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TESIS DOCTORAL

Medidas de adaptación del cultivo de girasol al cambio climático empleando experimentación y modelización

Adaptation measures of sunflower cultivation to climate change using experimentation and modeling

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TITULO: *MEDIDAS DE ADAPTACIÓN DEL CULTIVO DE GIRASOL AL CAMBIO CLIMÁTICO EMPLEANDO EXPERIMENTACIÓN Y MODELIZACIÓN*

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TÍTULO DE LA TESIS: Medidas de adaptación del cultivo de girasol al cambio climático empleando experimentación y modelización

DOCTORANDO/A: Javier García López

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

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

El Doctorando Javier García López inició su formación predoctoral en el ámbito del estudio del balance de agua en sistemas agrícolas mediterráneos. Esta línea de investigación le permitió obtener un amplio conocimiento de los sistemas agrícolas de secano y su modelización para el establecimiento de funciones de producción asociadas a condiciones meteorológicas. Esta formación se complementó con una estancia de 3 meses (de abril a julio de 2012) en el Istituto per le Macchine Agricole e Movimento Terra (IMAMOTER) en Turín, Italia, para el estudio del balance de agua en vid.

Tras esta fase, y debido a problemas con las fincas experimentales donde se realizaba su tesis doctoral, la temática de los trabajos del doctorando viran hacia la mejora de la sostenibilidad del cultivo del girasol en un contexto de cambio global. Así, los trabajos realizados por Javier García aúnan un intenso trabajo experimental, el empleo de bases de datos previas (RAEA) y la modelización del comportamiento del cultivo del girasol, obteniendo resultados de gran valor para mejorar la sostenibilidad del cultivo del girasol en Andalucía.

Dada la complejidad del trabajo experimental y los requisitos para obtener resultados fiables y de calidad, se han requerido 6 años de experimentación en campo (2012-2017) lo que ha supuesto un retraso en la lectura de la tesis. Igualmente, la integración de datos experimentales propios y previos para la obtención de funciones de respuesta del cultivo del girasol ha supuesto un esfuerzo añadido y que ha requerido un periodo de tiempo considerable.

La tesis se compone de 3 artículos científicos, todos ellos ya publicados en revistas Q1 (García-Lopez et al 2014 - Climatic Change 124, 147-162; García-López et al 2016 - Agricultural Water Management 176, 151-162; García-López et al 2019 - Agricultural Water Management 223, 105718). Además de estas publicaciones en revistas internaciones, el doctorando ha realizado varias publicaciones de divulgación (2 trabajos en la revista Agricultura, 1 en Vida Rural y 4 en SERVIFAPA) y ha presentado sus resultados en congresos internacionales (18 International Sunflower Association, Mar de Plata, Argentina, 2012).

La temática y metodología requerida para la realización de esta tesis, junto con las dificultades iniciales previamente descritas, han supuesto un duro ejercicio de perseverancia y esfuerzo por parte del doctorando, el cual ha sido superado con éxito viendo los resultados obtenidos en su tesis doctoral.

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

Córdoba, 25 de abril de 2019

Firma del/de los director/es

Fdo.: Ignacio J. Lorite Torres

Fdo.: Rafaela Ordoñez Fernández

Tesis por compendio de artículos

Esta tesis cumple el requisito establecido en el artículo 24 de Normativa de Doctorando de la Universidad de Córdoba para su presentación como compendio de artículos. Está constituida por tres artículos publicados en revistas incluidas en los tres primeros cuartiles de la relación de revistas del ámbito de la especialidad y referenciadas en la última relación publicada por el Journal Citations Report (SCI y/o SSCI).

Publicaciones:

- **García López J**, Lorite IJ, García Ruiz R, Domínguez J (2014). Evaluation of three simulation approaches for assessing yield of rainfed sunflower in a Mediterranean environment for climate change impact modelling. Climatic Change 35/223 (Environmental) Q1 Factor de impacto JCR: 3.43
  https://doi.org/10.1007/s10584-014-1067-6.

- **García López J**, Lorite IJ, García Ruiz R, Ordoñez R, Domínguez J (2016). Yield response of sunflower to irrigation and fertilization under semi-arid conditions. Agricultural Water Management 14/88 (Water resources) Q1 Factor de impacto JCR: 2.848
  https://doi.org/10.1016/j.agwat.2016.05.020.

- **García López J**, García Ruiz R, Domínguez J, Lorite IJ (2019). Improving the sustainability of farming systems under semi-arid conditions by enhancing crop management. Agricultural Water Management 9/89 (Agronomy) Q1 Factor de impacto JCR: 3.542
  https://doi.org/10.1016/j.agwat.2019.105718.

Actividades del plan de formación realizadas

A continuación se detallan las actividades del plan de formación realizadas por el doctorando:

- Asistencia a la jornada "La agricultura y el mercado eléctrico ¿Evolución? 1894– 2017", correspondiente a la actividad "Seminarios de actualidad sobre los retos de la investigación en la ingeniería agraria, alimentaria, forestal y del desarrollo rural sostenible" (11 de mayo de 2017).

