *et al*. (2019) and Pareja-Sánchez *et al*. (2019) for irrigated maize fields under Mediterranean conditions. This temporal evolution of soil CO_2 fluxes was characterized by low values during the fallow period, followed by a rapid increase of the emissions concomitant with the growth of the maize crop and reaching maximum values at the maize tasseling stage (VT) to decrease afterwards until the fallow period when the lowest values were measured.

This soil CO_2 flux pattern found during the maize growing season was partially explained by the effect of soil temperature, as it was demonstrated by the positive relationship found between these two variables as it has also been reported previously (Howard and Howard, 1993; Lloyd and Taylor, 1994; Fang and Moncrieff, 2001). The different response of soil CO_2 fluxes over the different periods (fallow vs growing season) was related with the combined effects of soil temperature and the presence of a crop and its growth that regulate the CO_2 emissions from the soil (Davidson and Janssens, 2006). Thus, the greater soil temperature, the root-derived CO_2 and the increase of C sources coming from the root exudates would have led to better conditions for the production of CO_2 in the soil during the growing season period than over the fallow period, when there are not root-derived CO_2 and colder temperatures can affect soil biological processes by the deactivation of enzymes (Sharpe & De Michelle 1977; Rochette and Flanagan, 1997).

Soil WFPS also affected soil CO_2 fluxes but with different response depending on the irrigation system. Hence, under F irrigation, soil CO_2 fluxes increased with WFPS up to 60% value but from this WFPS value onwards soil CO_2 fluxes decreased. In our soil conditions, this value of 60% WFPS is usually coincident with the field capacity point. Moreover, the 60% WFPS has been identified as a threshold for microbial activity since values higher than 60% WFPS lead to a reduction ofthe O_2 availability in soils and, thus, to a decrease of soil microorganism activity, one of the main processes involved in the production of CO_2 in soils (Linn and Doran, 1984). Under F irrigation, large amounts of water (from 80 to 100 mm) was applied in each irrigation event. These large additions of water usually increase WFPS to values above 60% during the following four days after the irrigation event. In contrast, S irrigation resulted in steady soil WFPS values (about 50-60%) over the growing season, which were close to the optimum WFPS values for microorganism activity (Linn and Doran, 1984) and, thus, contributing to the greater soil CO_2 fluxes found in S irrigation compared with F irrigation.

Cumulative soil CO_2 emissions measured in this work were similar to those reported by Forte *et al*. (2017) who compared the effects of minimum tillage (rotary harrow) and conventional tillage (mouldboard ploughing to 30 cm depth) on soil CO_2 emissions under irrigated maize in Campania (southern Italy). In our work, over the three maize growing seasons, S irrigation increased cumulative soil CO_2 emission by 24% compared with F irrigation. This increase of cumulative soil CO_2 emissions under S irrigation can be related with the effect of the irrigation system on soil WFPS, as explained before, but also with the effect of the total maize aboveground biomass on cumulative soil CO_2 emissions since maize root respiration can account for about 50% of the total soil respiration during the maize vegetative stages (Rochette and Flanagan, 1997). Thus, a positive impact of maize aboveground biomass on soil CO_2 emissions, as well as the linear increase of soil respiration with WFPS observed under S irrigation, could explain the higher cumulative soil CO_2 emissions measured under this irrigation system.

Throughout the three maize growing seasons, S irrigation increased by 10% the maize aboveground biomass compared with F irrigation. Segal *et al*. (2006), in a lysimeter study carried out at Arava research station (Arava Valley, Israel), observed increments of ornamental sunflower yields when the irrigation frequency was increased. In general, higher irrigation frequency results in greater soil water content and higher water potential in the root zone favouring plant water uptake. Consequently, in our study, the higher irrigation frequency in S irrigation compared with F irrigation (two times per week under S irrigation vs one time every 10 days under F irrigation) led to a relatively steady high WFPS levels in S irrigation during the growing season, which contributed to attain high crop yields. On the other hand, Ren *et al*. (2016) observed negative impacts on maize growth when water was maintained above the soil surface for 3 or 6 days. In our study, water above the soil surface was observed under F irrigation at least during the first 24h after the irrigation event. Then, WFPS started to decrease rapidly reaching values lower than 30%, which probably resulted in lower plant water uptake due to a lower water potential in the root zone. These facts would explain the lower aboveground biomass obtained in the F irrigation system compared with S irrigation.

In addition, CT increased cumulative soil CO_2 emissions by 21 and 39% compared with NTr and NT, respectively. The direct incorporation of the maize stover into the soil by tillage operations could increase the availability of C for soil microorganisms, thus increasing CO_2 production. This result is in agreement with the findings reported by Alluvione *et al*. (2009) in a similar experiment comparing conventional tillage and no-tillage in an irrigated maize monoculture. Moreover, several studies (e.g. Blanco-Canqui and Lal, 2008; Moebius-Clune *et al*., 2008; Stetson *et al*., 2012) have found that the removal of the maize stover from the field reduces SOC content. This fact would explain the lower cumulative soil CO_2 emissions observed in NT compared with NTr and CT, in agreement with the results reported by Maris *et al*. (2018) for sprinkler-irrigated maize under Mediterranean conditions in which the maize stover was removed or incorporated to the soil by tillage operations. Therefore, the results presented in this work supported the initial hypothesis of greater soil CO_2 emissions for the conventional tillage under sprinkler irrigation.

Soil CH_4 fluxes measured in this work were in the range of values reported by Álvaro-Fuentes *et al*. (2016) for sprinkler-irrigated maize in Mediterranean areas. Throughout the entire measurement period, no significant differences in soil CH_4 fluxes between tillage systems were observed in any of the irrigation systems. Higher WFPS values measured under F irrigation, reaching values of 100% right after the water application, did not increase the CH_4 emissions. This fact could be related with the methanogenesis process, which requires strict anaerobic soil conditions. Moreover, a redox potential value (Eh) of –150 mV is considered as critical value for CH_4 production, being necessary a progressive reduction of the different soil electron acceptors O_2, NO_3^-, Mn^{4+}, Fe^{3+}, SO_4^{2-} to reach this critical value of Eh (Wang et al., 1993; Peters and Conrad, 1996). Likewise, the production of CH4 soil can be inhibited by toxic effects (nitrite, NO_2^-) and by competition for H_2 between denitrifiers and methanogens (Kluber and Conrad, 1998). Therefore, the short period in which the flood irrigation system presented values of WFPS close to 100% (first 24 h after the irrigation event) as well as the presence of an important amount of NO_3^- could explain the absence of CH_4 production events associated with the flood irrigation.

In general, over the three maize growing seasons and the two fallow periods, cumulative CH_4 emissions were negative, this meaning that soil acted as a CH_4 sink, as observed by Sanz-Cobeña *et al*. (2014) under Mediterranean conditions. Methane consumption showed a trend to be greater under NTr, being 3.2 and 1.5 times higher compared with CT and NT tillage, respectively. These results were similar to those obtained by Pareja-Sánchez *et al*. (2019) in an irrigated maize field study under Mediterranean conditions, in which greater CH_4 uptake under no-tillage has been reported. Similarly, in soil core incubation experiments, Hütsch (2001) and Jacinthe *et al*. (2014) observed greater methanotrophic activity for agricultural soils under no-tillage. The increase in CH_4 uptake under no-tillage systems, especially for NTr treatments, could be related with the lower disturbance of the topsoil compared with tillage systems (Ussiri *et al*., 2009). No-tillage systems may improve soil structure resulting in better soil gas diffusivity and an optimal circulation of gases throughout the soil profile, thus providing a more suitable condition for methane consumption (Ball *et al*, 1999; Smith *et al*., 2003; Ball *et al*. 2008). Given this, our initial hypothesis of greater CH_4 emissions under F irrigation was not supported by the observed results.

5. Conclusions

In this experiment, it has been observed that under Mediterranean conditions two important management practices (irrigation and tillage) have a significant impact on the soil carbon cycle. Specifically, over three maize growing seasons, both irrigation and soil tillage system affected soil CO_2 emissions, but not CH_4 emissions. More stable soil WFPS values provided by sprinkler irrigation system compared with flood irrigation favoured maize growth, thus leading to optimal conditions for the microorganism activity, and, ultimately, to greater soil CO_2 emissions compared with flood irrigation. Moreover, the incorporation into the soil of the maize stover by tillage operations increased the soil CO_2 emissions compared with the no-tillage systems. Soil CH_4 emissions were affected by the tillage system in one out of the two fallow periods, while the irrigation system did not impact on these emissions. Over the entire measurement period, soil acted as a sink of CH_4 with minimum differences between irrigation systems and a trend to greater CH_4 consumption under no-tillage systems.

The results of this work suggest that no-tillage maintaining the crop stover and sprinkler irrigation is a win-win strategy for irrigated maize under Mediterranean conditions, which results in lower soil CO_2 emissions and the maintenance of maize aboveground biomass yields, compared with conventional tillage and flood irrigated systems.

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Declaration of Competing Interest

The authors declare no conflict of interest

Capítulo 3

Irrigation and tillage effects on soil nitrous oxide emissions in maize monoculture

S. Franco-Luesma, J. Cavero, D. Plaza-Bonilla, C. Cantero-Martínez, G. Tortosa, E. J. Bedmar, J. Álvaro-Fuentes. 2020, *Agronomy Journal* 112, 56-71

Irrigation and tillage effects on soil nitrous oxide emissions in maize monoculture

S. Franco-Luesma, J. Cavero, D. Plaza-Bonilla, C. Cantero-Martínez, G. Tortosa, E. J. Bedmar, J. Álvaro-Fuentes

ABSTRACT

Irrigation and soil management can impact soil nitrous oxide (N_2O) emissions. Flood and sprinkler irrigation systems together with conventional tillage are the main practices used in the high yielding maize systems in Mediterranean Spain. The objective of this field work was to quantify the effect of the irrigation system (i.e. flood, F; and sprinkler, S) and the soil tillage system (i.e. conventional tillage, CT; no-tillage maintaining the maize stover, NTr; and no-tillage removing the maize stover, NT) on the N_2O emissions from the soil during three years (2015, 2016 and 2017). S irrigation, with mean values of 1.35 kg N_2O-N ha^{-1} year^{-1} throughout the three years, obtained 42% lower N_2O emissions than F irrigation. On average of the three growing seasons, yield-scaled N_2O emissions by grain yield and by grain N uptake in F irrigation were two-fold higher than in S irrigation. Moreover, in one out of three growing seasons (2017), no-tillage systems (i.e. NTr and NT) showed greater yield-scaled N_2O emissions compared with CT. The higher maize grain yield with the S irrigation compared to F irrigation, as well as the lower N_2O emissions reported under S irrigation resulted in the reduction of the yield-scaled N_2O emissions. Our findings highlight the role of sprinkler irrigation decreasing N_2O emissions in comparison to flood irrigation in Mediterranean agroecosystems.

1. Introduction

Agricultural management practices such as irrigation, stover management, tillage and nitrogen fertilization have an important role on soil greenhouse gas emissions (GHG) and particularly on N_2O emissions (Reay *et al.*, 2012; IPCC, 2014). The production of N_2O in the soil is the result of the interaction between biotic and abiotic factors. Soil microbial communities throughout the nitrification, denitrification and nitrifier denitrification processes control soil N_2O production, which are influenced by the soil water-filled pore space (WFPS) (Bateman and Baggs, 2005; Bremner, 1997; Firestone and Davidson, 1989). Under aerobic conditions, when WFPS range between 35 to 60%, nitrification is the main process involved in the N_2O production. However, when WFPS is above 60% up to 80%, denitrification is the principal process responsible of N_2O production in the soil due to anaerobic conditions (Linn and Doran, 1984). In addition to biotic factors and WFPS, abiotic factors such as soil nitrate and soil ammonium contents, soil temperature and soil organic carbon are also key factors on the production and dynamics of N_2O in the soil (Davidson *et al.*, 2000; Bouwman *et al.*, 2002; Butterbach-Bahl *et al.*, 2013).

Trost *et al.* (2013) in a review of eight studies around the world about the effect of irrigation on soil N_2O emissions reported that soil N_2O emission increased after irrigation because increased the WFPS. Moreover, in Mediterranean areas, several studies have concluded that irrigation is an important agricultural practice contributing to soil N_2O emissions (Aguilera *et al.*, 2003b; Cayuela *et al.*, 2017; Sanz-Cobeña *et al.*, 2017). Similarly, Deng *et al.* (2018) evaluated the impact of the irrigation system on soil N_2O emissions for the California cropland using the DNDC model and predicted a reduction of 38% on soil N_2O emissions under sprinkler irrigation compared with flood irrigation.

Likewise, other studies reported different effects of tillage on soil N_2O emissions. For instance, Ball *et al.* (1999) and Venterea *et al.* (2011) observed an increase on soil N_2O

emission under no-tillage. However, Ussiri *et al*. (2009) and Omonode *et al*. (2011) reported lower emissions under no-tillage than under conventional tillage. In rainfed barley (*Hordeum vulgare* L.) monoculture in NE Spain, Plaza-Bonilla *et al*. (2018) recently observed a reduction on the N_2O emitted per unit of yield under no-tillage systems when compared to conventional tillage. This last work is in agreement with the results obtained by the same authors in a previous work (Plaza-Bonilla *et al*., 2014), in which they observed lower or similar emissions in no-tillage systems compared to conventional tillage systems, when no-tillage was performed for more than 10 years. However, in the first years after the implementation of no-tillage, they obtained higher emissions under no-tillage than conventional tillage, similar to the findings of Van Kessel *et al*. (2013).

Crop stover removal may influence soil microclimate conditions, favouring higher soil temperature and r soil water evaporation (Sauer *et al*., 1998). Additionally, a decrease on soil organic carbon (SOC) and a degradation of soil physical properties are associated with removing the stover from the field (Blanco-Canqui and Lal, 2008). Then, crop stover management could affect soil N_2O emissions, but their effect is no clear. Jin *et al*. (2017) observed higher N_2O emissions in irrigated maize when maize stover was maintained in the field. However, Bent *et al*. (2016) observed higher soil N_2O emissions when maize stover was removed in Ontario, Canada.

In Spain, maize is one of the main irrigated crops. Over the last 13 years, (2004-2017) maize accounted around 40% of the total irrigated cereal surface (MAPAMA, 2017b). Flood (F) and sprinkler (S) irrigation are the main irrigation systems used in Spain for maize with the 53% and 28% of the total maize irrigated surface through the period 2007-2017, respectively (MAPAMA, 2017b). In the last years, sprinkler irrigation of maize has significantly increased, due to the increase in crop yield and the automation of the irrigation (Playán and Mateos, 2006; Lecina *et al*., 2010). Moreover, in Spain, the adoption of no-tillage is low with only 10% of the total cereal surface and mostly under rainfed conditions (MAPAMA, 2017a).

In the last decade, several experiments have been carried out to study agronomical aspects of sprinkler irrigation systems regarding to the crop water requirements and crop performance under Mediterranean climatic conditions (Cavero *et al*., 2003; Robles *et al*., 2017; Cavero *et al*., 2018). However, limited studies have been done to assess the impact of different agronomical practices on N_2O emissions in Mediterranean climatic conditions under irrigation and mostly focused on nitrogen (N) fertilization management (Álvaro-Fuentes *et al*., 2016; Maris *et al*., 2018). Similarly, a limited number of studies have been conducted to compare the effect of different tillage practices on N_2O emissions in Mediterranean climatic conditions and all these studies were carried out under rainfed conditions (Plaza-Bonilla *et al*., 2014; Plaza-Bonilla *et al*., 2018).

This study was aimed to assess the impact of irrigation system, specifically sprinkler and flood irrigation systems, and the soil tillage system, conventional tillage and no-tillage systems, on soil N_2O emissions under Mediterranean climatic conditions. Since sprinkler irrigation allows to apply lower amounts of water at higher frequency than flood irrigation, we hypothesize that irrigation system would result in different soil water content during the growing season which would affect N_2O emissions and maize yields. Besides, given that tillage has also shown to affect N_2O emissions, we also hypothesize that irrigation system would interact with tillage.

2. Material and methods

2.1 Site description

A field study was performed during three maize seasons (2015-2017) at the experimental farm of the Experimental Station of Aula Dei, Zaragoza, Spain (41º 42´ N, 0º 49´ W, 225 m altitude). The area is characterized by a Mediterranean semiarid climate with annual mean air temperature of 14.1 ºC, annual precipitation of 298 mm and grass reference crop evapotranspiration (ETo) of 1243 mm and silty loam soils (Table 3.1).

Table 3.1. Soil characteristics of the experimental field.

Depth	pH	SOC†	$CaCO_3$	Sand	Silt	Clay	FC‡	WP§
––m––				–––––– % ––––––			–– m^3 m^{-3} ––	
0.00−0.05	7.98	1.93	34.9	15.7	61.9	22.3	0.26	0.14
0.05−0.10	8.20	1.85	34.9	15.4	62.9	21.7	0.26	0.14
0.10−0.25	8.03	1.75	35.1	15.9	62.1	22.0	0.25	0.16
0.25−0.50	7.95	1.51	35.3	16.0	63.6	20.3	0.25	0.16

† Soil organic carbon. ‡ FC, Field capacity (-0.033 MPa). § WP, Wilting point (-1.5 MPa).

2.2. Experimental design

Previously to the establishment of the experiment, the field had been under cultivation, alternating different cereal crops, mainly irrigated winter wheat (*Triticum aestivum* L.) and maize under conventional tillage and flood irrigation. The previous crop was winter wheat that was grown during one year (2014). In addition, this experimental field had the possibility to install a hand-move sprinkler irrigation system. Therefore, in 2015, the field was divided in two parts, one irrigated by flood irrigation and the other one by a hand-move sprinkler irrigation of 18 m × 18 m sprinkler square spacing and with a sprinkler application rate of 5 mm h^{-1}.

The experimental layout consisted on a split-block design with two factors and three replicates per treatment. Two irrigation systems (i.e. sprinkler, S, and flood, F) and three soil tillage systems (i.e. conventional tillage, CT; no-tillage maintaining the maize stover, NTr; and no-tillage removing the maize stover, NT) were combined obtaining six different treatments with a 6 x 18 m plot size.