- Asistencia a la jornada "Metodología de trabajo para reconstrucciones virtuales y uso de hardware libre para la documentación de la Mezquita-Catedral de Córdoba", correspondiente a la actividad "Seminarios de actualidad sobre los retos de la investigación en la ingeniería agraria, alimentaria, forestal y del desarrollo rural sostenible" (12 de mayo de 2017).

- Asistencia a la jornada "Impacto del cambio climático en la agricultura", correspondiente a la actividad "Seminarios de actualidad sobre los retos de la investigación en la ingeniería agraria, alimentaria, forestal y del desarrollo rural sostenible" (19 de mayo de 2017).

- Organización del seminario de actualidad denominado "Impacto del cambio climático en la agricultura", correspondiente con la actividad "Seminarios de actualidad sobre los retos de la investigación en la ingeniería agraria, alimentaria, forestal y del desarrollo rural sostenible" (19 de mayo de 2017).

- Asistencia a la jornada "Taller para la mejora de la empleabilidad" correspondiente a la actividad "Mejora de la empleabilidad y orientación laboral" (5 de abril de 2018).

- Visita a la Estación Experimental del Zaidín (CSIC) en Granada, como parte de la actividad formativa "Visita a centros, grandes instalaciones y laboratorios de investigación del sector privado y el público" (29 de marzo de 2019).

- Movilidad en el Istituto per le Macchine Agricole e Movimento Terra (Turín, Italia) bajo la supervisión del Dr. Eugenio Cavallo (Abril-Julio de 2012).

Resumen

En los últimos años en Andalucía se ha producido un descenso muy notable de la superficie cultivada con trigo, maíz y girasol. La causa de este descenso está relacionada con los problemas asociados a la baja rentabilidad de los sistemas agrícolas mediterráneos, especialmente los de secano. Por otro lado, el cultivo de girasol en sus áreas de producción tradicionales en el sur de Europa, como el Valle del Guadalquivir en Andalucía, está expuesto a severos impactos asociados a condiciones meteorológicas adversas como sequías y olas de calor, las cuales tenderán a agravarse como consecuencia del cambio climático. Si a los impactos anteriormente descritos unimos la escasez de estrategias de adaptación disponibles para los sistemas agrícolas de secano, se conforma un conjunto de circunstancias que suponen un serio factor limitante para la sostenibilidad económica de los sistemas agrícolas cultivados con girasol en el futuro.

En este contexto de incertidumbre sobre la sostenibilidad de los sistemas agrícolas de girasol se desarrolla esta tesis, abordando aspectos relacionados con la mejora de las prácticas agrícolas para hacer frente al impacto del cambio climático, y por lo tanto, incrementar la sostenibilidad de estos sistemas en el tiempo. Así, en el Capítulo 1 de esta tesis se desarrolla un modelo empírico de predicción de cosecha de girasol para condiciones semi-áridas teniendo en cuenta los efectos de las altas temperaturas y la escasez de agua durante los períodos críticos del cultivo. Además, se comparan las estimaciones de cosecha realizadas con el nuevo modelo experimental frente a otros modelos ya existentes y ampliamente utilizados como AquaCrop y la función de Stewart. De la comparación realizada se constata la utilidad de este tipo de enfoques empíricos que proporcionan una excelente herramienta de decisión para el análisis del impacto del cambio climático a escala regional.

Por otro lado, en los Capítulos 2 y 3 se evalúan distintas prácticas de intensificación sostenible y medidas de adaptación para el cultivo del girasol en el sur de la Península Ibérica. Así, entre las prácticas de intensificación se evaluaron estrategias de riego deficitario, aplicaciones de fertilización óptima y altas densidades de siembra y entre las medidas de adaptación al cambio climático, el adelanto de la fecha de siembra.

Concretamente en el Capítulo 2 se optimiza la combinación de dos prácticas agrícolas; la aplicación de estrategias de riego deficitario junto con diferentes dosis de abonado nitrogenado. A través de un completo trabajo de experimentación se recomiendan volúmenes de riego entre el 60 – 80% de las necesidades óptimas del cultivo, lo cual se traduce para las condiciones semi-áridas del sur de España en volúmenes entre 2000 y 2500 m^3 ha^{-1} y aplicaciones de abonado nitrogenado de entre 100 y 150 kg ha^{-1} en función de la cantidad de agua aplicada.

Tanto en el Capítulo 2 como en el Capítulo 3 se pone de manifiesto el efecto beneficioso que tiene el adelanto de la fecha de siembra en la cosecha de girasol (tanto en grano como en aceite), en comparación con las siembras tradicionales. Este incremento en la producción del cultivo se consigue a través de la mejora de las condiciones climáticas a las que el cultivo está expuesto durante todo su ciclo, y especialmente durante los períodos críticos de floración y llenado de grano.