In CT, tillage operations previous to maize sowing consisted in one pass of a subsoiler to 30 cm depth followed by one pass of a disk harrow both performed on December 2014, 2015 and 2016 and one pass of a rotary tiller just before maize sowing on April 2015, 2016 and 2017. No-tillage consisted in a total herbicide application (5 L glyphosate (36%)) before sowing. All tillage operations were made with commercial size machines. Maize cv. Pioneer P1785 was sown on 09 April 2015, 12 April 2016 and 17 April 2017 in rows 75 cm apart at a planting density of 89,500 plants ha^{-1}. Fertilizer operations were the same in all treatments consisting in one application of 800 kg ha^{-1} of a NPK (8 (ammonium N ($N\text{-}NH_4^+$))-15-15) compound fertilizer before planting on 09 April 2015, 12 April 2016 and 17 April 2017 and 740 kg ha^{-1} of calcium ammonium nitrate N-27% (13.5% ammonium N ($N\text{-}NH_4^+$) – 13.5 nitrate N ($N\text{-}NO_3$)) as top dressing (V6 – V8 growth stage) on 02 June 2015, 13 June 2016 and 07 June 2017. Harvest with a commercial combine was carried out on 30 September 2015, 5 October 2016 and 17 October 2017. The stover residue was chopped and spread over the soil by a chopper machine. Weed and pest control were carried out following the best management practices of the area. The crop stover of the NT treatment was removed manually on 23 December 2015, and 11 October 2016. Thus, the NT treatment was incorporated into the experimental design the second growing season (2016) after the 2015 harvest, when the crop residue was removed.

Maize daily crop evapotranspiration (ETc) was computed by multiplying the reference evapotranspiration (ETo), obtained by the FAO Penman-Monteith method (Allen *et al*., 1998), and the crop coefficient (Kc) determined using an equation developed in the same experimental farm based on a function of the thermal time (Kiniry, 1991; Martínez-Cob, 2008). Crop irrigation requirement (CIR) for each week was determined by subtracting the effective precipitation, 75% of the total weekly precipitation (Dastane, 1978), to the weekly ETc considering an irrigation efficiency of 85%. Irrigation water was applied by sprinkler irrigation to all the plots until V6 growth stage to favour plant emergence and to avoid differences in plant density among treatments.

Irrigation frequency depended on the irrigation system. Thereby, during the three growing seasons, sprinkler irrigation events occurred two times per week (Monday and Wednesday), whereas flood irrigation events occurred every 10-14 days. Although the sprinkler irrigation system allows applying an exact irrigation dose, this is not possible with flood irrigation. Thus, the irrigation water applied in the sprinkler system was each year within 2% of the CIR. However, the irrigation water applied in the flood system was 16% to 30% higher than in the sprinkler system (Table 3.2). Irrigation applied in the sprinkler system was measured with a flowmeter and in the flood system with a Cipolletti weir. All tillage treatments under the same irrigation system received the same amount of irrigation water.

Table 3.2. Calculated crop evapotranspiration (ETc), crop irrigation requirement (CIR) and irrigation water applied in both irrigation systems (sprinkler and flood) applied in the maize growing season of 2015, 2016 and 2017.

Season	ETc	CIR	Irrigation	
			Sprinkler	Flood
	mm			
2015	719	712	729	950
2016	763	722	708	824
2017	744	693	686	874

2.3. Air sampling and N_2O analyses

Two polyvinyl chloride (PVC) rings (31.5 cm internal diameter) per plot were inserted 10 cm into the soil on April 2015, before to start the soil gas measured. The rings were only removed at tillage, planting and harvesting operations. Soil N_2O emissions were measured with the closed chamber technique (Hutchinson and Moiser, 1981) from April 2015 to September 2017, using PVC chambers (20 cm height) covered with a reflective layer of aluminium film to diminish internal increases in temperature. On the center of the top of the chamber, a chlorobutyle septum was attached as a sampling port.

Soil N_2O emissions were measured weekly from planting until mid-August (VT growth stage), every two weeks from mid-August until harvest (late September) and every three weeks during the fallow period (October-March). During tillage operations, soil air samples were taken 24 h before, and 24 and 96 h after the tillage operations. Throughout the fertilization events, soil air samples were taken 24 h before and 24, 48, 72, 96, 144 and 192 h after fertilization. Finally, soil air sampling frequency was increased during the five days after of each irrigation event over the three growing seasons, in order to characterize the flood irrigation events.

Air samples were collected at 0, 20 and 40 min after chamber closure and 20 mL of air sample were transferred to an evacuated 12-mL Exetainer ® borosilicate glass vial (model 038W, Labco, High Wycombe, UK). Air temperature inside the chamber was measured introducing thermometers in the chamber before the enclosed of the chambers.

Concentration of N_2O in the air samples was measured by gas chromatography using an automatically injection system (PAL3 autosampler, Zwingen, Switzerland). The gas chromatography systems (Agilent 7890B, Agilent, Santa Clara, CA, United States) was equipped with an electron capture detector (ECD) and a HP-Plot Q column (15 m long, 320 µm in section and 20 µm thick), using He as a carrier gas at 2 mL min^{-1}. The injector and the oven temperatures were set to 50 and 35ºC, respectively. The temperature of the ECD was set to 280ºC and a 5% methane in Argon gas mixture at 30 mL min^{-1} was used as a make-up gas. Ultra-high purity N_2O standards (Carburos Metálicos, Barcelona, Spain) was used to calibrate the system. Emission rates (mg N_2O-N m^{-2} day^{-1}) were calculated by the linear increase in the N_2O concentration during the chamber enclosure time and corrected by the internal air chamber temperature.

2.4 Soil, biomass and grain yield sampling and analyses

Soil ammonium (NH_4^+) and nitrate (NO_3^-) contents were quantified on each air sampling date from the 0–5 cm soil layer by extracting 50 g of fresh soil with 100 mL of 1 M KCl. The extracts were frozen and later analysed with a continuous flow autoanalyser (Seal Autoanalyser 3, Seal Analytical, Norderstedt, Germany). Concentration values were transformed to kg N ha^{-1} using the soil bulk density and corrected by the soil moisture. Soil temperature and moisture content were measured using a Crison TM 65 probe (Carpi, Italy) and GS3 soil moisture probes (Decagon Devices, Pullman, WA), respectively. Volumetric soil moisture content and soil bulk density, measured once per month for each plot by the cylinder method (Grossman and Reinsch, 2002), were used to calculate soil water filled pore space (WFPS) assuming a soil particle density of 2.65 Mg m^{-3}.

Maize grain yield for each plot was determined by weighing the total grain harvested by a commercial combine and corrected to 14% moisture content. A grain subsample from each plot was dried at 60 ºC for 48 h and weighed to determine maize grain moisture. Afterwards grain subsamples were grinded and analysed to determine the N content by dry combustion (TruSpec CN, LECO, St Joseph, MI, USA).

2.5 Data analysis

Cumulative soil N_2O emissions on a mass basis (i.e., kg N ha^{-1}) were quantified using the trapezoid rule (Levy et al., 2017). Different repeated measures analysis of variance (ANOVA) with the REML (Restricted Maximum Likelihood) approach were performed for logarithm transformed data of N_2O fluxes, soil NH_4^+ and NO_3^- content, and WFPS, and soil temperature with soil tillage system, date of sampling and their interactions as sources of variation. Analyses were performed separately for sprinkler and flood irrigation and for 2015, 2016 and 2017 growing seasons (i.e. April - October) and for 15-16 and 16-17 fallow period (i.e. November – March).

In addition, different ANOVA were performed for 2015, 2016 and 2017 growing seasons for cumulative N_2O emissions, grain yield, N uptake by the grain, grain yield N_2O scaled emissions and grain N-uptake N_2O scaled emissions with irrigation system, soil tillage system and their interactions as sources of variation. When significant, differences between treatment means were evaluated by Tukey test at 5% significance level. The relationships between soil N_2O flux and concentration of soil soil NH_4^+ and NO_3^-, WFPS and soil temperature was evaluated by the significance of Pearson coefficients. All statistical analyses were performed with JMP 10 statistical package (SAS Institute Inc., 2012).

3. Results

3.1. Environmental conditions

Daily precipitation, mean daily air temperature and daily reference evapotranspiration, ETo, for the entire measurement period are shown in Fig. 3.1.

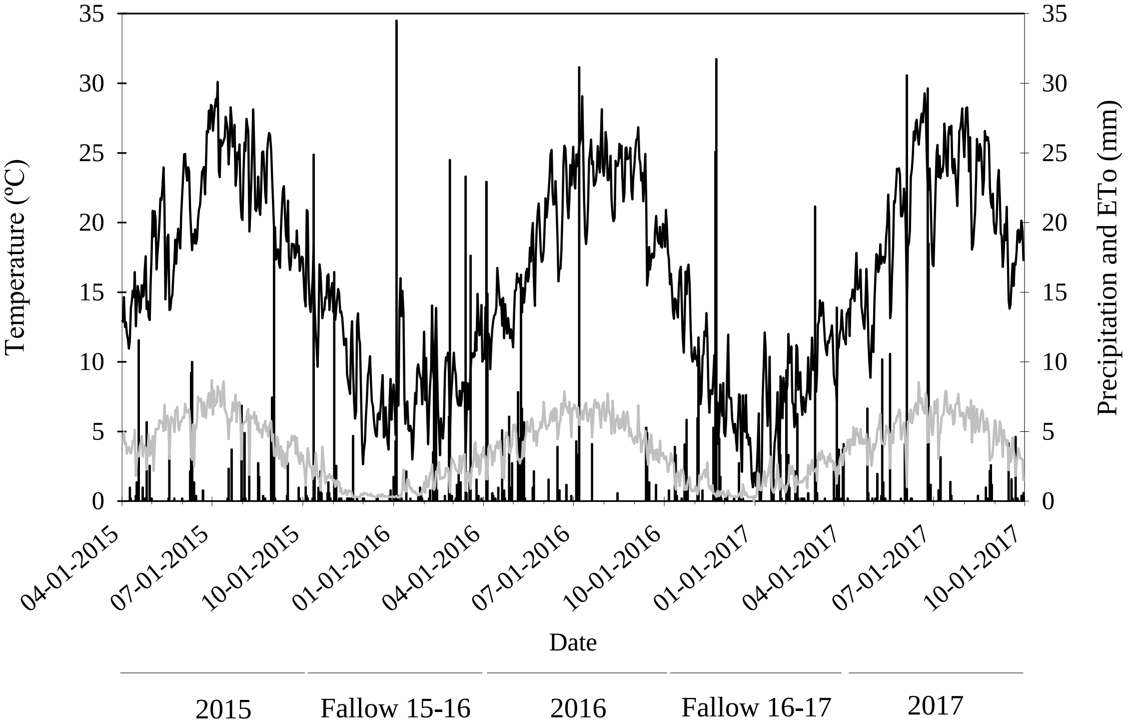

Figure 3.1. Air temperature (black continuous line), precipitation (vertical bars) and reference evapotranspiration (ETo) (grey continuous line).

On average throughout the maize growing seasons, air temperature was 21.9, 21.3 and 21.8ºC for 2015, 2016 and 2017 growing seasons (hereafter 2015; 2016; 2017), respectively. During the periods between growing seasons (i.e. fallow period), mean air temperature was 9.2 and 9.1ºC for fallow 15-16 and fallow 16-17, respectively. Total precipitation during fallow periods were 180 and 272 mm for fallow 15-16 and fallow 16-17, respectively. Whereas, during the growing seasons, total precipitation was 92 (2015), 111 (2016) and 139 mm (2017).

3.2. Soil WFPS, soil temperature and soil ammonium and nitrate content

Over the entire experimental time, WFPS was significantly affected by the interaction between tillage system and sampling date in both irrigation systems (Table 3.3, Fig. 3.2a and 2b). Under F irrigation, in which the crop irrigation requirement (CIR) of ten-fourteen days was applied in one irrigation event, large fluctuations on WFPS values were observed between two events. Before the irrigation event, WFPS values ranged between 20 and 30%, but during the 24 h after the irrigation event WFPS was close to 100% and decreased rapidly hereafter (Fig. 3.2b). In contrast, S irrigation showed steadier WFPS values, with average WFPS values of 46% throughout the three growing seasons and without reaching values higher than 80% WFPS (Fig. 3.2a).

Soil temperature was significantly affected by the interaction between tillage and sampling date in all measurement periods except during the fallow 15-16 for S irrigation (Table 3.3, Fig. 3.2c and 2d). Over the three growing seasons, mean soil temperature was 19.7 (2015), 17.7 (2016) and 18.2ºC (2017) in S irrigation, whereas under F irrigation mean soil temperature values were 19.4, 18.9 and 19.2ºC for 2015, 2016 and 2017 respectively.

Table 3.3 ANOVA (*p-value*) for soil water-filled pore space (WPFS) (0-5 cm), soil temperature (5 cm depth), and soil nitrate and ammonium content (0–5 cm) for sprinkler and flood irrigation as affected by tillage, date and their interaction over the different measurement periods.

	Period				
Variable and Effect	2015	Fallow 15-16	2016	Fallow 16-17	2017
			Sprinkler irrigation		
WFPS					
Tillage	*0.049*	*0.001*	*<0.001*	*0.047*	*<0.001*
Date	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*
Tillage x Date	*<0.001*	*<0.003*	*<0.001*	*<0.001*	*<0.001*
Soil Temperature					
Tillage	*0.024*	NS	*<0.001*	NS	*0.032*
Date	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*
Tillage x Date	*<0.001*	NS	*<0.001*	*0.008*	*<0.001*
Soil nitrate					
Tillage	NS	NS	NS	NS	*0.036*
Date	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*
Tillage x Date	NS	*0.016*	NS	*0.008*	*0.009*
Soil ammonium					
Tillage	NS	NS	NS	NS	NS
Date	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*
Tillage x Date	*<0.001*	NS	NS	NS	NS
			Flood irrigation		
WFPS					
Tillage	NS	*<0.001*	*0.002*	*0.01*	*<0.001*
Date	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*
Tillage x Date	*<0.001*	*<0.001*	*<0.001*	*0.008*	*<0.001*
Soil temperature					
Tillage	NS	*0.014*	*<0.001*	*<0.001*	NS
Date	*<0.001*	*<0.001*	*0.021*	*0.008*	*<0.001*
Tillage x Date	*<0.001*	*0.009*	*<0.001*	*0.003*	*<0.001*
Soil nitrate					
Tillage	NS	NS	NS	NS	NS
Date	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*
Tillage x Date	NS	*0.025*	*<0.001*	NS	NS
Soil ammonium					
Tillage	NS	NS	NS	NS	NS
Date	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*
Tillage x Date	*<0.001*	NS	NS	NS	*0.006*

NS, non-significant

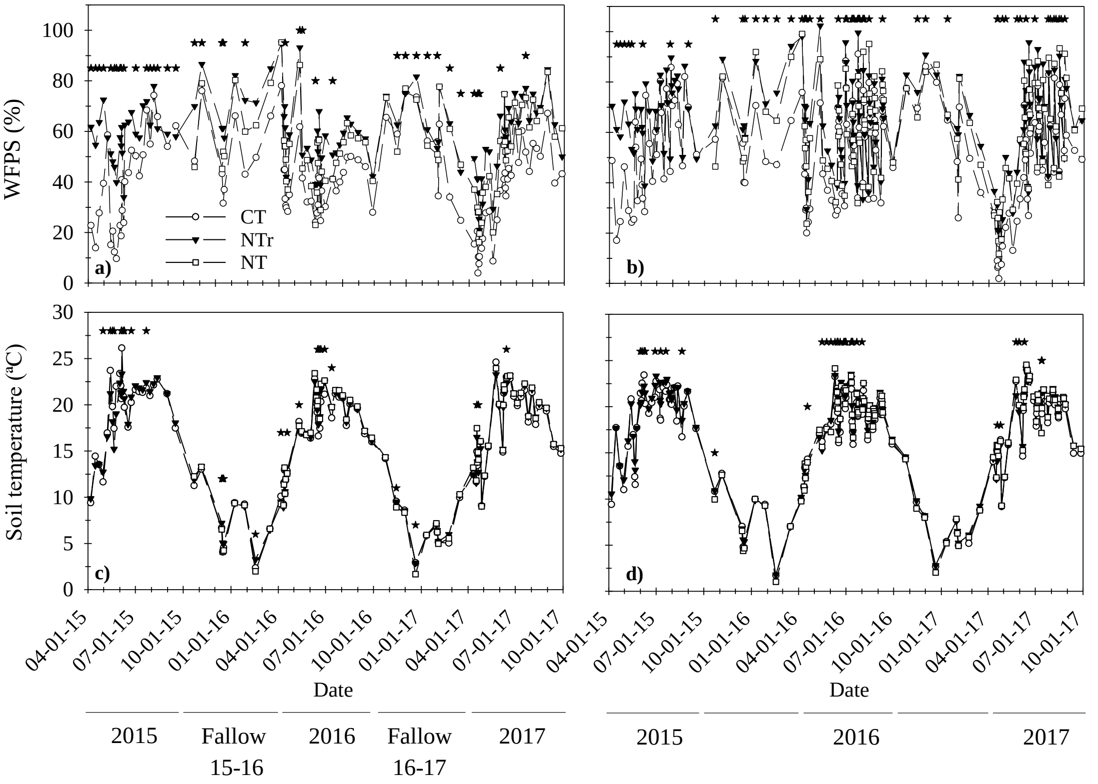

Figure 3.2. Soil water-filled pore space (WFPS) in the 0-5 cm depth and soil temperature at 5 cm depth for sprinkler (a, c) and flood (b, d) irrigated plots as affected by soil tillage systems: CT (conventional tillage), NTr (no-tillage maintaining maize stover), NT (no-tillage removing maize stover). *Indicates significant differences between treatments within a date at $p<0.05$.

In both irrigation systems, soil NO_3^- content (0-5 cm depth) increased after the pre-planting application of fertilizer for a period of 45 days. The maximum values were reached during the top dressing application (V6 growth stage) of nitrogen fertilizer and lasted 4 days, then soil NO_3^- content started to decrease (Fig. 3.3a and 3b). A significant interaction between soil tillage and sampling date was observed for both fallow periods and during 2017 under S irrigation, while under F irrigation the significant interaction between soil tillage and sampling date affected soil NO_3^- content in 2016 and fallow 15-16 (Table 3.3).

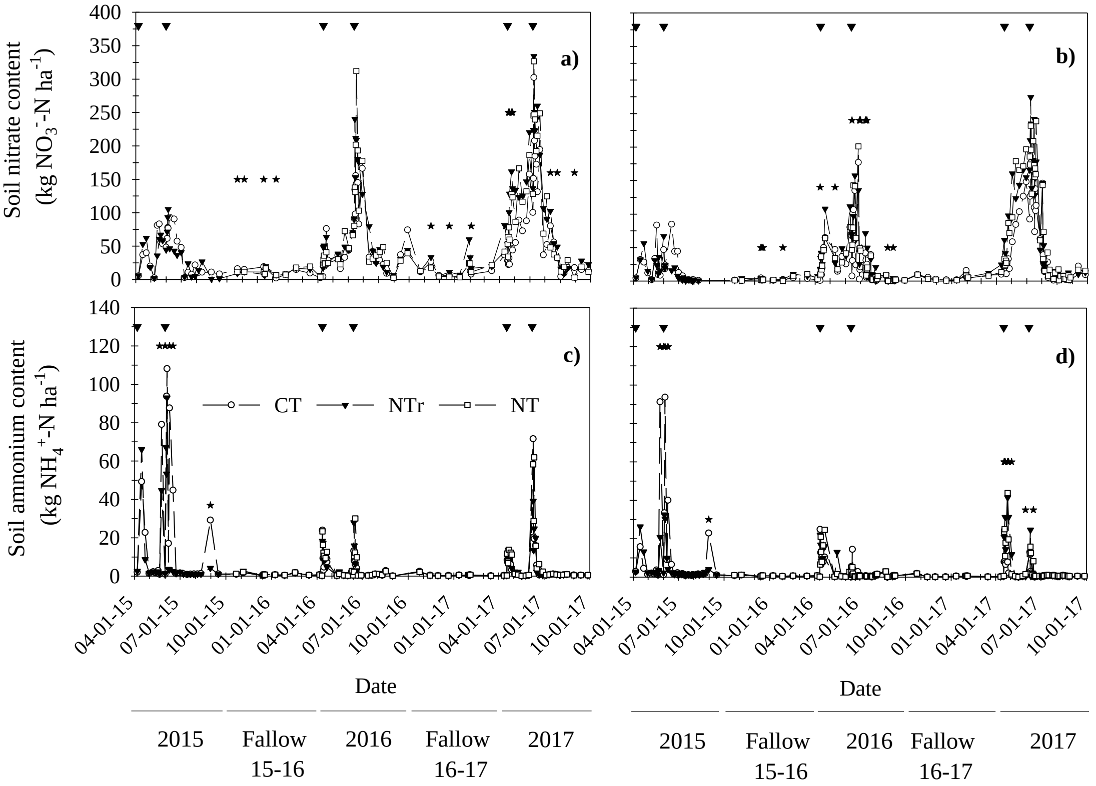

Figure 3.3. Soil nitrate content (NO_3^--N) (0-5 cm) and soil ammonium content (NH_4^+-N) (0-5 cm) for sprinkler (a, c) and flood (b, d) irrigation systems as affected by soil tillage system: CT (conventional tillage), NTr (no-tillage maintaining maize stover), NT (no-tillage removing maize stover). *Indicates significant differences between treatments within a date at $p<0.05$. Black triangles indicate N fertilizer applications.

Soil NH_4^+ content remained low during the most of the experimental time, showing a strong increase after the fertilizer applications (Fig. 3.3c and 3d). Under S irrigation a significant interaction between soil tillage and sampling date was observed in 2015, while under F irrigation the significant interaction between soil tillage and sampling date affected soil NH_4^+ content in 2015 and 2017 (Table 3.3).

3.3 Nitrous oxide emissions

In both irrigation systems, daily soil N_2O fluxes were significantly affected by the interaction between soil tillage and sampling date in 2016 and 2017 but not during 2015 nor in both fallow periods (Table 3.4). However, this interaction only occurred after each N fertilizer application. Under S irrigation, the interaction between soil tillage and sampling date was only observed in 34 and 12% of the sampling dates in 2016 and 2017, respectively. However, under F irrigation only 11 (2016) and 12% (2017) of the sampling dates showed significant soil tillage and sampling date interaction (Fig. 3.4).

For S irrigation the mean soil N_2O flux was 2.85 (2015), 0.85 (2016), 0.86 (2017) mg N_2O-N m^{-2} day^{-1}. For F irrigation the mean soil N_2O flux was 2.35 (2015), 2.77 (2016), 2.09 (2017) mg N_2O-N m^{-2} day^{-1}.

Table 3.4. ANOVA (*p-value*) for the daily soil N_2O flux for sprinkler and flood irrigation over the different measurement periods as affected by soil tillage, sampling date and their interaction.

	Soil N_2O flux				
Effect	2015	Fallow 15-16	2016	Fallow 16-17	2017
			Sprinkler irrigation		
Tillage	NS	NS	NS	NS	NS
Date	*<0.001*	*0.017*	*<0.001*	*<0.001*	*<0.001*
Tillage x Date	NS	NS	*<0.001*	NS	*0.044*
			Flood irrigation		
Tillage	NS	NS	NS	NS	NS
Date	*<0.001*	NS	*<0.001*	*0.029*	*<0.001*
Tillage x Date	NS	NS	*0.034*	NS	*0.023*

NS, non-significant

Soil daily N_2O fluxes were low during the most part of the entire measurement period (values lower to 1 mg N_2O-N m^{-2} day^{-1}). However, after fertilizer applications, soil N_2O flux peaks occurred, especially after top dressing applications of nitrogen fertilizers (Fig. 4). Under S irrigation, N_2O flux peaks after nitrogen applications reached values close to 15 mg m^{-2} day^{-1} in 2015, while in 2016 and 2017 the flux peaks dropped to 12 mg N_2O-N m^{-2} day^{-1} (Fig. 3.4a). In contrast, under F irrigation, N_2O flux peaks measured ranged between 30 and 60 mg N_2O-N m^{-2} day^{-1} (Fig. 3.4b).

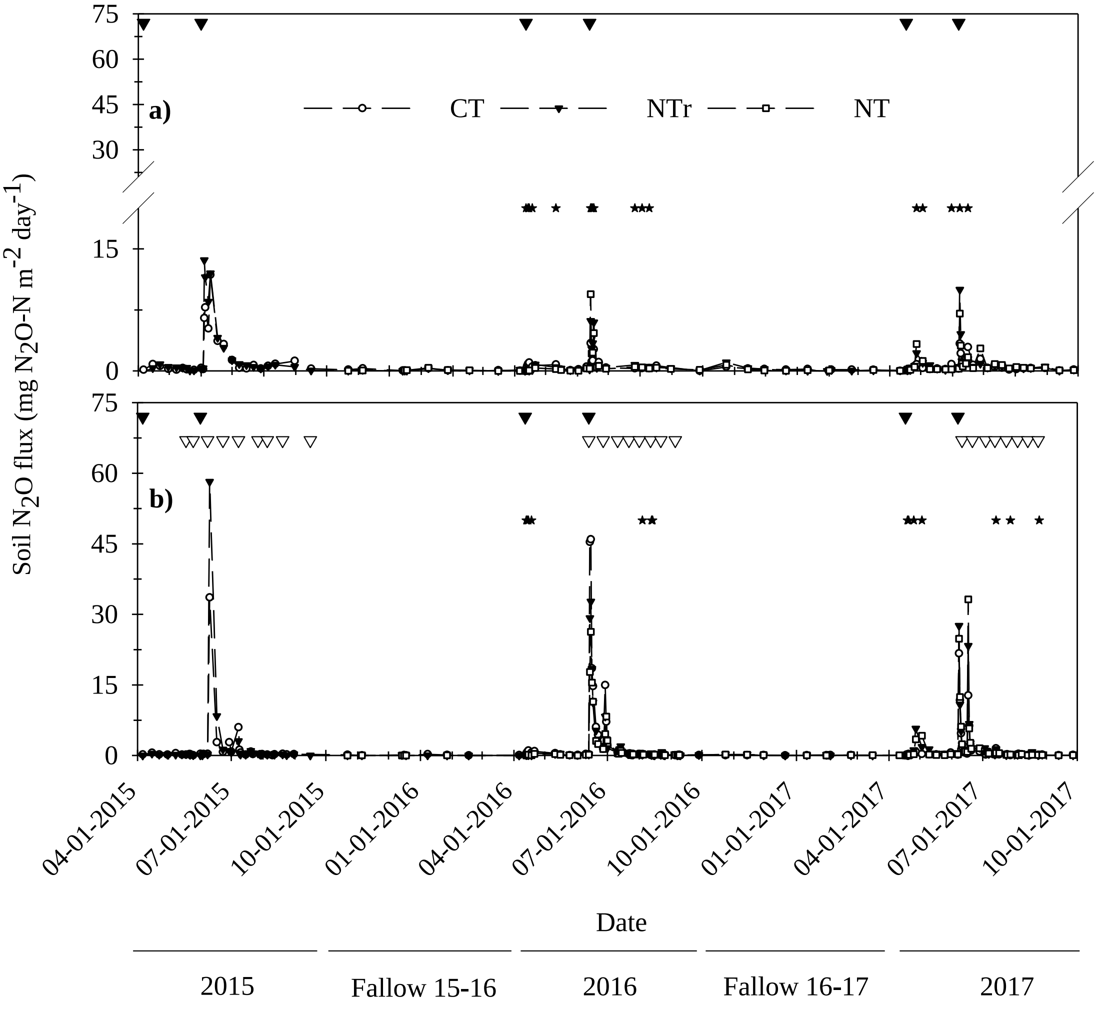

Figure 3.4. Soil N_2O flux for sprinkler (a) and flood (b) irrigation systems as affected by soil tillage systems: CT (conventional tillage), NTr (no-tillage maintaining maize stover), NT (no-tillage removing maize stover). *Indicates significant differences between treatments within a date at $p<0.05$. Black triangles indicate fertilizer applications. White triangles indicate flood irrigation events.

Over the entire measurement period, soil tillage did not affect the soil daily N_2O fluxes in neither irrigation systems (Table 3.4). Throughout the three growing seasons and under S irrigation, soil daily N_2O fluxes presented an average value of 1.09 ± 0.67, 1.50 ± 0.88 and 0.89 ± 0.04 mg N_2O-N m^{-2} day^{-1} for CT, NTr and NT respectively. Meanwhile, for the same period, CT, NTr and NT showed an average value of soil daily N_2O fluxes of 2.09 ± 0.88, 2.39 ± 0.10 and 2.09 ± 0.32, respectively, under F irrigation.

Moreover, soil N_2O flux showed positive exponential relationships with soil temperature at 5 cm depth (Fig. 3.5a), and total available soil inorganic nitrogen content (nitrate and soil ammonium) at 0-5 cm depth (Fig. 3.5b) for S and F irrigation systems. These relationships were similar in both irrigation systems, showing a quick increase on soil daily N_2O fluxes when soil temperature was above 20ºC and when the total available soil inorganic nitrogen content increased due to the N fertilizer application, especially during the top dressing application (June).

In addition to the relationships between daily soil N_2O fluxes and soil temperature and total available N, daily soil N_2O fluxes showed a significant relationship with the WFPS for both irrigation systems (Fig. 3.5c). This positive relationship between soil N_2O fluxes and WFPS were only observed during the pre-planting and top dressing applications of N fertilizers (i.e. 24 h prior and 24, 48 72 and 96 h after N fertilizer application). However, no significant relationship between soil N_2O fluxes and WFPS were observed during the rest of the measurement period. Daily soil N_2O fluxes showed a strong increase when WFPS values were higher than 60% and reaching the highest fluxes at 80% of WFPS. This large impact of the WFPS on the daily soil N_2O fluxes were only observed for F irrigation (black triangles), which resulted in soil N_2O peak fluxes three times higher compared with S irrigation (empty circles) (Fig. 3.5c).

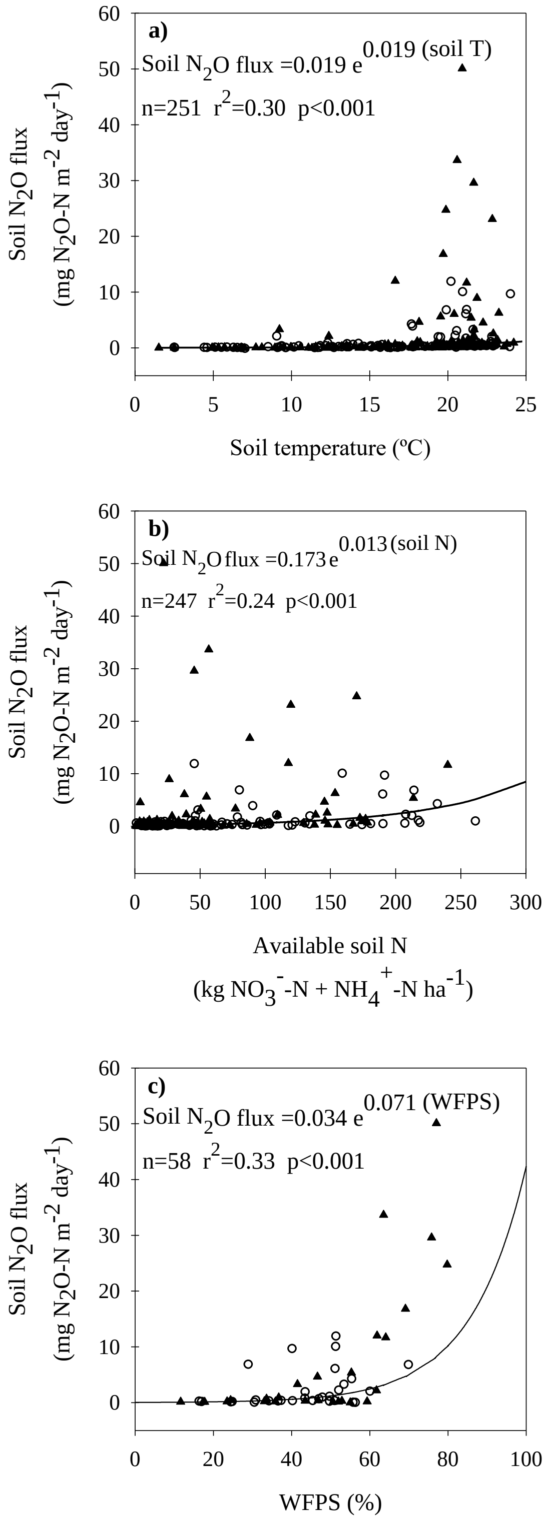

Figure 3.5. Regression analysis for sprinkler (empty circles) and flood (black triangles) irrigation systems between soil N_2O flux and soil temperature (5 cm depth) (a) for the entire measurement period, available soil inorganic nitrogen content (0-5 cm depth) (b) for the entire measurement period and WFPS (0-5 cm depth) during the N fertilization events. Each point represents the average value of all treatments for each sampling date.

Irrigation system significantly affected cumulative soil N_2O emissions in 2015, 2016 and 2017 (Table 3.5). In the three growing seasons, S irrigation resulted in a reduction of cumulative N_2O emissions of 34, 51 and 40% for 2015, 2016 and 2017, respectively, compared with F irrigation. Cumulative soil N_2O emissions were not affected significantly by the tillage system nor by its interaction with the irrigation system (Table 3.5).

Table 3.5. Cumulative N_2O emissions, for 2015, 2016 and 2017 growing seasons (i.e. April – October) as affected by irrigation system (S, sprinkler; F, flood), soil tillage (CT, conventional tillage, NTr no-tillage with crop stover, NT, no-tillage without crop stover) and their interactions.

Effects and levels[†]	Cumulative N_2O emissions		
	2015	2016	2017
	——— kg N_2O-N ha^{-1} ———		
Irrigation system	*0.019*	*0.003*	*0.018*
S	2.20 ± 0.34 b	0.89 ± 0.21 b	0.95 ± 0.24 b
F	3.33 ± 1.24 a	1.83 ± 0.54 a	1.59 ± 0.56 a
Tillage system	NS	NS	NS
CT	2.30 ± 0.70	1.60 ± 0.86	0.95 ± 0.23
NTr	3.23 ± 1.32	1.40 ± 0.49	1.51 ± 0.74
NT		1.08 ± 0.45	1.34 ± 0.41
Irrigation system x Tillage system	NS	NS	NS
CT-S	2.11 ± 0.42	0.92 ± 0.22	0.81 ± 0.19
NTr-S	2.30 ± 0.30	1.04 ± 0.19	0.97 ± 0.19
NT-S		0.71 ± 0.08	1.06 ± 0.34
CT-F	2.50 ± 0.96	2.28 ± 0.64	1.10 ± 0.18
NTr-F	4.16 ± 0.94	1.76 ± 0.40	2.05 ± 0.68
NT-F		1.45 ± 0.29	1.62 ± 0.29

[†] For each effect and growing season values followed by different letters are significantly different according to a Tukey test at p=0.05 level. NS, non-significant. *p-values* are given when significant.

Grain yield was differently affected by the irrigation and the tillage system depending on the growing season. In 2015, a significant interaction between irrigation and tillage system was observed, increasing grain yield in the order NTr-S>CT-S=CT-F>NTr-F, with values ranged between 10.15 to 14.34 Mg ha^{-1}. Likewise, the interaction between irrigation and tillage system affected significantly the grain yield in 2016, in which NTr tillage obtained the greatest values under S irrigation (13.26 Mg ha^{-1}) compared with F irrigation (10.21 Mg ha^{-1}) (Table 3.6). However, in 2017, irrigation and tillage system, but no their interaction, had a significant impact on the grain yield, obtaining the greatest values under S irrigation and CT tillage, 17.08 and 17.00 Mg ha^{-1} respectively.