Finalmente, el Capítulo 3 se centra en determinar el efecto, en términos de incremento de cosecha y rentabilidad, de diferentes estrategias de intensificación sostenible para los sistemas agrícolas de girasol en el sur de España. De este modo se evaluó la combinación de diversas prácticas agrícolas como la aplicación de estrategias de riego deficitario y abonado óptimo, y de modificaciones en la densidad y en la fecha de siembra. Los resultados obtenidos a través de numerosos años de experimentación concluyen que la combinación de altas densidades de siembra con siembras tempranas, apoyadas por riegos deficitarios y fertilización limitada en función de la disponibilidad de agua, constituye una estrategia de intensificación innovadora para el cultivo de girasol en condiciones semi-áridas. Por último, en el Capítulo 3 se elabora un completo análisis económico de las prácticas agrícolas propuestas. Así, este análisis pone de manifiesto la clara conexión entre la disponibilidad de agua y las prácticas de manejo óptimo de la densidad de siembra, la fecha de siembra y la fertilización.

Introducción general

El aumento de la concienciación de la sociedad sobre la necesidad de promover estrategias que garanticen la **seguridad alimentaria** a nivel mundial ha hecho que la predicción, cuantificación e incremento de la producción de los cultivos sea considerado un aspecto estratégico (Therond et al., 2011). A pesar de esta relevancia, el despoblamiento rural (Battino y Lampreu, 2019) y la baja rentabilidad de los sistemas agrícolas mediterráneos (García-Ruiz et al., 2010) son algunos de los factores que están poniendo en peligro la sostenibilidad de estos sistemas a medio y largo plazo. Además, los efectos del cambio global, en especial los cambios relacionados con el clima agravaran estos factores. Así, la creciente escasez de recursos hídricos disponibles para la agricultura (WWAP, 2012) y el impacto de eventos extremos sobre las cosechas (Guarin et al., 2018) son algunos de los factores que influirán decisivamente sobre los sistemas agrarios mediterráneos y que, por lo tanto, requieren de un estudio detallado.

Las principales consecuencias del **cambio climático** sobre el sur de Europa han sido definidas por modelos de circulación general (GMC) evaluados por el Grupo Intergubernamental de Expertos sobre el Cambio Climático (IPCC). Así, dependiendo del escenario de emisiones considerado, se espera un incremento de las temperaturas en Europa occidental y meridional durante las épocas estivales, especialmente en las zonas del sudoeste (Francia, España y Portugal), alcanzando incrementos en las temperaturas superiores a 6ºC a finales de siglo, y una disminución de las precipitaciones en el sur y centro de Europa (IPCC, 2014). Igualmente, las predicciones indican que las olas de calor y las sequías ocurrirán con mayor frecuencia debido al efecto combinado de temperaturas más cálidas y menos precipitación (Lotze-Campen, 2011). Además de estos efectos, el cambio climático contribuirá a aumentar la incertidumbre y la variabilidad interanual y espacial de las cosechas.

Ante estos retos la **agricultura de secano** presenta una elevada vulnerabilidad comparada con otros sistemas agrícolas. Este tipo de agricultura se basa principalmente en técnicas específicas de cultivo de bajos insumos, principalmente para cultivos de trigo, girasol y leguminosas, que permiten un uso eficiente y efectivo de la humedad del suelo. Si bien la agricultura es uno de los sectores más vulnerables al impacto del cambio climático global (Tingem et al., 2009), los sistemas de secano son especialmente vulnerables a los cambios previstos en las condiciones climáticas frente a aquellos sistemas con disponibilidad de agua de riego (Valverde et al., 2015). En la actualidad, la agricultura de secano se restringe a zonas con baja o nula disponibilidad de agua para riego. En zonas con disponibilidad de agua, el empleo del regadío es muy limitado en cultivos como el girasol por la creencia de los agricultores de que aplicar agua a estos cultivos no es económicamente rentable, ya que esa agua podría aplicarse a otros cultivos que potencialmente podrían generar un mayor beneficio (Lorite et al., 2012; 2013). Sin embargo, en los últimos años la rentabilidad de la agricultura de regadío también ha disminuido significativamente, con valores de productividad del agua de riego muy cercanos a los límites de rentabilidad en algunos cultivos como el maíz en el sur de la Península Ibérica (Lorite et al., 2012; 2013). Por este motivo es frecuente encontrar comunidades de regantes en donde la cantidad de agua disponible es mayor que la demanda, debido a la falta de alternativas rentables. Afrontando esta nueva situación, en zonas con acceso al riego, aunque sea limitado, aparecen alternativas como la utilización de nuevos cultivos de regadío como aquellos destinados a la obtención de biomasa, frutos secos, o incluso, el empleo de cultivos tradicionalmente de secano con riego de apoyo o deficitario.

En este contexto de **cambio e incertidumbre**, en los últimos años se ha producido un descenso muy notable de la superficie dedicada a los cereales (trigo y maíz) y al girasol. Así, para este último cultivo en 2018 en Andalucía se ha producido un descenso del 28% respecto a la media entre 2013 y 2016. La causa de este descenso está relacionada con problemas asociados a la baja rentabilidad de las explotaciones. Esto es debido a que los costes de producción han aumentado progresivamente, empujados por el incremento del precio de los insumos, mientras que el precio que se paga por los productos agrarios en los mercados se mantiene constante, e incluso tiende a la baja. Según el Observatorio de Precios de la Junta de Andalucía, los costes del girasol, incluyendo el coste de la maquinaria y de la tierra, están en torno a 548 €/ha, lo cual supondría que a un precio según lonja de 315 €/Tm (precios de la lonja de Sevilla y Córdoba en 2018), sería necesario cosechar más de 1,700 kilogramos de semilla de girasol por hectárea para cubrir los costes de cultivo. Este rendimiento es muy superior al que se obtiene en los secanos andaluces, en donde la media de la campaña 2018 fue de 1,200 kg/ha.