S irrigation resulted in higher grain N uptake compared with F irrigation over the three growing season (Table 3.6). In 2015, the interaction between irrigation and tillage system affected grain N-uptake (Table 3.6). Under sprinkler irrigation, the NTr treatment produced higher N uptake than the CT treatment, but no differences were found between tillage treatments under flood irrigation. (Table 3.6). In contrast, in 2016 and 2017, irrigation and tillage systems affected the grain N-uptake but not their interaction. CT tillage showed higher grain N-uptake than NTr and NT tillage in 2016, while in 2017 significant differences were only observed between CT and NT tillage (Table 3.6).

Table 3.6. Maize grain yield (14% moisture) and maize grain N-uptake, for 2015, 2016 and 2017 growing seasons as affected by irrigation system (S, sprinkler, F, flood), soil tillage (CT, conventional tillage, NTr no-tillage with crop stover, NT, no-tillage without crop stover) and their interactions.

Effects and levels[†]	Grain yield			Grain N-uptake		
	2015	2016	2017	2015	2016	2017
	Mg ha^{-1}			kg ha^{-1}		
Irrigation system	*0.002*	NS	*0.012*	*<0.001*	*0.018*	*<0.001*
S	13.60 ± 0.86 a	13.67 ± 1.44	17.08 ± 0.92 a	158 ± 11 a	150 ± 16 a	180 ± 11 a
F	10.78 ± 0.92 b	12.16 ± 1.87	15.23 ± 1.28 b	116 ± 10 b	124 ± 17 b	150 ± 14 b
Tillage system	NS	*<0.001*	*0.029*	NS	*<0.001*	*0.014*
CT	12.13 ± 0.96	14.65 ± 0.61 a	17.00 ± 0.75 a	135 ± 18	154 ± 13 a	178 ± 17 a
NTr	12.25 ± 2.33	11.74 ± 1.99 b	16.13 ± 1.53 ab	139 ± 32	125 ± 25 b	163 ± 17 ab
NT		12.35 ± 1.00 b	15.33 ± 1.56 b		134 ± 13 b	155 ± 22 b
Irrigation system x Tillage system	*0.003*	*0.019*	NS	*0.015*	NS	NS
CT-S	12.85 ± 0.32 b	14.93 ± 0.73 a	17.44 ± 0.37	150 ± 6 b	165 ± 6	191 ± 5
NTr-S	14.34 ± 0.3 a	13.26 ± 1.70 abc	17.13 ± 1.66	168 ± 3 a	144 ± 21	176 ± 13
NT-S		12.82 ± 1.08 bcd	16.65 ± 0.08		142 ± 10	174 ± 9
CT-F	11.41 ± 0.8 b	14.37 ± 0.41 abc	16.56 ± 0.83	121 ± 11 c	143 ± 4	164 ± 11
NTr-F	10.15 ± 0.54 c	10.21 ± 0.09 d	15.13 ± 0.33	111 ± 8 c	103 ± 3	149 ± 5
NT-F		11.89 ± 0.82 cd	14.00 ± 0.91		122 ± 9	136 ± 6

[†] For each effect, growing season and variable the values followed by different letters are significantly different according to Tukey test at p=0.05 level. NS, non-significant. *p-values* are given when significant

Finally, grain yield N_2O scaled emissions (g N_2O-N Mg^{-1} grain) and grain N-uptake N_2O scaled emissions (g N_2O-N kg^{-1} N grain) were significantly affected by the irrigation system in the three growing seasons, presenting the lowest values under S irrigation compared with F irrigation (Table 3.7). In the three growing seasons, S irrigation reported a reduction of the grain yield N_2O scaled emissions of 49 (2015), 59 (2016) and 47% (2017) compared with F irrigation. Similarly, the grain N-uptake N_2O scaled emissions showed a decrease of 53, 59 and 51% for 2015, 2016 and 2017, respectively, under S irrigation compared with F irrigation (Table 3.7).

In 2017, the tillage system showed significant differences for grain yield N_2O scaled emissions and grain N-uptake N_2O scaled emissions, with the greatest values under NTr and NT tillage for both indexes (Table 3.7). However, in 2015 and 2016, no significant differences were observed neither in grain yield N_2O scaled emissions nor in grain N-uptake N_2O scaled emissions between tillage systems, even when the scaled emissions were almost two times greater under NTr compared with CT as it was observed in the 2015 maize growing season (Table 3.7).

Table 3.7. Scaled soil N_2O emissions by maize grain yield and maize grain N-uptake, for 2015, 2016 and 2017 growing seasons as affected by irrigation system (S, sprinkler, F, flood), soil tillage (CT, conventional tillage, NTr no-tillage with crop stover, NT, no-tillage without crop stover) and their interactions.

Effects and levels[†]	Scaled soil N_2O emissions					
	by grain yield			by grain N-uptake		
	2015	2016	2017	2015	2016	2017
	g N_2O-N Mg^{-1} grain			g N_2O-N kg^{-1} grain		
Irrigation system	*0.002*	*<0.001*	*0.015*	*0.009*	*<0.001*	*0.009*
S	162 ± 24 b	66 ± 18 b	56 ± 15 b	13.86 ± 1.91 b	6.00 ± 1.79 b	5.27 ± 1.35 b
F	315 ± 137 a	151 ± 40 a	106 ± 40 a	29.22 ± 12.51 a	14.81 ± 3.81 a	10.72 ± 3.95 a
Tillage system	NS	NS	*0.014*	NS	NS	*0.014*
CT	190 ± 54	109 ± 59	56 ± 17 b	17.19 ± 5.36	10.73 ± 6.30	5.46 ± 1.61 b
NTr	287 ± 157	127 ± 59	96 ± 17 a	25.88 ± 15.09	11.99 ± 5.65	9.58 ± 5.24 a
NT		89 ± 43	90 ± 22 a		8.50 ± 4.37	8.96 ± 3.56 a
Irrigation system x Tillage system	NS	NS	NS	NS	NS	NS
CT-S	163 ± 28	61 ± 12	46 ± 11	13.99 ± 2.26	5.54 ± 8.25	4.26 ± 1.05
NTr-S	161 ± 24	80 ± 25	57 ± 9	13.73 ± 1.98	7.45 ± 10.54	5.50 ± 0.90
NT-S		55 ± 4	64 ± 21		5.01 ± 14.16	6.06 ± 1.69
CT-F	216 ± 66	158 ± 40	66 ± 12	38.04 ± 11.04	15.92 ± 8.60	6.67 ± 1.01
NTr-F	414 ± 116	173 ± 41	135 ± 45	16.53 ± 8.25	16.53 ± 8.25	13.65 ± 4.25
NT-F		123 ± 33	116 ± 21		11.99 ± 11.45	11.86 ± 1.93

[†] For each effect, growing season, and variable the values followed by different letters are significantly different according to Tukey test at p=0.05 level. NS, non-significant. *p-values* are given when significant.

4. Discussion

In the irrigated Mediterranean conditions evaluated in this study, it has been assessed that irrigation system impacted soil N_2O emission in maize monocropping systems. In similar Spanish conditions, Sanchéz-Martín *et al*. (2008) obtained soil N_2O fluxes for a furrow-irrigated maize similar to the measured in this work under F irrigation. The higher soil N_2O fluxes found with F irrigation compared to S irrigation in our work were closer to those measured by Omonode *et al*. (2011) in a non-irrigated maize in Indiana.

Comparing with sprinkler irrigated maize studies, soil N_2O fluxes measured in this work were in the range of values reported by Liu *et al*. (2005) in Colorado. Under Mediterranean conditions, Sanz-Cobeña *et al*. (2012) reported similar soil N_2O fluxes when they used an irrigation scheduling similar to our work. In contrast, Álvaro-Fuentes *et al*. (2016), in the same study area, observed soil N_2O fluxes three and ten times lower than the values measured in our study (for S and F irrigation systems, respectively). Differences between studies could be related to the different air sampling protocol used in both studies since in the Álvaro-Fuentes *et al*. (2016) study did not increase air sampling frequency during the fertilization events. Moreover, these differences in soil N_2O fluxes between both studies could be also related with the high temporal and spatial variability of soil N_2O emissions associated to different factors, such as soil properties, climate, management and microorganism populations (Leip *et al*., 2011; Venterea *et al*., 2012).

In 2016 and 2017 but not in 2015 and for both irrigation systems, soil N_2O fluxes were affected by the interaction between soil tillage system and sampling date. This interaction was observed after the fertilizer application events, especially after the top dressing application, when the greatest peak of soil N_2O fluxes occurred as other researchers observed previously (Smith *et al*., 1997; Shen *et al*., 2018).

The increase in total available soil nitrogen content (ammonium and nitrate) after N fertilizer applications had an impact on soil N_2O fluxes in both irrigation systems, as it is demonstrated in a relationship shown (Fig. 5b). This relationship agrees with other studies (McSwiney and Robertson, 2005; Hoben *et al*., 2011; Zhou *et al*., 2016) which pointed out the key role of N fertilizer applications on the N_2O emitted from the soil (Dobbie and Smith, 2003; Vallejo *et al*., 2005). Moreover, the soil N_2O flux peaks observed during the top dressing application were related not only with the high N fertilizer rates applied (200 kg N ha^{-1}) but also with the high soil temperatures measured, similar to the observations reported by other authors (Dobbie and Smith, 2001; Zhou *et al*., 2016). The warmer soil temperature during the top dressing application (June), could lead in more optimal conditions for the production of N_2O by soil microorganisms, favouring a rapidly increase of the soil N_2O fluxes, “pulsing effect”, since soil temperature is a key factor that control nitrification, denitrification and nitrifier denitrification processes (Bouwman *et al*., 2002; Sanchéz-Martín *et al*., 2008; Butterbach-Bahl *et al*., 2013).

Soil N_2O peaks measured under F irrigation were 3 to 4 times greater compared to the peaks measured under S irrigation. The difference in soil N_2O peaks between irrigation systems were related to the different WFPS found. Maximum N_2O peak values (observed during top dressing N fertilizer application) were measured under F irrigation when WFPS were between 70 to 80%, considered as the optimum values for N_2O production (Davidson, 1991). However, under S irrigation, WFPS values were always lower than 60%. Therefore, differences in WFPS explained also the higher cumulative N_2O emissions under F irrigation found compared with S irrigation. On average of the three growing seasons studied, S irrigation reduced cumulative soil N_2O emissions by 42% compared with F irrigation.

The large difference found between irrigation systems was in the range of the results reported by Deng *et al*. (2018), who predicted a reduction of the 38% on soil N_2O emissions for sprinkler-irrigated maize systems compared with surface-irrigated systems in Californian croplands. In two previous meta-analysis for Mediterranean conditions, Cayuela *et al*. (2017) reported mean cumulative N_2O emission values of 3.7±3.3 kg N_2O-N ha^{-1} for sprinkler irrigation systems, with a mean N application rate of 226±75 kg N ha^{-1}, while Aguilera *et al*. (2013) estimated 4±2.6 kg N_2O-N ha^{-1} for furrow and sprinkler irrigation systems, with a mean N application rate of 137 kg N ha^{-1}. In our experiment, mean cumulative N_2O emissions over the three growing seasons for the S irrigation system were 63 and 66% lower than the values reported by these authors, respectively. In contrast, neither of the two meta-analysis reported data of cumulative soil N_2O emissions for flood-irrigated maize. Furthermore, values of cumulative soil N_2O emissions for the different tillage systems were in the range of the values estimated by Aguilera *et al*. (2013) for standard tillage (1.1±1.4 kg N_2O-N ha^{-1}) and minimum tillage (1.9±2.6 kg N_2O-N ha^{-1}). Differences in the emission values found between the two previous meta-analysis and our study were expected since the values obtained in the meta-analyses covered a broad range of different cropping systems, management practices (e.g., N sources and amount, irrigation systems, tillage, etc.) and soil and climate types.

The effect of soil tillage system on soil N_2O emissions varies depending on the study. Some authors reported higher soil N_2O emission under conventional tillage than under no-tillage in different word regions (Halvorson *et al*., 2008b; 2010; Perego *et al*., 2016), while other showed higher soil N_2O emissions under no-tillage than under conventional tillage systems (Ball *et al*., 1999; Venterea *et al*., 2005). Moreover, several researchers found no significant effect of the tillage system on soil N_2O emissions as we observed in this work (Liu *et al*. 2005; Heller *et al*.; 2010; Forte *et al*., 2016). Likewise, stover removal did not impact soil N_2O emissions, similarly to the results reported by others (Guzman *et al*., 2015; Johnson and Barbour, 2018; Fang *et al*. (2019). All these studies justified their results based mainly on the effect of soil available N and WFPS on N_2O emissions. In our study, the soil available N content was not significantly different between tillage systems in neither of two irrigation systems over the entire period, fact that could explain the no significant effect of the tillage systems and stover management on the soil N_2O due to the key role of N on the N_2O emissions, as explained previously.

Maize grain yields were in the range of the values reported in other studies performed in the same region (Robles *et al*., 2017; Cavero *et al*., 2018). In general, grain yields and grain N uptake in F irrigation plots were 14 and 20% lower respectively, compared with S irrigation plots. Increasing the frequency of irrigation, which only can be easily done with sprinkler irrigation, has been found to increase crop yield because the soil water content is more stable (Rawlins and Raats, 1975). The lower grain yields and grain N uptake under F irrigation could be related with the negative impact of the waterlogging, which occurs during F irrigation after the large amount of irrigation water applied in every irrigation event (80-100 mm). Ren *et al*. (2016) observed that waterlogging affected the ear formation in maize, reducing ear volume and decreasing sink capacity when maize was under waterlogging conditions at different growth stages. Furthermore, F irrigation is prone to favour plant water stress due to the long periods between consecutive irrigation events. In contrast, higher irrigation frequency under S irrigation provided more stable soil water content (Segal *et al*., 2006), increasing the availability of water for the plant and avoiding plant water stress.

Furthermore, over the three growing seasons, conventional tillage trended to result in greater grain yield and grain N uptake compared with no-tillage systems. Afzalinia and Zabihi (2014) and Salem *et al*. (2015) observed similar reductions in crop yields during the first year of implementation of the no-tillage systems for a maize crop under Mediterranean conditions. Several reasons such as waterlogging, poor crop establishment, lower root development by compaction, nutrient deficiencies or time of implementation are pointed out as possible reasons, which would explain the worst crop performance under no-tillage systems (Pittelkow *et al*., 2015). In our work, the lower mean soil bulk density found in conventional tillage compared with no-tillage systems (1.38, 1.53 and 1.53 for CT, NTr and NT, respectively) would lead to more optimal conditions for the development of maize roots and thus the better crop performance under conventional tillage (Cid *et al*., 2015).

Grain yield N_2O scaled emissions measured were in the range of the values obtained by Omonode *et al*. (2015) for a maize crop under conventional tillage and no-tillage systems with a nitrogen application rate of 200 kg N ha^{-1} year^{-1}. Likewise, grain N uptake N_2O scaled emissions presented in this work were in the range of values reported by Álvaro-Fuentes *et al*. (2016) in the same region. For both N_2O scaled emissions, by grain yield and by grain N uptake, irrigation system had a significant impact. The S irrigation system presented lower values compared with the F irrigation system over the three growing seasons studied. The lower cumulative N_2O emissions and the higher grain yields and N-uptake by grain obtained under S irrigation system explained the lower N_2O yield-scaled emissions by grain yield and by N-uptake by grain found. Moreover, in 2017, no-tillage systems resulted in an increment of the N_2O scaled emissions compared with CT tillage mainly due to the decrease in grain yield and grain N-uptake found under no-tillage systems.

5. Conclusions

In the Mediterranean conditions studied, the irrigation system is an important strategy to reduce soil N_2O emissions. Throughout three maize seasons, the sprinkler irrigation system reduced soil N_2O emissions, and grain yield and grain N uptake N_2O scaled emissions, compared to the flood irrigation system. Sprinkler irrigation is a win-win system for irrigated maize: more grain yield and lower soil N_2O emissions. The soil tillage system affected daily soil N_2O fluxes, especially after the fertilization events, but it had not effect on the seasonal mean soil N_2O emissions. However, no-tillage systems showed a trend to increase the grain yield and grain N uptake N_2O scaled emissions compared to conventional tillage systems when the same amount of water was applied. More information about the performance of no-tillage in irrigated maize monoculture systems is needed to consider no-tillage systems as a mitigation strategy of N_2O emissions under Mediterranean conditions. This work pointed out the importance of an appropriate selection of irrigation and tillage system to minimize soil N_2O emissions in Mediterranean agroecosystems.

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Capítulo 4

Influence of irrigation time and frequency on greenhouse gas emissions in a solid-set sprinkler-irrigated maize under Mediterranean conditions

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Influence of irrigation time and frequency on greenhouse gas emissions in a solid-set sprinkler-irrigated maize under Mediterranean conditions

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Abstract

Irrigation management may influence soil greenhouse gas emissions (GHG). Solid-set sprinkler irrigation systems allow to modify the irrigation time and frequency. The objective of this study was to quantify the effect of two irrigation times (daytime, D; nighttime, N) and two irrigation frequencies (low, L; high, H) on soil carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) emissions in a solid-set sprinkler-irrigated maize (*Zea mays* L.) field located in NE Spain during 2015 and 2016 growing seasons and the fallow period between growing seasons. Compared with D irrigation, N irrigation increased soil water content (0-5 cm) in both growing seasons. Irrigation management did not affect CH_4 emissions and the soil acted as a sink of CH_4. Cumulative CO_2 emissions were affected by the measurement period (growing season vs fallow) with the greatest values in 2015 growing season, being 81 and 32 % higher over the fallow period and over the 2016 growing season, respectively, due to the effect of the preceding crop, alfalfa, and a better soil moisture conditions for the microorganism activity. Similarly, cumulative N_2O emissions showed the highest values in 2015, reporting values 90 and 51% greater than the fallow period and the 2016 growing season, respectively. Moreover, N irrigation increased cumulative N_2O emissions by 29 % compared with D irrigation, but irrigation frequency did not affect cumulative N_2O emissions. Irrigation time did not affect cumulative N_2O emissions scaled per grain yield or per N uptake because N irrigation increased maize yield by 11% compared with D irrigation. Due to the lack of differences in the scaled N_2O emissions, N irrigation should be consider as an appropriate strategy to optimize grain yield without compromising soil GHG emissions per unit of grain yield in Mediterranean agroecosystems.

Keywords

Soil N_2O emissions, sprinkler irrigation management, maize monoculture, yield scaled N_2O emissions

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1. Introduction

Agricultural practices have an important role in GHG emissions (Smith *et al*., 2008). According to the latest National GHG Inventory, agriculture is responsible of about 11 % of the total GHG emissions in Spain. Soils are the principal source of non-CO_2 agricultural emissions (MAPAMA, 2018a).

It is well established that soil water content is a major factor in soil GHG emissions. Soil CH_4 production and consumption is controlled by many different factors, such as soil water content, pH and redox potential among the most important (Wang *et al*., 1993). Le Mer and Roger (2001) described methanogenesis as a biological process that requires strict anaerobiosis and low oxidation-reduction potentials. For example, in a Mediterranean rice paddy experiment, a midseason drainage favoured the oxidation conditions in the soil and thus the decrease of CH_4 emissions (Meijide *et al*., 2017). Moreover, Wang *et al*. (2016) observed an increment in the CH_4 net uptake when surface drip irrigation was compared with flood irrigation systems due to the lower soil moisture in drip irrigation systems. Soil microorganisms through the nitrification and denitrification processes (Firestone and Davidson, 1989; Bremner, 1997) control N_2O production in the soil. Nitrification is the main process contributing to N_2O production under aerobic conditions, when the water-filled pore space (WFPS) is below 60%. However, when WFPS is above this threshold (60 % WFPS), denitrification is the predominant process involved in N_2O production (Linn and Doran, 1984; Davidson *et al*., 2000; Bateman and Baggs, 2005). Moreover, CO_2 emissions from soils are a consequence of root respiration and microbial decomposition of organic matter and are regulated by soil temperature and soil water content (Davidson and Janssens, 2006). Thus, the increase of soil moisture content due to irrigation water applied can result in more optimal conditions for soil microorganism activity, and thus resulting in an increase of CO_2 emissions from the soil (Linn and Doran, 1984).

Irrigation systems, due to their capacity to modify the soil water content may have an important role in soil GHG emissions, especially under Mediterranean conditions where irrigation is a common practice (Aguilera *et al.*, 2013b; Sanz-Cobeña *et al.*, 2017).

Sprinkler irrigation systems are widely used around the world and increasingly adopted in many irrigated areas of Spain due to several reasons: the higher crop yields provided compared with traditional surface irrigation systems (Lecina *et al.*, 2010), because they allow applying small amounts of irrigation water so runoff and drainage are minimized, and because they allow automation, thus reducing labour requirement and costs for farmers (Playán and Mateos, 2006). Although center pivots are mainly used as sprinkler system around the world, the solid-set sprinkler system is mainly used in many areas of Spain.

Solid-set systems are more flexible than center pivots for irrigation management, allowing easily to choose the irrigation time (day or night) and frequency. These irrigation management factors affect soil water content and crop yields (Urrego-Pereira *et al.*, 2013b; Cavero *et al.*, 2016; Cavero *et al.*, 2018). Thus, soil water content decreases with daytime sprinkler irrigation due to the higher water evaporation losses (Urrego-Pereira *et al.*, 2013a; Cavero *et al.*, 2016). Besides, increasing irrigation frequency decreased soil water content when sprinkler irrigation was performed during daytime (Cavero *et al.*, 2018).

In the river Ebro valley of Spain maize is one of the main irrigated crops under sprinkler irrigation. In this area, solid-set sprinkler irrigation is scheduled at one to five days intervals, 08:00h and 20:00h being the most used irrigation starting times (Salvador *et al*., 2011a). In the last decade, several experiments have been carried in this area to evaluate the efficiency of sprinkler irrigation on crop water requirements and crop performance (Cavero *et al*., 2003; Dechmi *et al*., 2003; Salvador *et al*., 2011b). These studies identified irrigation scheduling as an important factor in crop production. Recently, other investigations have determined the impact of nitrogen fertilization management on soil greenhouse gas (GHG) emissions in sprinkler-irrigated maize (Álvaro-Fuentes *et al*., 2016; Maris *et al*., 2018). However, to date there is no information about the influence of sprinkler irrigation management and, particularly, the effect of sprinkler irrigation time and frequency on GHG emissions in Mediterranean soils.

Hence, this study was aimed to evaluate the impact of the irrigation time (daytime or nighttime) and frequency (low and high) on soil GHG emissions in a maize crop irrigated with of a solid-set sprinkler system.

2. Material and Methods

2.1 Site description and experimental design

The field experiment was carried out during 2015 and 2016 in a 2.34 ha maize field irrigated with a solid-set sprinkler system, located at the experimental farm of the Aula Dei Experimental Station, Zaragoza, Spain (41º 43´ N, 0º 48´ W, 225 masl). The climate is Mediterranean semiarid with annual mean air temperature of 14.1 ºC, annual precipitation of 298 mm and grass reference crop evapotranspiration (ETo) of 1243 mm. The soil is a clay loam classified as Typic Xerofluvent (Soil Survey Staff, 2014). Specific properties of the experimental soil are detailed in Table 1.

Table 4.1. Soil characteristics of the experimental field (Cavero *et al.*, 2016).

Depth	pH	C	N	$CaCO_3$	Sand	Silt	Clay	FC[a]	WP[b]
(m)				(%)				(m^3 m^{-3})	
0.0−0.3	8.2	1.12	0.14	35	19.6	50.2	30.2	0.351	0.189
0.3−0.6	8.3	0.77	0.11	35	14.9	47.5	37.6	0.381	0.227
0.6−0.9	8.3	0.54	0.10	32	7.7	47.5	44.8	0.364	0.207
0.9−1.2	8.2	0.43	0.08	31	11.9	47.1	41.0	0.359	0.187
1.2−1.6	8.3	0.43	0.07	33	20.3	49.2	30.5	0.344	0.187

[a] FC, field capacity (-0.033 MPa). [b] WP, permanent wilting point (-1.5 MPa).

2.2 Experimental design

A field experiment under sprinkler irrigation was established in 2015 to compare the effect of the irrigation time and the irrigation frequency on a maize (*Zea mays* L.) monoculture. Prior to the establishment of the field experiment, alfalfa cv. Aragón (*Medicago sativa* L.) was grown during three years (2012-2014).

The experimental field was divided in twelve irrigation sectors, which were irrigated independently by four sprinklers. The sprinkler spacing was a square of 18 m × 18 m. Sprinkler application rate was 5 mm h^{-1} and the wetted radius was 15 m.

Tillage operations consisted of one pass of a subsoiler to 30 cm depth followed by one pass of a disk harrow and one pass of a rotary tiller just before planting. All tillage operations were made with commercial tillage equipment (Table 4.2). Maize cv. Pioneer P1785 was planted on April in rows 75 cm apart at a planting density of 89,500 plants ha^{-1} (Table 4.2). Fertilization consisted of 64 kg ha^{-1} N, 120 kg ha^{-1} P_2O_5, and 120 kg ha^{-1} K_2O applied before sowing, and 100 kg ha^{-1} N of N-32 (8 % ammonium N ($N\text{-}NH_4$) - 8 % nitrate N ($N\text{-}NO_3$) - 16% amide N ($N\text{-}NH_2$)) solution applied with the irrigation water in two growth stages (at V6 and V12) as top dressing application. In 2015 only one top dressing of N (100 kg ha^{-1} N) was applied with the irrigation water at V6 because of the carryover N effect of the previous alfalfa crop (Table 4.2). Fertigation with N-32 solution was done in one irrigation lasting 2 hours followed by an additional one-hour irrigation to wash out the nitrogen fertilizer from the maize plants and incorporate it into the soil. Harvest was carried out with a commercial combine (Table 4.2). The maize stover was chopped and spread over the soil by the same machine. Weed and pest control was done according to best management practices in the area.

Table 4.2. Field operation scheduling.

Field operation	**2015**	**2016**
Tillage operation		
Subsoiler and disk harrow	10/12/2015	17/01/2016
Rotary tiller	13/04/2015	13/04/2016
Planting operation		
Sowing	14/04/2015	13/04/2016
Fertilization operation		
Preplanting application	09/04/2015	11/04/2016
Top dressing application	15/06/2015	06/06/2016; 04/07/2016
Harvest operation		
Harvest	30/09/2015	06/10/2016

Maize evapotranspiration (ETc) was calculated using ETo and crop coefficient (Kc) values (Allen *et al*., 1998). Meteorological data from a weather station located 1 km southwest from the field experiment were used to compute ETo using the FAO Penman-Monteith method (Allen *et al*., 1998). Crop coefficients (Kc) were calculated as a function of thermal time using an equation developed by Martínez-Cob (2008) at the same location of the experiment. Thermal time was computed as the cumulative daily difference between daily mean air temperature and a basal air temperature of 8 °C (Kiniry, 1991). Daily crop evapotranspiration of maize (ETc) was then obtained as ETo multiplied by Kc. The crop irrigation requirements (CIR) were determined weekly as the difference between the ETc and the effective precipitation, which was estimated as 75% of total weekly precipitation (Dastane, 1978). The irrigation amount applied to the crop was equal to the CIR (Table 4.3). Irrigation was applied at nighttime to all the experimental plots until the crop was well established (V6 to V8 growth stage) in order to have the same plant density and because limitations for irrigation scheduling at nighttime are generally not relevant during the period of lower CIR.

Table 4.3. Crop evapotranspiration (ETc), precipitation (P), crop irrigation requirement (CIR) and irrigation water applied to maize in the 2015 and 2016 growing seasons.

Growing season	ETc (mm)	P (mm)	CIR (mm)	Irrigation (mm)
2015	741	115	606	614
2016	772	130	609	601

The experimental layout was a randomized factorial design with two factors (with two levels each) and three replicates per treatment, so twelve plots were used. The plot size was 18 m x 18 m, coinciding with that of the irrigation sector. The two factors tested were irrigation time of the day and irrigation frequency. For irrigation time the levels were daytime (D) or nighttime (N). For irrigation frequency the levels were: two irrigation events per week on Monday and Thursday (low frequency, L) or daily irrigation (high frequency, H). Therefore, four different treatments were tested: daytime low frequency, DL; daytime high frequency, DH; nighttime low frequency, NL, and nighttime high frequency, NH. The same amount of irrigation water was applied to all the treatments and was calculated weekly, as explained. The starting time for irrigation was generally 10.00 h Greenwich Mean Time (GMT) for daytime irrigations and 22.00 h GMT for nighttime irrigations. The irrigation duration of the high frequency treatment was at least 1 h, so if the weekly CIR was lower than 7 h, irrigation was not applied daily.

2.3 Gas sampling and analyses

Gas sampling began in April 2015 and extended until September 2016 using the closed chamber technique (Hutchinson and Moiser, 1981). Soil greenhouse gases (CO_2, CH_4 and N_2O) were measured weekly from planting until mid-August (tasseling stage, VT growth stage), every two weeks from mid-August until harvest and every three weeks during the fallow period (November-March). Gas sampling frequency was increased during tillage, planting and fertilization operations. For tillage operations, soil gas samples were taken 24 h before and 24 and 96 h after tillage operations. In the case of planting and fertilization operations, soil gas samples were taken 24 h before and 24, 48, 72, 96, 144 and 192 h after each operation. In 2015, gas sampling was performed every Tuesday, after all the four different treatments were irrigated during the day and the night before, so less than 24 h passed between the irrigation and the gas sampling. However, in 2016, in order to maximize the effect of the irrigation frequency, gas sampling was performed every Thursday, that is less than 24 h passed between the irrigation and the gas sampling for the high irrigation frequency treatments, but more than 48 h for the low irrigation frequency treatments.

At the beginning of the field experiment, two polyvinyl chloride (PVC) rings (31.5 cm internal diameter) per plot were inserted 5 cm into the soil. The rings were only removed at tillage, planting and harvesting operations. PVC chambers (20 cm height) were fitted into the rings before gas sampling. A polytetrafluoroethylene vent (10 cm long and 0.4 cm internal diameter) was installed on one side of the chambers to prevent possible changes in pressure during the deployment of chambers and gas sampling (Plaza-Bonilla *et al.*, 2014). In order to diminish internal increases in temperature the chambers were covered with a thermal reflective insulation fabric (AislaTermic®, Arelux, Cuarte de Huerva, Zaragoza, Spain) that consisted of two reflective layers of aluminium film bonded to an inner layer of polyethylene bubbles. A metal fitting was attached in the center of the top of the chamber and lined with two silicone-FEP (Tetrafluoroethylene-hexafluoropropylene) septa as a sampling port.

Gas samples were collected at 0, 20 and 40 min after chamber closure using a 20-mL polypropylene syringe (Becton-Dickson, Plastipak ^{TM}) with a 25 mm-long needle (Becton-Dickson, Microlance^{TM}), and 20 mL of gas sample was transferred to an evacuated 12-mL Exetainer® borosilicate glass vial (model 038W, Labco, High Wycombe, UK). The air temperature inside the chamber was measured introducing a thermometer in the chamber before closing the chambers.

Concentrations of CO_2, CH_4 and N_2O were measured in the gas samples with an Agilent 7890B gas chromatograph equipped with a flame ionization detector (FID) for CO_2 and CH_4 and an electron capture detector (ECD) for N_2O. A previous stage is necessary to determine the CO_2 concentration in the gas samples, consisting in passing the gas samples through a methanizer before entry into the FID detector. Gas samples were injected automatically using a PAL3 autosampler. A HP-Plot Q column (15 m long, 320 µm in section and 20 µm thick) was used, with helium as a carrier gas at 2 mL min^{-1}. The injector and the oven temperatures were set to 50 and 35ºC, respectively. The temperatures of the FID, the methanizer and the ECD were set to 250, 375 and 280ºC, respectively. For the FID, helium was used as a make-up gas at 25 mL min^{-1} and a 5% methane in argon gas mixture at 30 mL min^{-1} was used as a make-up gas for the ECD. The volume of sample injected was 1 mL. The system was calibrated using ultra-high purity CO_2, CH_4 and N_2O standards (Carburos Metálicos, Barcelona, Spain).

Emission rates were calculated taking into account the linear increase in the gas concentration within the chamber during the sampling time and correcting for the air temperature inside the chamber.

2.4 Soil, biomass and grain yield sampling and analyses

Soil samples from the 0–5 cm soil layer were collected on each sampling date close to every gas sampling chamber to quantify the ammonium (NH_4^+) and nitrate (NO_3^-) ions content in the soil. Besides, soil temperature and water content were measured using a Crison TM 65 probe (Carpi, Italy) and GS3 soil probes (Decagon Devices, Pullman, WA), respectively. Soil NH_4^+ and NO_3^- contents were obtained by extracting 50 g of fresh soil with 100 mL of 1 M KCl. The extracts were frozen and afterwards analysed with a continuous flow autoanalizer (Seal Autoanalyzer 3, Seal Analytical, Norderstedt, Germany). Both ions were transformed to kg N ha^{-1} taking into account soil moisture and bulk density. Soil bulk density was determined using the cylinder method (Grossman and Reinsch, 2002). The WFPS (%) was calculated from the volumetric soil moisture content and soil bulk density measurements, assuming a soil particle density of 2.65 Mg m^{-3}.

Maize aboveground biomass and grain yield were determined manually before the machine harvest by cutting the plants at the soil surface level on 3 m along the planting row at two randomly selected locations per plot. The number of plants and ears was counted. The grain was separated from the cob and both parts were dried at 60 ºC for 48 h and weighed. Besides, a sub-sample of four entire plants was taken, oven-dried at 60 °C for 48 h and weighed. Afterwards the plant and grain subsamples were grounded and analyzed to determine the C and N content by combustion (TruSpec CN, LECO, St Joseph, MI, USA). The rest of maize plants at each experimental plot was harvested with a commercial combine. Maize grain moisture was determined and grain yield was standardized to 14 % moisture content.

2.5 Data analysis

Cumulative soil C and N emissions due to the fluxes of CO_2, CH_4 and N_2O during the whole experimental period were quantified on a mass basis (i.e., kg C ha^{-1} and kg N ha^{-1}) using the trapezoid rule. This involves linear interpolation between the data points, calculating the area of each trapezoid formed and summing these areas to give the cumulative emissions (Levy et al., 2017). Sqrt-transformations were done for CO_2 fluxes and WFPS values, and a logarithm transformation was done for N_2O fluxes. Transformed data for CO_2 and N_2O fluxes, and WFPS and soil NH_4^+ and NO_3^- content, and soil temperature were analyzed performing different repeated measures analysis of variance (ANOVA) with the REML (Restricted Maximum Likelihood) approach with irrigation time, irrigation frequency, date of sampling and their interactions as sources of variation. Each measurement period (i.e. 2015, 2015 growing season; fallow, fallow period; 2016, 2016 growing season) was analyzed separately. In addition, different ANOVA were performed for cumulative C and N emissions, grain yield, grain yield-scaled N_2O emissions ratio and grain N-uptake scaled N_2O emissions ratio with irrigation time, irrigation frequency, measurement period and their interactions as sources of variation. Previous to the ANOVA analysis, logarithm transformations were done for cumulative N_2O emissions, grain yield-scaled N_2O emissions ratio and grain N-uptake scaled N_2O emissions. When significant, differences between treatments were identified at 0.05 probability level of significance using a Tukey test. The relationships between the fluxes of CO_2, CH_4 and N_2O and the soil NH_4^+ and NO_3^- content, the WFPS and the soil temperature were analysed by simple regressions. All statistical analyses were performed with JMP 10 statistical package (SAS Institute Inc., 2012).

3. Results

3.1 Environmental conditions, WFPS and soil ammonium and nitrate content.

Daily precipitation, mean daily air temperature and daily reference evapotranspiration, ETo, for the 2015 and 2016 growing seasons are shown in Figure 4.1.