El **cultivo del girasol** en Andalucía es predominantemente de secano, llegando al 90% del total de superficie cultivada, y en ausencia total de fertilización. El sistema de cultivo tradicional del girasol en Andalucía está basado en la rotación trigo-girasol. El girasol constituye una alternativa muy adecuada a los cereales de invierno ya que explora un horizonte más profundo del suelo y permite, por lo tanto, un mejor uso de las reservas hídricas y de fertilizante no utilizado por el cultivo anterior. Tradicionalmente, el período de siembra se extiende desde finales de febrero hasta mediados de abril, en función de cuando las lluvias permitan preparar el terreno para la siembra. La densidad de siembra empleada viene determinada por la forma de control de las malas hierbas, requiriéndose que la distancia entre las líneas de siembra sea al menos de 65 cm para poder pasar los cultivadores. En estas circunstancias, el cultivo del girasol en sus áreas de producción tradicionales en el sur de Europa, como el Valle del Guadalquivir en Andalucía, está expuesto a severos **impactos del cambio climático** relacionados con la escasez de agua y las altas temperaturas (Debaeke et al., 2017). Los daños son especialmente relevantes cuando los eventos extremos ocurren durante períodos críticos del ciclo del cultivo, como la fase que comprende desde el comienzo de la floración hasta la etapa de llenado del capítulo (Ploschuk y Hall, 1995). Así, los principales impactos del cambio climático sobre el girasol se asocian al incremento de las temperaturas y al descenso de las precipitaciones (especialmente en los meses de primavera-verano), acompañados por el aumento en los eventos extremos como sequías prolongadas u olas de calor. De este modo, el girasol, a pesar de tener una cierta resistencia a la sequía y a las altas temperaturas, es especialmente vulnerable al impacto del cambio climático, con drásticas reducciones en la cosecha, tanto al estrés hídrico como al estrés térmico, especialmente cuando éstos coinciden con el periodo de floración hasta llenado del grano (Doorenbos y Kassam, 1979; Chimenti y Hall, 2001). Con estrés hídrico la planta limita su transpiración a través del cierre estomático, reduciendo la asimilación de carbono y disminuyendo la producción de biomasa (Demir et al, 2006), generando disminuciones de cosecha. El estrés térmico durante las fases vegetativas del cultivo disminuye tanto la tasa fotosintética como la eficiencia en el uso del agua y los nutrientes, y se incrementa la tasa de evapotranspiración (Hernández et al., 2018), afectando negativamente a la cosecha, aunque de forma menos severa que en las fases reproductivas. Entre las fases reproductivas, la floración es la más sensible al estrés térmico, ya que se ha observado que la viabilidad del polen es especialmente sensible a este estrés en la mayoría de las especies cultivadas (Driedonks et al., 2016; Mesihovic et al., 2016). Además de estos impactos, la escasez de estrategias de adaptación disponibles para la agricultura de secano constituye un factor limitante para la sostenibilidad económica futura de los sistemas agrícolas cultivados con girasol.

Ante la necesidad de prever el comportamiento de los cultivos en condiciones diferentes a las actuales, se hace preciso el desarrollo de **modelos de simulación** que sean capaces de evaluar el funcionamiento de los sistemas agrarios en el futuro. La complejidad de los modelos de simulación varía desde modelos mecanicistas a modelos empíricos. Los primeros simulan el comportamiento de los cultivos empleando ecuaciones basadas en procesos fisiológicos y físicos, y parámetros considerando la dinámica de los eventos climáticos (como AquaCrop; Steduto et al., 2012 u OILCROP-SUN; Villalobos et al., 1996). Los modelos empíricos, por el contrario, se basan en coeficientes de cultivo (Allen et al., 1998) o funciones de respuesta simples (Steward et al., 1977). Si bien la precisión de los modelos mecanicistas es mayor, un aspecto limitante de estos es el elevado número de datos requeridos para la correcta caracterización del cultivo y suelo. Así, para realizar correctamente esta caracterización, se requieren ensayos y calibración in situ (Hsiao et al., 2009), mientras que para caracterizar el suelo se requieren estudios locales específicos, tareas que no son accesibles cuando el área de estudio es grande y heterogénea. A diferencia de los modelos mecanicistas, los modelos empíricos utilizan datos de campo previos para determinar las relaciones funcionales entre variables y parámetros numéricos para obtener el modelo de salida. Originalmente, estos modelos se desarrollaron para la evaluación del rendimiento en áreas extensas (Álvarez, 2009; van Ittersum et al., 2013), y en los últimos años se han utilizado para evaluar los impactos del cambio climático para diferentes cereales como el maíz o el sorgo (Urban et al., 2012; Ramírez-Villegas et al., 2013), con resultados muy positivos. En cualquier caso, es imprescindible la correcta calibración con datos empíricos de buena calidad (Hansen y Jones, 2000). Las comparaciones entre modelos mecanicistas y empíricos han demostrado la capacidad de los segundos para capturar las principales fuentes de variación en la evaluación del comportamiento de los cultivos. Así, Calviño et al. (2003) o Lobell y Burke (2010) compararon modelos mecanicistas, como CROPGRO y CERES-Maize, con modelos empíricos, obteniendo resultados muy satisfactorios que demuestran que estos enfoques empíricos podrían desempeñar un papel importante en la evaluación del impacto del cambio climático.

Una vez definidos los impactos del cambio climático sobre el cultivo del girasol empleando trabajo experimental y modelización, la última etapa es la identificación de **medias de adaptación** que mejoren la sostenibilidad de los sistemas de girasol en Andalucía. Así, a nivel de parcela, estas adaptaciones incluyen modificaciones en las fechas de siembra, cambios en las rotaciones de cultivos, un mejor manejo del agua tanto en sistemas en regadío como en secano, un uso optimizado de fertilizantes y la adopción de prácticas de labranza mejoradas (Adam et al., 1998). En concreto, para el cultivo del girasol en Andalucía las dos principales medidas de adaptación al cambio climático descritas han sido el adelanto en la fecha de siembra (Soriano et al., 2004; Nouri et al., 2017) y el empleo de estrategias de riego de apoyo o deficitario (Karam et al., 2007). Con el adelanto de la fecha de siembra se pretende conseguir una doble adaptación, por un lado el cultivo se puede beneficiar de las lluvias invernales y de la mayor cantidad de humedad en el suelo durante los primeros estadios de su desarrollo, y por otro, se consiguen adelantar los períodos críticos del cultivo, haciéndolos coincidir con los meses en los que las temperaturas máximas son más suaves y en los que hay menos probabilidades de sufrir un período prolongado de altas temperaturas y/o sequía. Por otra parte, el uso de estrategias de riego deficitario se basa en la aplicación de cantidades de agua en torno al 60% de las necesidades óptimas del cultivo, lo que se traduce en unos volúmenes de riego inferiores a los 2500 m^3 por hectárea. Este volumen de riego se concentra principalmente en el periodo en el que la planta comienza a desarrollar el botón floral hasta el final del llenado del grano, que son las etapas del cultivo más sensibles al estrés hídrico. Con esta medida no solo se evitan estreses severos a la planta, sino que también se potencian los beneficios de prácticas como el incremento de la densidad o la fertilización.

Ante los evidentes problemas medioambientales y de rentabilidad de los sistemas agrícolas tradicionales Mediterráneos, especialmente los de secano, se antoja fundamental realizar cambios en el modelo de producción para conseguir un incremento de las cosechas y de la rentabilidad de las explotaciones, sin afectar al medio natural. La integración de estos factores supondrá una mejora de la resiliencia de estos sistemas productivos, lo cual asegurará su supervivencia en el futuro. Para dar respuesta a este reto en un contexto de mayor competencia por los recursos, emerge el concepto de **intensificación sostenible**. Así, la intensificación sostenible se define como el conjunto de procesos o estrategias que logran incrementar los rendimientos sin un impacto ambiental adverso, y sin la conversión de nuevas tierras de cultivo (Pretty y Bharucha, 2014). Por tanto, la intensificación sostenible persigue desarrollar e implantar estrategias de intensificación de la producción por medio de la mejora de prácticas agronómicas destinadas a mejorar la eficiencia de los sistemas agrícolas (Gadanakis et al., 2015; Kumar et al., 2018). Esta estrategia es válida para todos los sistemas agrícolas, incluso para aquellos que están experimentando un alto crecimiento de la productividad, en donde un uso más eficiente de los recursos naturales y las nuevas tecnologías pueden conseguir mantener la tendencia ascendente de las producciones y, al mismo tiempo, reducir los impactos ambientales negativos (Garnett et al., 2013).

Centrados en la **intensificación de los sistemas de girasol en secano**, el agua es el factor más limitante para la producción, aunque otros factores como la temperatura durante la etapa de floración (Ploschuk y Hall, 1995) y la fertilización (Sarmah et al., 1994) son también relevantes. Estos factores limitantes tendrán una clara influencia en la rentabilidad de las explotaciones, pudiendo generar serios perjuicios a la producción, que podrían ser acrecentados por el impacto del cambio climático en el futuro. Para hacer frente a estas limitaciones, la evaluación e implantación de estrategias de intensificación de la producción, junto con la promoción de medidas destinadas a mejorar la eficiencia de los sistemas, serán imprescindibles para asegurar la sostenibilidad de estos sistemas. Sin embargo, la correcta aplicación de estas estrategias en los sistemas agrícolas no es fácil puesto que muchas de ellas interaccionan con prácticas agronómicas como la fecha o densidad de siembra. Así, por ejemplo, una suficiente disponibilidad de agua puede potenciar los beneficios del adelanto de la fecha de siembra o el incremento de la densidad (Diepenbrock et al., 2001; Barros et al., 2004). Entre las medidas para incrementar la producción desde un punto de vista sostenible para el cultivo del girasol destaca la implantación de prácticas de riego deficitario o de apoyo, centradas en aportar una cantidad de riego por debajo de las necesidades óptimas del cultivo, pero capaces de incrementar la productividad y sostenibilidad de las explotaciones (Karam et al., 2007). Igualmente, el manejo adecuado de la densidad de siembra es una de las prácticas agrícolas más recomendadas para lograr un aumento en la productividad de los cultivos (Escalante-Estrada et al., 2008; Jia et al., 2018). Así, se ha comprobado como un número apropiado de plantas individuales por unidad de área mejora el uso del agua. La densidad de siembra óptima para el cultivo del girasol está influenciada por varios factores como la temperatura, la fertilidad del suelo, la disponibilidad de agua y el genotipo (Villalobos et al., 1994;