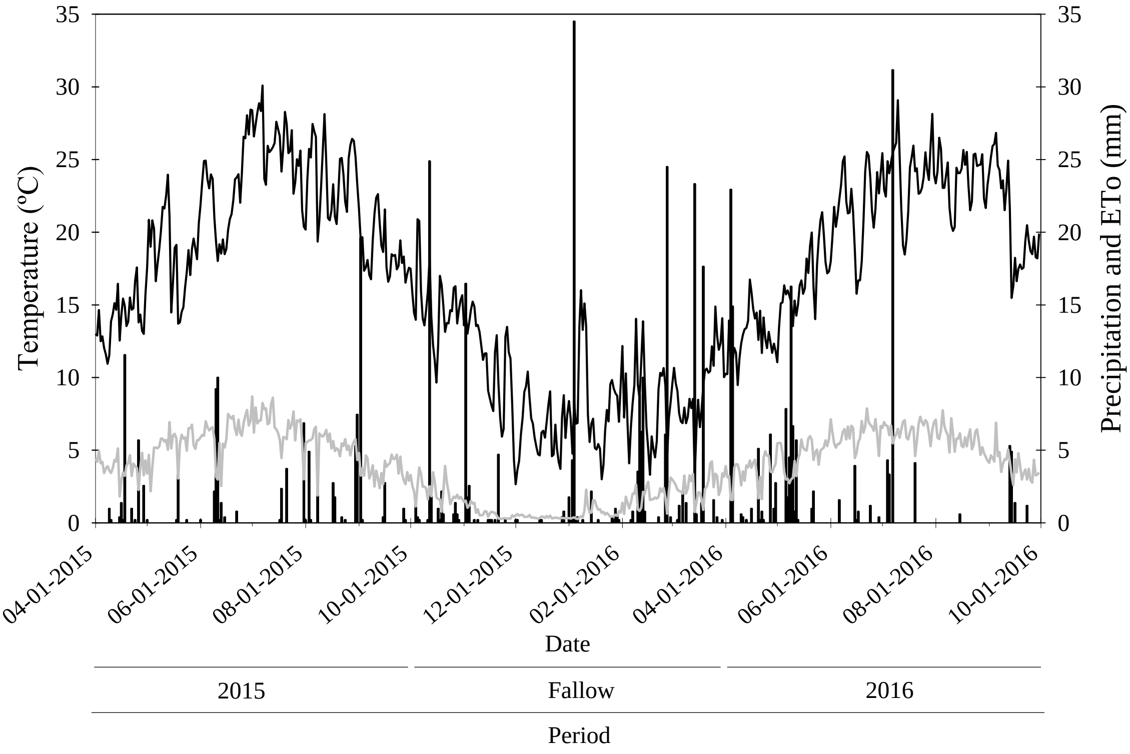

Figure 4.1. Air temperature (black continuous line), precipitation (black bars) and reference evapotranspiration (ETo) (grey continuous line) during the experimental period.

A large variation in temperature and precipitation were recorded during the two growing seasons as expected in Mediterranean conditions. Air temperature showed the highest values during the summer months (June-August) and the lowest during the winter months (December-February).

The sampling date was significant for the most part of the variables considered in this work (Table 4.4). Moreover, for some of these variables the interaction between sampling date and irrigation time and frequency was also significant. Table 4.4 only shows the results of irrigation time, irrigation frequency and their interaction. However, when the interaction between irrigation time, irrigation frequency and sampling date was significant, the results are presented graphically.

The WFPS was affected differently depending on the measurement period (i.e. 2015 growing season, fallow, 2016 growing season) (Table 4.4, Figure 4.2). The WFPS was affected by the irrigation time and frequency during the 2016 growing season (2016 hereafter) maize season, while it was affected by the interaction of both variables in 2015 growing season (2015 hereafter).

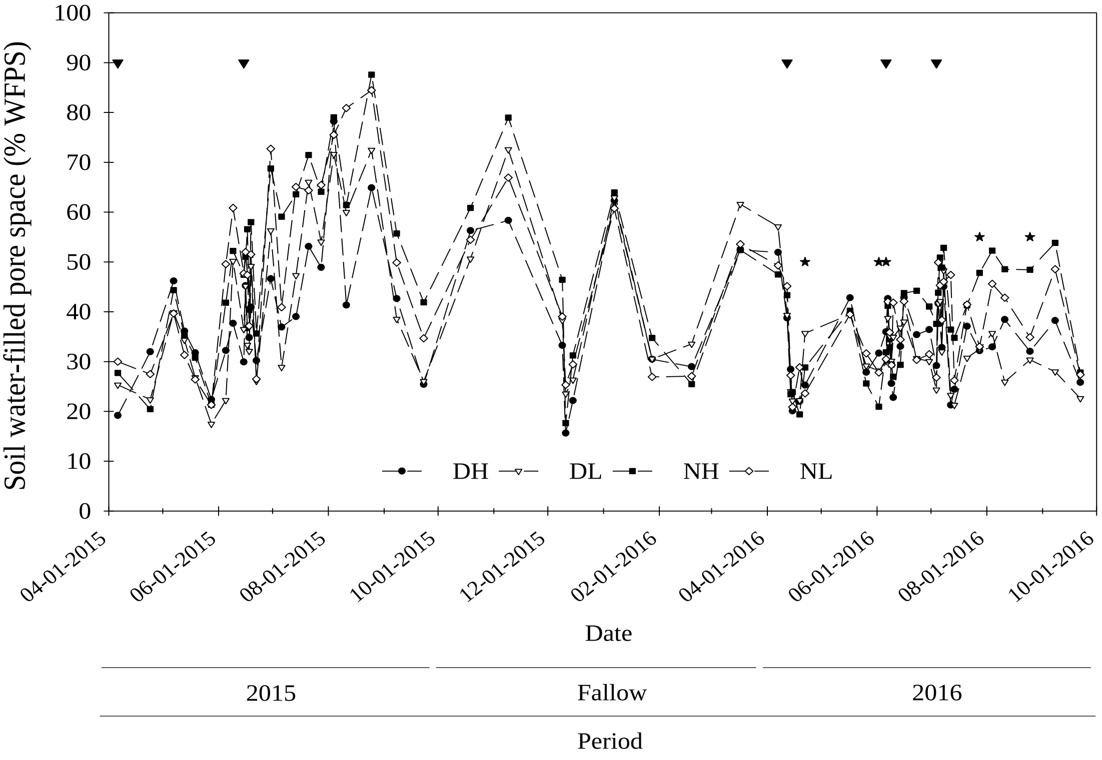

Figure 4.2. Soil water-filled pore space (WFPS) as affected by irrigation time and irrigation frequency (DH, daytime high frequency; DL, daytime low frequency; NH, nighttime high frequency; NL, nighttime low frequency). *Indicates significant differences between treatments for each date at $p<0.05$. Triangles indicate fertilizer applications.

In both growing seasons, the nighttime irrigation showed greater WFPS compared to the daytime irrigation. Besides, in 2016 high frequency irrigation showed greater WFPS compared to low frequency irrigation. However, in 2015, the high irrigation frequency only increased the WFPS when irrigation was applied at night. As expected, the WFPS during the fallow period was not affected by the irrigation management, because irrigation water was not added during this period.

Soil NO_3^- and NH_4^+ contents were significantly affected by the sampling date (Table 4.4). Moreover, in 2015, soil NH_4^+ content showed a significant interaction between irrigation time and sampling date. In this period, the highest value of soil NH_4^+ was observed under D irrigation during the week after the top dressing application of the nitrogen fertilizer.

Table 4.4 Analysis of variance (ANOVA) of soil water-filled pore space (WPFS), nitrate and ammonium content in soil (0–5 cm) and fluxes of CO_2, CH_4 and N_2O by measurement period as affected by irrigation time (D, daytime; N, nighttime), irrigation frequency (H, high; L, low) and date of sampling and their interactions.

Effect and levels†	WFPS			Soil nitrate content			Soil ammonium content			Gas fluxes								
	(%)			(kg NO_3^{-}-N ha^{-1})			(kg NH_4^{+}-N ha^{-1})			CO_2 (g CO_2-C m^{-2} day^{-1})			CH_4 (mg CH_4-C m^{-2} day^{-1})			N_2O (mg N_2O-N m^{-2} day^{-1})		
	2015	Fallow	2016	2015	Fallow	2016	2015	Fallow	2016	2015	Fallow	2016	2015	Fallow	2016	2015	Fallow	2016
D	40.65 b	43.44	32.23 b	36.56	28.95	71.66	3.56	0.62	5.31	2.27 a	0.38	1.72 a	-0.18	-0.14	-0.07	1.89 b	0.10	2.20
N	50.40 a	44.60	36.90 a	40.20	24.26	62.59	2.60	0.65	6.40	2.17 b	0.41	1.51 b	-0.12	-0.01	-0.14	3.12 a	0.17	1.68
H	45.72	43.55	35.26 a	40.42	26.80	72.00	3.01	0.62	5.71	2.24	0.40	1.58	-0.09 a	-0.09	-0.11	2.56	0.14	1.74
L	45.33	44.50	33.86 b	36.28	26.41	62.25	3.21	0.65	6.00	2.20	0.38	1.64	-0.21 b	-0.06	-0.09	2.43	0.13	2.13
DH	40.27 c	41.18	32.74	37.73	29.14	78.07	3.54	0.61	5.29	2.20 ab	0.40	1.69	-0.12	-0.17	-0.07	1.75	0.11	1.81
DL	41.04 c	45.71	31.72	35.38	28.77	65.24	3.59	0.63	5.33	2.34 a	0.36	1.74	-0.24	-0.10	-0.07	2.03	0.09	2.58
NH	51.14 a	45.92	37.79	43.09	24.47	65.93	2.49	0.63	6.13	2.27 ab	0.40	1.48	-0.06	0.00	-0.16	3.37	0.17	1.67
NL	49.65 b	43.28	36.01	37.19	24.05	59.26	2.82	0.66	6.68	2.06 b	0.41	1.54	-0.19	-0.01	-0.11	2.85	0.17	1.68
ANOVA																		
Irrigation Time	*<0.001*	NS	*<0.001*	NS	NS	NS	NS	NS	NS	*<0.05*	NS	*<0.01*	NS	NS	NS	*<0.05*	NS	NS
Irrigation Frequency	NS*	NS	*<0.01*	NS	NS	NS	NS	NS	NS	NS	NS	NS	*<0.05*	NS	NS	NS	NS	NS
Date	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	NS	NS	NS	*<0.001*	*<0.001*	*<0.001*
Time x Frequency	*<0.05*	NS	NS	NS	NS	NS	NS	NS	NS	*<0.05*	NS	NS	NS	NS	NS	NS	NS	NS
Time x Date	*<0.001*	NS	*<0.001*	NS	NS	NS	*<0.001*	NS	NS	*<0.001*	*<0.01*	*<0.001*	NS	NS	NS	NS	NS	*<0.001*
Frequency x Date	*<0.001*	NS	*<0.001*	NS	NS	NS	NS	*<0.001*	NS	NS	NS	*<0.001*	NS	NS	NS	NS	NS	*<0.001*
Time x Frequency x Date	NS	NS	*<0.01*	NS	NS	NS	NS	NS	NS	*<0.05*	NS	*<0.001*	NS	NS	NS	NS	NS	*<0.001*

†For each effect, period and variable values followed by different letters are significantly different according to a Tukey test at P = 0.05 level. * NS, No significant

3.2 Soil CO_2, CH_4 and N_2O fluxes.

Soil CO_2 emissions were affected by irrigation time, irrigation frequency and sampling date in 2015 and 2016, but not during the fallow period (Table 4.4, Figure 4.3).

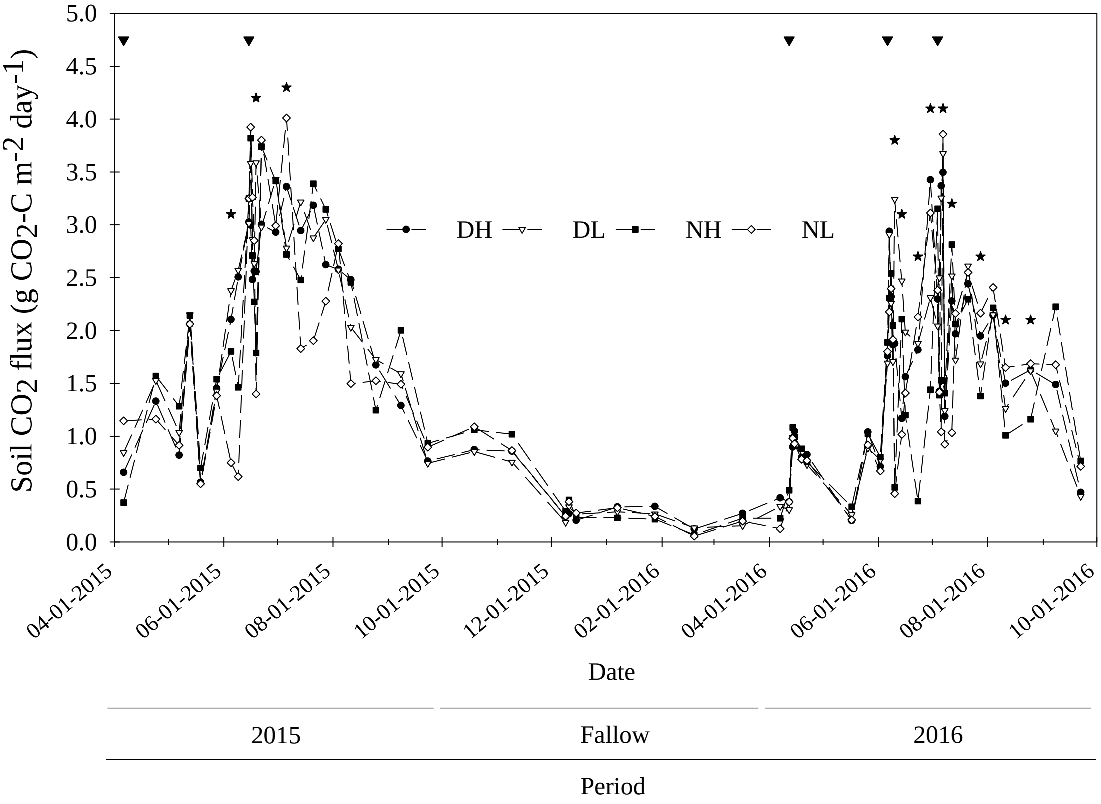

Figure 4.3. Soil CO_2 flux as affected by irrigation time and irrigation frequency (DH, daytime high frequency; DL, daytime low frequency; NH, nighttime high frequency; NL, nighttime low frequency). *Indicates significant differences between treatments for each date at $p<0.05$. Triangles indicate fertilizer applications.

During both growing seasons, soil CO_2 fluxes showed a similar behaviour with an increase in the emission rates along the maize crop growth reaching the maximum values in July coinciding with maize tasseling stage (VT). Moreover, in 2015, mean CO_2 flux values ranged between 2.34 to 2.06 g CO_2-C m^{-2} day^{-1}, while in 2016 the mean CO_2 flux values varied from 1.74 to 1.48 g CO_2-C m^{-2} day^{-1} involving a reduction of 27% in the CO_2 flux mean in 2016 compared with 2015. After this maximum emission value, soil

CO_2 fluxes decreased reaching the minimum values during the fallow period, with mean CO_2 flux values lower than 0.5 g CO_2-C m^{-2} day^{-1} in most of the sampling dates (Figure 4.3).

In 2015, soil CH_4 fluxes showed significant differences between irrigation frequencies, with greater net CH_4 uptake in L irrigation compared with H irrigation (Table 4.4). For the rest of measurement periods no significant differences were observed for soil CH_4 fluxes.

In 2015, soil N_2O fluxes were affected by irrigation time with the greatest N_2O emissions observed under N irrigation compared with D irrigation (Table 4.4, Figure 4.4). Furthermore, in 2016, the interaction between irrigation time, frequency and date was significant for soil N_2O fluxes.

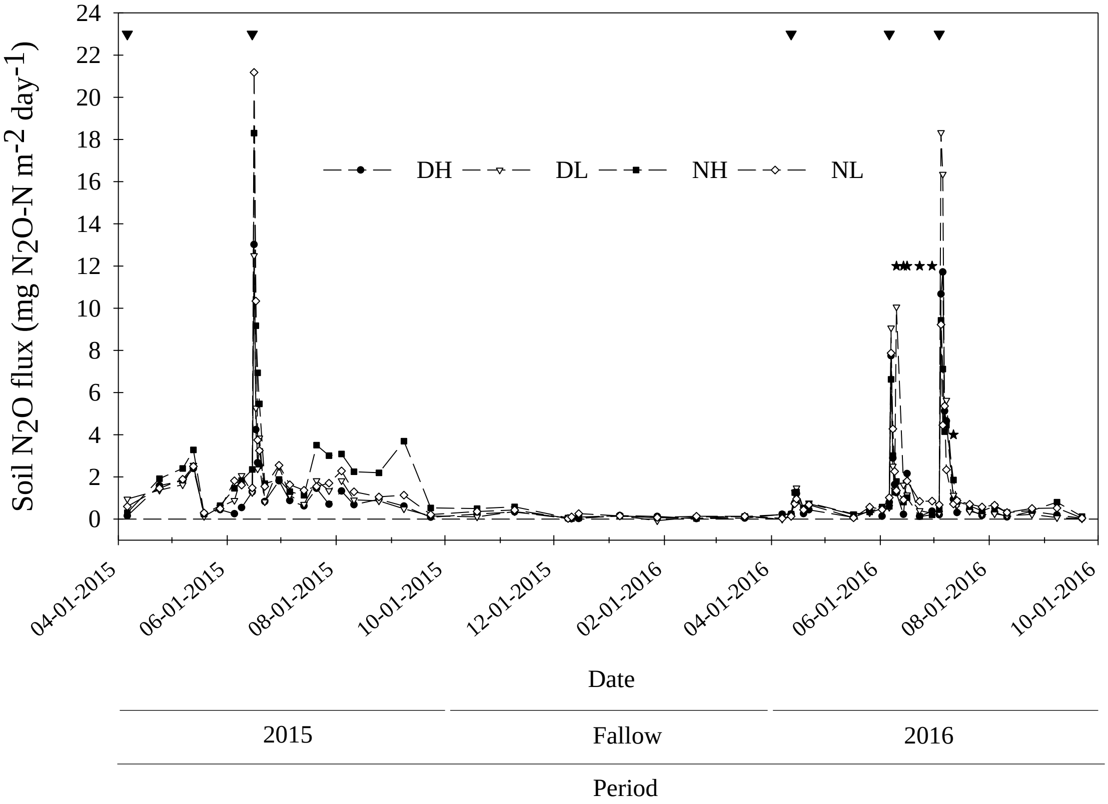

Figure 4.4. Soil N_2O fluxes as affected by irrigation time and irrigation frequency (DH, daytime high frequency; DL, daytime low frequency; NH, nighttime high frequency; NL, nighttime low frequency). *Indicates significant differences between treatments for each date at $p<0.05$. Triangles indicate fertilizer applications.