Diepenbrock et al., 2001). Con la reciente aparición de líneas de girasol tolerantes a distintas materias activas utilizadas para el control de malas hierbas, el agricultor ya no necesita mantener una distancia de 65 cm entre líneas para facilitar el paso de la maquinaria, por lo que se plantea una oportunidad para aumentar la densidad de plantación. Otra práctica agrícola recomendable en ambientes mediterráneos semiáridos es la implantación de fechas de siembra tempranas (Nouri et al., 2017). Esta práctica permite que el cultivo se beneficie de temperaturas menos severas al final del ciclo de cultivo y de las precipitaciones de finales de invierno, reduciendo además el volumen de agua requerido para mantener la producción (Sarno et al., 1992; Soriano et al., 2004). La práctica de la siembra de invierno para el girasol en Andalucía se desarrolló por primera vez en la década de 1980. Los estudios realizados durante ese período en la región (Gimeno et al., 1989), mostraron claros aumentos en la producción, de hasta un 30% sobre el rendimiento habitual para la zona. Sin embargo, este cambio en la fecha de siembra no pudo ser puesto en práctica por los agricultores debido a la dificultad de llevar a cabo un control adecuado de malas hierbas. Un adelanto en la fecha de siembra resulta en una mayor cantidad de malas hierbas durante el invierno, las cuales con siembras de primavera convencionales se controlan fácilmente mediante la labranza de la tierra antes de la siembra. Con los nuevos cultivares resistentes a herbicidas con tecnología Clearfield y ExpressSun se ha identificado una clara oportunidad para resolver las limitaciones producidas por el aumento de malas hierbas cuando se lleva a cabo un adelanto en la fecha de siembra. Finalmente, una correcta fertilización coordinada con el adecuado suministro de riego constituye un factor de gran importancia para el correcto manejo del cultivo de girasol (Debaeke et al., 2006; Sinha et al., 2017), y representa una técnica útil de intensificación sostenible, especialmente en sistemas afectados por estrés hídrico.

Aunque la disponibilidad de agua y la fertilización son factores claves en la producción de girasol, no son muy comunes los estudios que evalúan de forma conjunta ambos factores (Muriel et al., 1980; Alvarez de Toro, 1987), centrándose la mayoría de ellos en la evaluación del riego (Rinaldi, 2001; Göksoy et al., 2004; Sezen et al., 2011) o en el impacto de la fertilización en la producción (Reau et al., 2001; Ozer et al., 2004; Massignam et al., 2009), de forma independiente. Por otro lado, en el cultivo del girasol no se han encontrado trabajos específicos sobre intensificación sostenible, al contrario que en otros cultivos extensivos como el maíz (Welde y Gebremariam, 2016) o el trigo (Abolpour, 2018), por lo que se hace preciso avanzar sobre estos aspectos para garantizar la sostenibilidad de los sistemas agrícolas cultivados con girasol en el futuro.

Para llevar a cabo un estudio pormenorizado de las prácticas de manejo del cultivo del girasol que incrementen la producción, pero que también consideren el aspecto medioambiental, es preciso una caracterización detallada de estos sistemas. Esta caracterización, basada en un trabajo sólido de experimentación, será la base para la modelización de los sistemas de girasol, tanto en condiciones actuales como futuras, y permitirán evaluar estrategias de intensificación específicas para los sistemas de girasol andaluces. Como ejemplo de experimentación previa y que puede ser de gran utilidad para esta labor se encuentra la **Red Andaluza de Experimentación Agraria** (RAEA). La RAEA comenzó sus actividades en el año 1987 y desde entonces la subred de ensayos de variedades de girasol, incluida dentro del Programa de Cultivos Herbáceos, ha proporcionado resultados anualmente, convirtiéndose en una referencia para el sector de las semillas oleaginosas (agricultores, empresas privadas de semillas, cooperativas agrícolas, asociaciones agrarias, etc.) en la región. Así, esta red cumple con el objetivo de proporcionar al agricultor información útil generada a partir de experimentación en condiciones de cultivo similares a las de sus explotaciones. Actualmente se continúa desarrollando este objetivo con ensayos de producción, de variedades resistentes a enfermedades (jopo y mildiu) y de variedades resistentes a herbicidas (híbridos con tecnología Clearfield, Clearfield Plus, ExpressSun) en las diferentes zonas de cultivo en Andalucía. Esta red se complementa también desde IFAPA con experimentación específica sobre prácticas de intensificación sostenible y medidas de adaptación al cambio climático específicas para el cultivo del girasol con el fin de aumentar su rentabilidad y sostenibilidad.