Soil N_2O fluxes were low in most of the sampling dates, especially during the fallow period. In contrast, soil N_2O flux showed a great increment after the fertilizer was added, especially after top dressing applications of the nitrogen fertilizer (N-32 % solution). These N_2O peak events occurred 24 h and 48 h after the fertilizer applications (Figure 4.4). In 2015, the maximum N_2O flux, 21 mg N_2O-N m^{-2} day^{-1}, was measured after the top dressing application of the nitrogen fertilizer. In contrast, in 2016, two high emissions peak events of N_2O were observed, with maximum values of 11 and 19 mg N_2O-N m^{-2} day^{-1} for the first and the second top dressing application respectively.

Significant relationships were found between soil temperature at 5 cm depth and soil CO_2 and N_2O fluxes. Both relationships showed an exponential growth of soil CO_2 (Figure 4.5a) and N_2O (Figure 4.5b) fluxes as the soil temperature increased. Nevertheless, any of the correlations between GHG fluxes and neither soil water content nor soil NO_3^- and NH_4^+ contents were significant (data not shown).

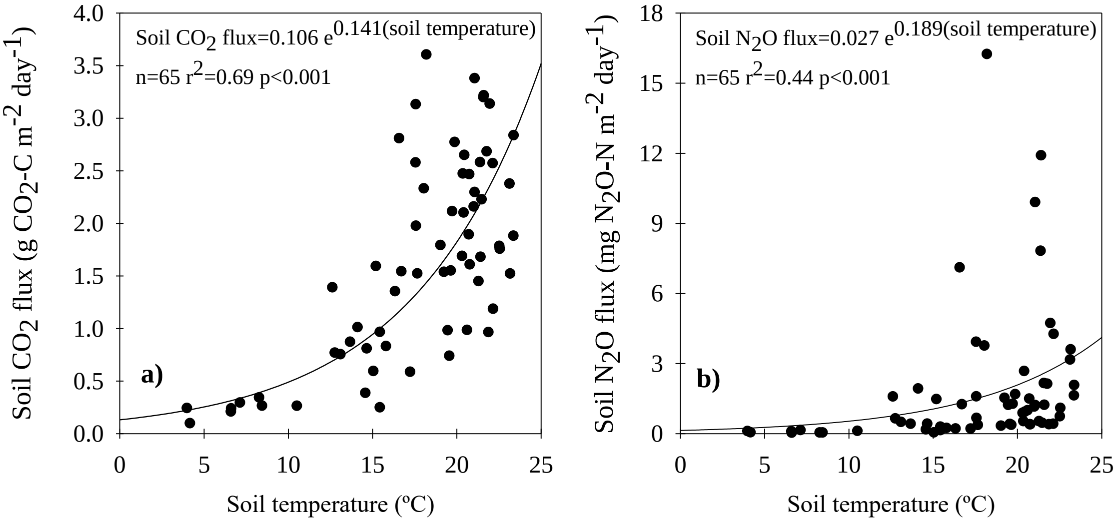

Figure 4.5. Regression analysis between soil temperature (5 cm depth) and CO_2 (a) and N_2O (b) fluxes. Each point represents the average value of all treatments for each sampling date.

3.3 Cumulative soil CO_2, CH_4 and N_2O emissions, grain yield and yield-scaled emissions.

Cumulative soil CO_2 emissions were affected by the interaction between irrigation time, frequency and measurement period (Table 4.5 and Figure 4.6). Cumulative soil CO_2 emissions in 2015 were higher compared with 2016 and the fallow period. The lowest cumulative CO_2 values occurred during the fallow period.

Table 4.5. Analysis of variance (ANOVA) of cumulative CO_2, CH_4 and N_2O emissions, grain yield and the ratios between N_2O emission and grain yield and grain N uptake, as affected by the measurement period (2015, 2015 growing season; 2016, 2016 growing season; fallow, fallow period between growing seasons), irrigation time (D, daytime; N, nighttime), irrigation frequency (H, high; L, low) and their interactions.

Effect and levels†	Cumulative emissions			Grain yield	N_2O-N emission ratio to	
	CO_2 (Mg CO_2-C ha^{-1})	CH_4 (kg CH_4-C ha^{-1})	N_2O (kg N_2O-N ha^{-1})	(Mg ha^{-1})	Grain yield (g Mg^{-1})	N uptake (g kg^{-1})
2015	3.32 a	-0.23	2.61 a	14.09 b	182.4 a	10.39 a
Fallow	0.63 c	-0.13	0.25 c			
2016	2.27 b	-0.21	1.29 b	15.78 a	82.5 b	5.42 b
D	2.12	-0.23	1.17 b	14.00 b	120.2	7.48
N	2.03	-0.15	1.60 a	15.87 a	144.7	8.15
H	2.09	-0.17	1.41	14.84	135.5	7.52
L	2.05	-0.21	1.36	15.03	129.4	8.06
DH	2.12	-0.23	1.04	13.53 c	110.2	6.72
DL	2.11	-0.23	1.3	14.47 b	130.1	8.24
NH	2.08	-0.11	1.78	16.15 a	160.8	8.49
NL	1.99	-0.19	1.41	15.59 a	128.6	7.87
ANOVA						
Period	<0.001	NS	<0.001	<0.001	<0.001	<0.001
Irrigation Time	NS*	NS	<0.001	<0.001	NS	NS
Irrigation Frequency	NS	NS	NS	NS	NS	NS
Time x Frequency	NS	NS	NS	<0.05	NS	NS
Period x Irrigation Time	NS	NS	NS	NS	NS	NS
Irrigation Frequency	NS	NS	NS	NS	NS	NS
Period x Time x Frequency	<0.01	NS	NS	NS	NS	NS

†For each effect and variable the numbers with different letters are significantly different according to a Tukey test at P = 0.05 level. * NS, No significant

In 2015, the NL treatment resulted in lower cumulative CO_2 emissions than the DL and NH treatments. However, in 2016 and the fallow period, the irrigation treatments did not affect cumulative CO_2 emissions (Figure 6).

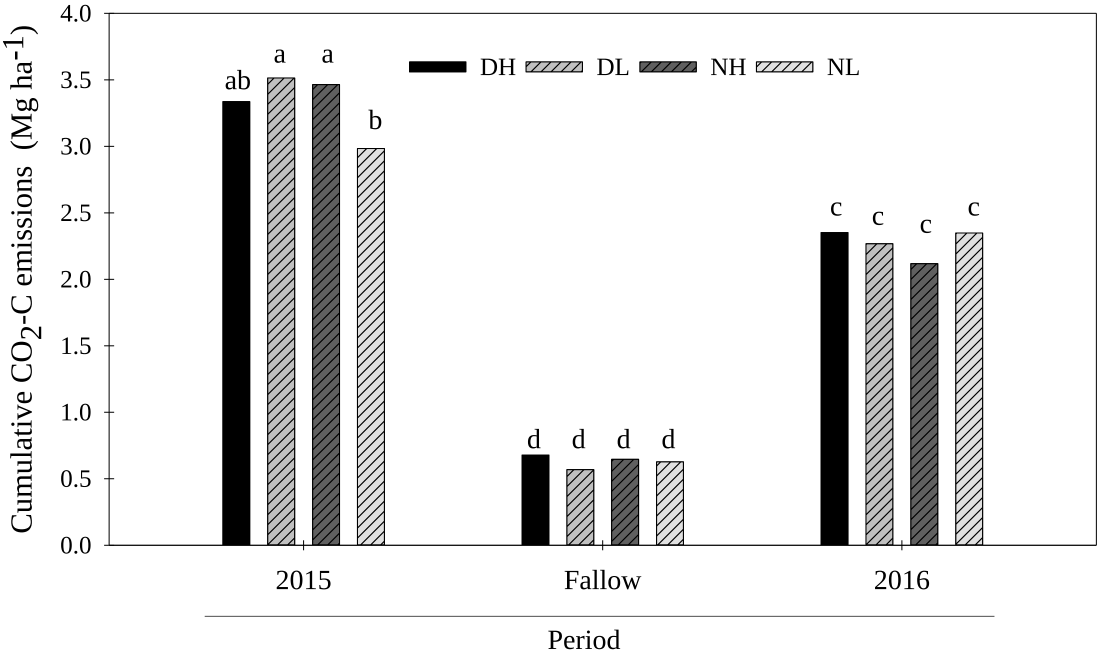

Figure 4.6. Cumulative CO_2 emissions as affected by measurement period (2015, 2015 growing season; 2016, 2016 growing season; fallow, fallow period between growing seasons), irrigation time and irrigation frequency (DH, daytime high frequency; DL, daytime low frequency; NH, nighttime high frequency; NL, nighttime low frequency). Different letters indicate significant differences between treatments at $p<0.05$.

Cumulative soil CH_4 emissions were not affected by the period, irrigation time or frequency (Table 4.5). As an average of treatments and sampling dates, a net uptake of CH_4 was observed.

Cumulative soil N_2O emissions were significantly affected by the measurement period and by the irrigation time (Table 4.5). Regarding the measurement period, 2015 was the measurement period with the greatest cumulative N_2O emissions, 2.61 kg N_2O-N ha^{-1}, being two and eleven times higher compared with the values observed in 2016 and in the fallow period, respectively. Furthermore, N presented the highest cumulative N_2O emission with a mean value throughout the three measurement periods of 1.60 kg N_2O-N ha^{-1} that was 36% higher compared with D irrigation.

Grain yield was affected by the measurement period, irrigation time and the interaction between irrigation time and frequency (Table 4.5). Grain yield was higher in 2016 compared with 2015. Grain yield was higher when the irrigation water was applied at nighttime. H frequency irrigation decreased the grain yield when irrigation was applied at daytime, while irrigation frequency did not affect grain yield when irrigation was applied at nighttime. Finally, grain yield scaled N_2O emissions and N-uptake scaled N_2O emissions were only affected by the measurement period. In 2015, the scaled N_2O emissions almost doubled those measured in 2016.

4. Discussion

4.1. Sprinkler irrigation management and GHG emissions

According to the results obtained in this study, sprinkler irrigation management affected soil water content leading to a considerable impact not only on soil GHG emissions but also on maize grain yield.

The soil CO_2 fluxes measured for the entire gas sampling period were in the range of values found in the literature for sprinkler-irrigated maize systems (e.g. Alluvione *et al*., 2009; Ghimire *et al*., 2017). Irrigation time and frequency together with the sampling date affected daily CO_2 fluxes in both maize growing seasons but not during the fallow period. Soil CO_2 fluxes tended to increase in the treatments that were irrigated during D time. This trend could be related with greater WFPS observed under N compared with D, due to the lower water losses during N irrigation events (Playán *et al*., 2005; Cavero *et al*., 2008; Martínez-Cob *et al*., 2008). These greater WFPS values in N treatments could resulted in lower gas diffusivity conditions (Smith *et al*., 2003; Ball *et al*., 2008) because of the negative impact of WFPS on the soil diffusivity (Buckingham, 1904; Penman, 1940; Millington and Quirk, 1961) resulting in lower CO_2 fluxes under N irrigation.

Irrigation time and frequency and the measurement period had an impact on the cumulative CO_2 emissions. On average, cumulative CO_2 emissions in 2015 were 1.46 times higher than those in 2016, and 5.3 times greater than during the fallow period. It is important to know that soil CO_2 emissions measured in this study are the combination of the autotrophic (i.e. root derived) and heterotrophic (i.e. microorganism derived) respiration. Thus, the higher soil CO_2 emission obtained in both maize growing seasons compared with the fallow period were explained by the presence of the crop as well as the effect of soil temperature on the microorganism activity (Lloyd and Taylor, 1994;

Fang and Moncrieff, 2001), as it was shown in the positive relationship between soil temperature and soil CO_2 fluxes. Furthermore, the higher WFPS values in 2015 could result in more optimal conditions for microorganism activity (Linn and Doran, 1984) along with the crop residues of the previous alfalfa crop, which could explain the greater cumulative CO_2 emissions measured in 2015 compared to those in 2016. This finding agrees with the results of Adviento-Borbe *et al.* (2010), who found higher cumulative CO_2 emission in the maize growing season of a maize-alfalfa rotation compared with a continuous maize, due to the capacity of legumes to improve the availability of carbon and nitrogen in the soil (Aulakh *et al.* 2001; Tejada *et al.* 2008).

Soil CH_4 fluxes were in the range of values observed by Sánchez-Martin *et al.* (2010) in Mediterranean areas. During all the experimental period, cumulative CH_4 emissions were negative, which means that soil acted as a CH_4 sink, as observed by Sanz-Cobeña *et al.* (2014). As reported by Hütsch (2001), there are different factors controlling CH_4 oxidation by the methanotophic bacteria, like soil NO_3^- and NH_4^+ content, oxygen availability, pH, etc. In addition, Le Mer and Roger (2001) described methanogenesis as a biological process that requires strict anaerobiosis and low oxido-reduction potentials. In this study, WFPS values were far from the values needed for a strict anaerobiosis condition. Moreover, these low WFPS values could positively affect soil diffusivity resulting in a better air-filled porosity and an optimal circulation of soil gases (Ball *et al*, 1999; Smith *et al.*, 2003; Ball *et al.* 2008), thus providing a more suitable condition for methane consumption.

Soil N_2O fluxes were similar to the fluxes found in other studies for irrigated maize (Halvorson *et al.*, 2010a; Lui *et al.*, 2005). In both maize growing seasons, irrigation management through its effect on the WFPS had an important effect on N_2O fluxes. The

WFPS is considered as a key factor on the production of N_2O in the soil (Bouwman *et al*., 2002; Butterbach-Bahl *et al*., 2013).

In 2015, irrigation time affected soil N_2O fluxes. In this growing season, N irrigation presented a mean N_2O flux value 1.65 times greater than D. The greatest N_2O flux under N was explained by the increment of 19 % in WFPS values with N irrigation compared to D irrigation. In 2016 growing season, however, it was the interaction between the irrigation treatments and the sampling date, which influenced the daily N_2O fluxes. This interaction mainly affected the N_2O fluxes just after the first top dressing application of the nitrogen fertilizer and the following month, observing the greatest N_2O peak under DL treatment.

Regarding the cumulative N_2O emissions, the values reported in this work were close to the values obtained by Álvaro-Fuentes *et al*. (2016) and Maris *et al*. (2018) for sprinkler-irrigated maize systems in the Ebro Valley (NE Spain), but lower than the values reported in the two meta-analysis published for Mediterranean conditions (Aguilera *et al*., 2013b; Cayuela *et al*., 2017). These two studies reported cumulative soil N_2O emissions of 4 kg ha^{-1} for sprinkler irrigation and cumulative N_2O emissions close to 5 kg ha^{-1} for maize. However, cumulative N_2O emissions in this study were 35% (2015) and 70 % (2016) lower compared with the cumulative N_2O emissions presented in the previous meta-analysis for sprinkler irrigation under Mediterranean conditions (Aguilera *et al*., 2013; Cayuela *et al*., 2017). Differences between the two previous meta-analyses and our study could be explained by the fact that both meta-analysis used a large number of studies with different combinations of sources and rates of nitrogen fertilizer, irrigation systems, crops, etc.

Cumulative N_2O emissions measured were different in the three periods of measurement. Cumulative emissions observed in both growing seasons were 10 (2015) and 5 (2016) times higher than in the fallow period since during the fallow period no nitrogen fertilizer nor irrigation water were applied. Furthermore, cumulative N_2O emissions in 2015 were two-fold greater than in 2016. Differences in WFPS and in the the carbon and nitrogen provided by the residues of the previous alfalfa crop could explain this difference. According to Bateman and Baggs (2005), nitrification is the predominant process contributing to N_2O emissions when WFPS values range between 35–60 % WFPS. In contrast, when WFPS values are higher than 60% denitrification mainly control the production of N_2O. In 2015, in 69% of the sampling dates WFPS values were within the optimum range for nitrification and denitrification processes while in 2016, only the 46% of the sampling dates reached these optimal conditions. Although less N fertilizer was applied in 2015, the higher production of N_2O this year was probably related with the fact that the previous crop was a legume, which usually results in an increment of the availability of nitrogen in the soil for the following crop (Ballesta and Lloveras *et al.*, 2010, Salmerón *et al.*, 2010; Cela *et al.*, 2011). Therefore, the greater number of sampling dates in which nitrification and denitrification processes could occur, together with the N mineralized from the residues of the previous alfalfa could lead to more optimal conditions for the N_2O productions during the 2015 maize growing season.

4.2. Grain yield- and N uptake-scaled GHG emissions

Under this high-yielding maize system, grain yield values were similar to the values obtained by Urrego-Pereira *et al*. (2013a) and Robles *et al*. (2017) in the same location.

Irrigation time affected the maize grain yield, reporting a decrease of the 13% in D irrigation compared with N irrigation. The reduction of maize yield with daytime irrigation is explained by the lower irrigation uniformity, the reduction of net photosynthesis, the higher WDEL (i.e. wind drift and evaporation losses), and the higher accumulation of Na^+ in maize (Cavero *et al*., 2009; Urrego-Pereira *et al*., 2013a and b; Cavero *et al*., 2018). Besides, the decrease in maize grain yield when sprinkler irrigation frequency was increased at D irrigation was related to the higher water losses and the increased Na^+ in the maize plant (Cavero *et al*., 2018).