Ante las condiciones de cambio a las que se enfrenta el cultivo del girasol en Andalucía, se ha planteado la realización de una **tesis doctoral** en la que se ha integrado trabajo experimental específico y el empleo de bases de datos previas (principalmente de RAEA) para el estudio del comportamiento del cultivo del girasol en condiciones climáticas futuras, y para la evaluación de diferentes medidas de adaptación e intensificación específicas para el cultivo del girasol en el Valle del Guadalquivir. Así, la tesis se ha estructurado en 3 capítulos que coinciden con 3 artículos publicados en revistas internacionales de alto impacto:

- ***García López J***, *Lorite IJ, García Ruiz R, Domínguez J (2014). Evaluation of three simulation approaches for assessing yield of rainfed sunflower in a Mediterranean environment for climate change impact modelling. Climatic Change 35/223 (Environmental) Q1 Factor de impacto JCR: 3.43*

- ***García López J***, *Lorite IJ, García Ruiz R, Ordoñez R, Domínguez J (2016). Yield response of sunflower to irrigation and fertilization under semi-arid conditions. Agricultural Water Management 14/88 (Water resources) Q1 Factor de impacto JCR: 2.848*

- ***García López J**, García Ruiz R, Domínguez J, Lorite IJ (2019). Improving the sustainability of farming systems under semi-arid conditions by enhancing crop management. Agricultural Water Management 9/89 (Agronomy) Q1 Factor de impacto JCR: 3.542*

Más allá del ámbito de esta tesis doctoral, la investigación y transferencia específica para el cultivo del girasol a medio y largo plazo requerirá continuar con el estudio de diferentes combinaciones de técnicas de cultivo que maximicen la rentabilidad y aseguren una correcta adaptación del cultivo al cambio global. Así, la integración de siembras tempranas con altas densidades de plantación, apoyadas con riegos deficitarios o de apoyo, y aplicaciones de fertilización óptima en función de la disponibilidad de agua, deberán ser estudiadas con mayor profundidad. Este estudio deberá considerar las diferentes zonas agroclimáticas presentes en Andalucía para, de este modo, proporcionar una respuesta específica a cada comarca andaluza con el fin último de mejorar la sostenibilidad de los sistemas agrarios mediterráneos cultivados con girasol.

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Objetivos

- Definir funciones de respuesta a eventos extremos como herramienta de apoyo en la determinación del impacto del cambio climático para el cultivo de girasol, por medio de un modelo empírico que servirá de base para la estimación robusta de la cosecha teniendo en cuenta los efectos de las altas temperaturas y la escasez de agua en los períodos críticos del cultivo (1er capítulo).

- Comparar las estimaciones de cosecha realizadas con el nuevo modelo experimental frente a otros modelos ya existentes y ampliamente utilizados (1er capítulo).

- Evaluar el efecto de diferentes prácticas agrícolas como el uso de estrategias de riego de apoyo, fertilización óptima, altas densidades de plantación y adelanto de la fecha de siembra sobre la cosecha de girasol (tanto en grano como en aceite) (2º y 3er capítulo)

- Determinar el estado nutricional del girasol a partir del índice de nutrición nitrogenada (INN) en función de distintos calendarios de riego y aportaciones de abonado (2º capítulo).

- Evaluar la optimización y combinación de diversas técnicas de cultivo para la mejora de la rentabilidad y sostenibilidad del girasol bajo las condiciones semi-áridas del sur de España empleando estrategias de intensificación sostenible (3er capítulo).

- Realizar un análisis económico del cultivo del girasol en Andalucía bajo un amplio rango de escenarios con diferentes prácticas agronómicas determinando los límites de rentabilidad del cultivo en función del precio de la cosecha y del coste del agua de riego (3er capítulo).

Capítulo 1: Evaluation of three simulation approaches for assessing yield of rainfed sunflower in a Mediterranean environment for climate change impact modelling

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1.1 Abstract

The determination of the impact of climate change on crop yield at a regional scale requires the development of new modelling methodologies able to generate accurate yield estimates with reduced available data. In this study, different simulation approaches for assessing yield have been evaluated. In addition to two well-known models (AquaCrop and Stewart function), a methodological proposal considering a simplified approach using an empirical model (SOM) has been included in the analysis. This empirical model was calibrated using rainfed sunflower experimental field data from three sites located in Andalusia, southern Spain, and validated using two additional locations, providing very satisfactory results compared with the other models with higher data requirements. Thus, only requiring weather data (accumulated rainfall from the beginning of the season fixed on September 1st, and maximum temperature during flowering) the approach accurately described the temporal and spatial yield variability observed (RMSE = 391 kg ha^{-1}). The satisfactory results for assessing yield of sunflower under semi-arid conditions obtained in this study demonstrate the utility of empirical approaches with few data requirements, providing an excellent decision tool for climate change impact analyses at a regional scale, where available data is very limited.