The ratio of N_2O emissions per unit of crop yield or per unit of grain N-uptake (i.e. grain yield-scaled N_2O emissions and N-uptake-scaled N_2O emissions) is a good estimator of the N_2O efficiency of a cropping system (Van Groenigen *et al*., 2010). N_2O emissions per unit of grain yield and per unit of grain N-uptake obtained in this study were in the range of the values reported by Venterea *et al* (2011) and Omonode *et al* (2015) for maize under different tillage and different N sources and N rates application. In our study, only 2015 showed differences in N_2O scaled emissions due to the lower grain yield in 2015 and the effect of the preceding alfalfa crop. Sprinkler irrigation time affected N_2O emissions, but when emissions were expressed on the basis of grain yield or grain N uptake, differences disappeared due to the effect of irrigation time on maize yield and, consequently, on N uptake (Pandey *et al*., 2000).

5. Conclusions

The results of this work showed that the sprinkler irrigation time had a greater impact on the soil GHG emissions and on the grain yields compared with the sprinkler irrigation frequency. Nighttime irrigation increased N_2O emissions and grain yields, regardless if the irrigation was applied with a high or low frequency. However, N_2O emissions did not show differences due to irrigation management when emissions were estimated based on the grain yields or based on the N uptake. Due to lack of differences found in scaled N_2O emissions and in order to optimize the grain yield and reduce water losses, sprinkler irrigation should be applied at nighttime. Finally, this work emphasize the importance of the appropriate management of the irrigation under Mediterranean conditions to increase the yields without a significant increment of the GHG.

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Discusión general

Discusión general

La implementación del riego en los cultivos de zonas semiáridas, caracterizadas por una baja y errática distribución de la precipitación, junto con un número importante de días libres de helada, permite alcanzar altos rendimientos. De igual modo, la adopción de nuevos sistemas de manejo del suelo, como la siembra directa, pueden mejorar las propiedades físico-químicas del suelo (Lal, 2004; Triplett y Dick, 2008), resultando en unas condiciones más favorables para el desarrollo de los cultivos (Ismail *et al*., 1994). Sin embargo, el riego, junto al manejo del suelo, puede generar una serie de impactos sobre los recursos suelo, agua y aire tal y como se ha observado en otras partes del mundo (Smith *et al*., 2014). En esta Tesis Doctoral se ha abordado, en concreto, el impacto de dos de las principales prácticas de cultivo (riego y manejo del suelo) de los sistemas de maíz del valle del Ebro en la producción y emisión de gases de efecto invernadero (GEI) del suelo.

Impacto del sistema y manejo del riego

Los sistemas de riego, dada su capacidad para modificar el contenido de humedad del suelo, pueden tener una gran influencia en los factores bióticos y abióticos responsables de la producción y transporte de GEI en el suelo (Smith *et al*., 2008).

El riego por aspersión (riego presurizado) y el riego por inundación (riego por gravedad) son los tipos de riego más utilizados en el mundo para regar cultivos extensivos como el maíz. El riego por aspersión permite el fraccionamiento del riego en diversos eventos, incluso en un mismo día. Esta característica da la posibilidad de ajustar las dosis de riego en función de las necesidades hídricas del cultivo, manteniendo un contenido de humedad del suelo más estable a lo largo del ciclo de cultivo (Rawlins y Raats, 1975).

Por el contrario, el riego por inundación posee una frecuencia de riego menor, siendo habitual la aplicación de dosis de riego que oscilan entre los 80-100 mm por evento de riego. Durante los tres ciclos de cultivo de maíz evaluados en esta Tesis, el riego por aspersión presentó valores de espacio de poroso del suelo lleno de agua (WFPS, en inglés) que oscilaron entre 50-60%, rango descrito como óptimo para los procesos de respiración de los microorganismos del suelo (Linn y Doran, 1984). Sin embargo, en el riego por inundación los valores de WFPS del suelo fluctuaron desde el 20 hasta el 100% entre eventos de riego (10 días). Estas diferencias entre ambos sistemas de riego mostraron una gran influencia sobre la producción y emisión de GEI, especialmente sobre el CO_2 y el N_2O, así como sobre el desarrollo y productividad del cultivo de maíz.

En el riego por aspersión se observó un aumento de las emisiones de CO_2 del suelo con el incremento de WFPS. Por el contrario, en el riego por inundación las emisiones de CO_2 del suelo aumentaron con el WFPS hasta un valor del 60%, a partir del cuál las emisiones de CO_2 disminuyeron al aumentar el WFPS del suelo. Esta disminución de las emisiones de CO_2 en el riego por inundación se explicó por la menor producción de CO_2 en el perfil del suelo bajo este sistema de riego. Los elevados valores de WFPS, hasta del 100% tras cada evento de riego por inundación, limitaron la difusión del O_2 en suelo, dando lugar a una menor producción de CO_2 asociada a los procesos de respiración microbiana (Linn y Doran, 1984; Smith *et al*., 2003; Ball *et al*., 2008).

Además, a lo largo de los tres ciclos de cultivo de maíz se observó un incremento de las emisiones de CO_2 del suelo al aumentar los rendimientos del cultivo. Esto es debido a la contribución de las raíces al total de la respiración del suelo. En concreto, la respiración radicular puede llegar a suponer hasta un 50% de la respiración total del suelo durante los estadios fenológicos vegetativos del maíz (Rochette y Flanagan, 1997). La mayor frecuencia de riego bajo aspersión produce un menor estrés hídrico para el cultivo en comparación con el riego por inundación (Segal *et al*., 2006). Además, la situación de encharcamiento tras cada evento de riego por inundación afecta al desarrollo de la planta de maíz a lo largo de las diferentes fases fenológicas (Ren *et al*., 2016). Estos hechos explicaron la reducción del 14% en los rendimientos de cultivo en el sistema de riego por inundación y contribuyeron a explicar las menores emisiones de CO_2 bajo este sistema de riego. Asimismo, la presencia de cultivo, junto con el efecto positivo de la temperatura sobre la actividad de los microorganismos del suelo, explicaron las mayores emisiones de CO_2 registradas en ambos sistemas de riego durante los ciclos de cultivo del maíz frente a los periodos de barbecho (Linn y Doran, 1984; Rochette y Flanagan, 1997).

La combinación de factores claves para los procesos de producción de N_2O en el suelo, como los fertilizantes nitrogenados y el agua de riego, durante el periodo cálido del año (verano), dio lugar a una serie de picos de producción de N_2O en el suelo y su consiguiente emisión a la atmósfera (Bouwman *et al*., 2002; Butterbach-Bahl *et al*., 2013; Sánchez-Martín *et al*., 2008). Estos picos de producción de N_2O tuvieron lugar a lo largo del perfil del suelo en ambos sistemas de riego. Sin embargo, los valores máximos de concentración se observaron a diferentes profundidades dependiendo del sistema de riego. En el sistema de riego por inundación las mayores concentraciones de N_2O asociadas a estos picos de producción se observaron a 0,10 y 0,20 m de profundidad, mientras que en el sistema de riego por aspersión los mayores valores de concentración de N_2O fueron medidos a 0,40 m de profundidad. Estas diferencias entre sistemas de riego se debieron a que los valores de WFPS óptimos para la producción de N_2O en el suelo (70 - 80%) se alcanzaron a diferentes profundidades (Davidson, 1991). Del mismo modo, la mayor frecuencia y duración en el tiempo de estos valores de WFPS, en torno al 70-80% bajo en el riego por inundación, explicaron las mayores concentraciones de N_2O en este sistema de riego, que duplicaron los valores de concentración y emisión de N_2O observados en el sistema de riego por aspersión.

No solamente el sistema de riego, sino también su manejo, tuvo un impacto sobre las emisiones de GEI del suelo y los rendimientos del cultivo. Durante los dos ciclos de cultivo de maíz en los que se evaluó el efecto del momento y la frecuencia de aplicación del riego por aspersión, el momento de aplicación nocturno mostró un mayor contenido de humedad del suelo, debido a las menores pérdidas de agua cuando el riego se aplica de noche (Playán *et al*., 2005). El mayor contenido de humedad bajo el riego nocturno pudo dar lugar a una reducción de la difusividad de los gases en el suelo, explicando así los menores flujos de CO_2 y la reducción de un 4% de las emisiones acumuladas en el momento de aplicación nocturno en comparación con el momento diurno. En cambio, el mayor contenido de humedad en el suelo de los tratamientos de riego nocturno favoreció la emisión de N_2O en comparación con los tratamientos de riego diurno. No obstante, cuando las emisiones de N_2O se expresaron sobre el rendimiento de grano y sobre el contenido de N en grano, no se observaron diferencias entre momentos de aplicación del riego, debido a los menores rendimientos obtenidos bajo el riego diurno. La reducción del rendimiento de grano de maíz con el riego diurno se explicó por la menor uniformidad del riego, las mayores pérdidas por evaporación y arrastre (WDEL, por sus siglas en inglés), así como por la mayor acumulación de sodio (Na^+) en el maíz cuando el riego se aplicó de día (Cavero *et al*., 2009; Urrego-Pereira *et al*., 2013a y b; Cavero *et al*., 2018). Sin embargo, las diferentes frecuencias de riego por aspersión evaluadas (riego diario *vs* 2 eventos de riego por semana) no mostraron un impacto sobre las emisiones de GEI del suelo.

Pese a lo que cabría esperar, el sistema de riego por inundación no dio lugar a una mayor producción y emisión de CH_4 en comparación con el sistema de riego por aspersión. Una posible explicación a esta ausencia de diferencias puede ser las estrictas condiciones de anaerobiosis que precisa la producción de CH_4. El proceso de metanogénesis requiere alcanzar un valor de potencial de óxido-reducción en el suelo (Eh) de –150mV, para lo cual es necesaria la progresiva reducción de una serie de aceptores de electrones presentes en el suelo tasles como O_2, NO_3^-, Mn^{4+}, Fe^{3+}, SO_4^{2-} (Wang *et al*., 1993; Peters y Conrad, 1996). Sin embargo, la corta duración de la situación de encharcamiento, menos de 24 horas, pudo no ser suficiente en el sistema de riego por inundación para alcanzar las condiciones de anaerobiosis y Eh del suelo necesarias. Además, la producción de metano pudo verse afectada por la presencia de grandes cantidades de amonio (NH_4^+) y nitrato (NO_3^-) asociadas a la fertilización nitrogenada. La metanogénesis puede ser inhibida por toxicidad debida a nitritos (NO_2^-), asociados a los procesos de nitrificación y desnitrificación, así como por la competencia por el hidrógeno (H_2) entre las comunidades desnitrificantes y metanogénicas presentes en el suelo (Kluber y Conrad, 1998). Por tanto, la combinación de ambos procesos pudo explicar la ausencia de producción de CH_4 en el sistema de riego por inundación.

Impacto del manejo del suelo

Los sistemas de manejo del suelo modifican las propiedades físico-químicas de éste, con el consiguiente impacto en la dinámica del C y N del suelo y en los rendimientos de los cultivos (Plaza-Bonilla *et al*., 2010; Álvaro-Fuentes *et al.*, 2013).

El laboreo convencional genera unas condiciones favorables para la oxidación del COS por parte de los microorganismos debido a la incorporación de los restos de cultivo y al efecto que genera el laboreo en los agregados del suelo, favoreciendo la ruptura de éstos (Paustian *et al*., 1997, Álvaro-Fuentes *et al*., 2007). En esta Tesis, estas condiciones más favorables para la oxidación del COS dieron como resultado un incremento de las emisiones de CO_2 del 21 y del 39% en los sistemas de laboreo convencional en comparación con la siembra directa manteniendo el rastrojo en campo y con la siembra directa sin rastrojo, respectivamente. Además, el sistema de riego por aspersión favoreció las emisiones de CO_2 en los sistemas de laboreo convencional debido a unas condiciones de humedad del suelo más favorables para el desarrollo de los procesos de oxidación del C orgánico del suelo. Sin embargo, el riego por inundación favoreció unas menores emisiones de CO_2 en los sistemas de siembra directa debido a los mayores valores de humedad y, por tanto, menor difusividad de los gases observada en este sistema.

Además, la mayor compactación del suelo en los sistemas de siembra directa, con un valor promedio de densidad aparente un 11% mayor que el laboreo convencional, pudo favorecer las menores emisiones de CO_2 medidas en los sistemas de siembra directa. Suelos más compactados dificultan la difusión del O_2 a través del suelo (Ball, 2013), resultando en una menor disponibilidad de oxígeno para los procesos de oxidación del C orgánico del suelo y por tanto en una menor producción y emisión de CO_2. Asimismo, la retirada de los restos de cultivo de la superficie del suelo bajo los sistemas de siembra directa pudo dar lugar a una disminución de los aportes de materia orgánica asociada a los restos de cultivo junto con una menor humedad del suelo a causa de una mayor evaporación directa (Sauer *et al*., 1998; Blanco-Canqui y Lal, 2008), explicando las menores emisiones de CO_2 observadas bajo estos sistemas.

Sin embargo, a diferencia de otros estudios, la mayor compactación del suelo observada en los sistemas de siembra directa no generó un aumento en las emisiones de N_2O del suelo (Ball *et al*., 1999; and Venterea *et al*., 2011). La ausencia de diferencias en la emisión de N_2O entre sistemas de manejo del suelo pudo deberse a las mínimas diferencias observadas en la disponibilidad de N entre sistemas de manejo del suelo, tal y como han observado otros autores (Liu *et al*. 2005; Guzman *et al*., 2015; Forte *et al*., 2017; Johnson y Barbour, 2019). Esta disponibilidad es un factor clave para la producción y emisión de N_2O del suelo (Butterbach-Bahl *et al*., 2013). A lo largo de los tres ciclos de cultivo junto con los dos periodos de barbecho evaluados en esta Tesis Doctoral únicamente se observaron diferencias significativas en el contenido de NO_3^- del suelo en el ciclo de cultivo de 2017 bajo el sistema de riego por aspersión. Además, las diferencias encontradas en la humedad del suelo entre sistemas de riego pudieron enmascarar el efecto del sistema de manejo del suelo, así como de la interacción entre ambas prácticas agrícolas.

Los tres sistemas de manejo del suelo evaluados actuaron como sumidero de CH_4 atmosférico independientemente del sistema de riego. No obstante, se observó una tendencia a un mayor consumo de CH_4 en los sistemas de siembra directa, especialmente cuando se mantuvo el rastrojo en campo. Los microorganismos del suelo se organizan y disponen en biofilms que recubren los agregados del suelo (Peters y Conrad, 1996). De esta manera, estos biofilms se convierten en centros de alta actividad biológica (Hütsch, 2001) que proliferan en el suelo en ausencia de perturbación. En este sentido, los sistemas de siembra directa son más favorables para el desarrollo de estos biofilms y, por tanto, para la actividad de microorganismos del suelo. Esto último podría explicar la tendencia al mayor consumo de CH_4 observado en los sistemas de siembra directa.

Conclusiones generales

Conclusiones generales.

1. El sistema de riego por aspersión presentó unas condiciones de humedad del suelo más estables y favorables para los procesos de oxidación del COS y para los procesos de respiración radicular, observándose una mayor concentración de CO_2 a lo largo del perfil del suelo bajo este sistema de riego, lo que supuso un incremento de un 24% de las emisiones de CO_2 del suelo a la atmósfera frente al sistema de riego por inundación.

2. La mayor frecuencia de aplicación del sistema de riego por aspersión evitó que se alcanzaran valores de WFPS en torno al 70-80%, rango óptimo para la producción de N_2O del suelo mediante los procesos de desnitrificación, resultando en una reducción del 50% de la concentración de N_2O en el perfil del suelo y, por tanto, en una disminución del 42% de las emisiones de N_2O del suelo en comparación con el sistema de riego por inundación.

3. Las menores emisiones de N_2O del suelo bajo el sistema de riego por aspersión junto a unas condiciones de humedad del suelo más favorables para el desarrollo de los cultivos, que supusieron un aumento del 14% de los rendimientos de maíz bajo este sistema de riego, dieron lugar a una disminución de las emisiones de N_2O por kg de grano de maíz del 51% en el sistema de riego por aspersión frente al sistema de riego por inundación.

4. En ambos sistemas de riego se observó un pico de producción de CH_4 asociado a la aplicación de compuestos fertilizantes NPK. Sin embargo, pese a los mayores valores de humedad del suelo, llegando a alcanzar la saturación completa, el sistema de riego por inundación no dio lugar a un incremento de la concentración de CH_4 en el perfil del suelo. Sin embargo, bajo el sistema de riego por aspersión se observó una reducción de la concentración de CH_4 a 0,40 m de profundidad asociado a un evento de metanotrófia. Pese a estas diferencias en la concentración de CH_4 en el perfil del suelo, las emisiones de CH_4 del suelo a la atmósfera fueron similares en ambos sistemas de riego

5. El momento de aplicación nocturno del riego por aspersión resultó en un mayor contenido de humedad del suelo lo que supuso una reducción de las emisiones de CO_2 y un aumento de las emisiones de N_2O del suelo frente al momento de aplicación diurno. Sin embargo, el momento de riego no presentó diferencias en las emisiones de N_2O por kg de grano de maíz debido al incremento de los rendimientos observados en el riego por aspersión nocturno.

6. El uso de la siembra directa manteniendo o retirando los restos de cultivo de la superficie del suelo llevó a una reducción del 30% de las emisiones de CO_2 del suelo respecto al sistema de laboreo convencional.

7. Los sistemas de siembra directa, no dieron lugar a un aumento de las emisiones de N_2O del suelo, en comparación con el sistema de laboreo convencional a pesar del mayor contenido de humedad del suelo observado.

8. Tanto los sistemas de siembra directa como el laboreo convencional mostraron un consumo neto de CH_4. Sin embargo, la ausencia de perturbación del suelo en los sistemas de siembra directa, especialmente, cuando no se retiran los restos de cultivo, favoreció un mayor consumo de CH_4 frente al sistema de laboreo convencional.

En conclusión, la implementación de sistemas de riego por aspersión con la posibilidad de aplicar el riego durante la noche, conjuntamente con sistemas de siembra directa manteniendo el rastrojo en el campo, mostró ser una alternativa viable para la reducción de las emisiones de gases de efecto invernadero del suelo sin merma en los rendimientos de cultivo bajo condiciones mediterráneas.

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