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1.2 Introduction

Currently, due to the increase in the concern for food security in the world, caused, among other factors, by water resource shortages and heat stresses associated with climate change effects, the forecast and determination of crop yield at a regional scale has been considered as a strategic topic (Therond et al., 2011).

Climate change contributes to increasing the uncertainty on crop yields, promoting the development of crop simulation models for yield assessment (Moriondo et al., 2011; van Ittersum et al., 2013). Traditionally, yield estimation has been based on empirical data and, lately, on simulation models (Cabelguenne et al., 1999; Rinaldi et al., 2003). The complexity of these simulation models has varied from deterministic models, which determine yield using physical equations and parameters considering the dynamics of weather events (such as AquaCrop; Steduto et al., 2012 or OILCROP-SUN; Villalobos et al., 1996), to simple evapotranspiration (ET) based models (Doorenbos and Kassam, 1979). However, one limiting aspect of these models is the numerous data requirements (referring to crop and soil characterization). While crop characterization could be determined by in situ trials and calibration (Hsiao et al., 2009), soil characteristics require specific local studies, prohibitive tasks when the study area is large and heterogeneous. An intermediate approach was proposed by Hansen and Jones (2000), who recommended empirical corrections to simulation models based on climatic factors. Finally, unlike deterministic models, empirical simulation models use previous field data to determine functional relations between variables and numerical parameters in order to obtain the output model. Originally, these models were developed for large-area model yield assessment (Alvarez, 2009; van Ittersum et al., 2013), and in the past few years they have been used to assess climate change impacts on different cereals like maize or sorghum (Urban et al., 2012; Ramirez-Villegas et al., 2013) with very satisfactory results, although here a previous calibration process with good-quality empirical data is essential (Hansen and Jones, 2000).

Comparisons between empirical models and process-based crop simulation models have proved the ability for the empirical model to capture the main sources of variation in the crop yield assessment. Thus, Calviño et al. (2003) or Lobell and Burke (2010) compared process-based models as CROPGRO and CERES-Maize respectively with empirical models, obtaining very satisfactory results demonstrating that these approaches could play an important role in impact assessment of climate change effect.

In order to evaluate different simulation models for yield assessment under climate change conditions, a semiarid region located in Southern Spain was selected. Sunflower, a traditional rainfed crop in this region, was chosen for the analysis. Sunflower (*Helianthus annuus* L.) is an oilseed plant grown in Spain since the 1960's and characterized by its adaptability to a wide range of environments. The sunflower is nowadays the most important oilseed crop in Spain, with over 850,000 ha in 2009, with an approximate average yield of 1100 kg ha^{-1} (MARM 2009).

This study, thanks to the use of a very valuable sunflower dataset (RAEA) collected during the last 25 years in different locations in Southern Spain, will allow to carry out a robust estimation of the effects of high temperature and water stress in critical periods on crop yield assessment. For this task different approaches (including empirical and process-based models) were considered using as reference the observed sunflower yields, extending previous studies as those carried out by Chimenti and Hall (2001), Rondanini et al. (2006), Cicchino et al. (2010) or Moriondo et al. (2011).

1.3 Material and methods

1.3.1. Experimental fields and characterization

1.3.1.1. RAEA

The Andalusian Network of Agricultural Trials (RAEA in Spanish) was started in 1986 and, since then, it has been producing data from different crop trials. The RAEA-sunflower has been providing results annually and has become a reference for the oilseed sector in the region (farmers, private seed companies, agricultural cooperatives, etc.), meeting its goal of furnishing the information generated by on-farm testing.

Due to the rainfed conditions of the experimental fields included in the RAEA, the obtained observed yields describe the water-limited potential yield only affected by weather conditions (water and temperature stress), but not by other limitations frequent in commercial fields (such as crop management). This fact could cause overestimation in the simulation model results, as described by Therond et al. (2011) or Hall et al. (2013), due to the non-optimal conditions found in commercial fields, where in addition to water stress, deficient crop management practices such as low uniformity in the implantation, delayed sowing dates, poor pests control or lack of fertilization are common, reducing significantly farmer´s yield (van Ittersum et al., 2013).

1.3.1.2. Experimental fields

To carry out the analysis of different methodologies for yield estimation, five experimental locations included in the RAEA were selected. For calibration purposes, three locations (Carmona, Osuna and Trigueros; Table 1) with around 13 seasons for each one have been considered, while the other two locations with around 12 seasons for each (Córdoba and Jerez; Table 1) were used for validation and model comparison. For each location, around 30 cultivars were tested each season. The average yield ranged between 1544 kg ha^{-1} in Osuna to 2284 kg ha^{-1} in Jerez (Table 1). The changes in yield were significant when years and locations were analyzed (CV around 34%), and lower when varieties were analyzed (CV around 12%). Crop management was similar to the one carried out by the farmers in the region: rainfed conditions, no fertilizer application, and integrated into the wheat - sunflower biyearly rotation. Soil characteristics are described in Table 1, and were determined with specific texture analyses for each location. The experimental datasets considered in the current study constitute very valuable information for the objectives of this study. In fact, previous analyses such as Moriondo et al. (2011) developed similar analyses with data at regional scale, with poor spatial resolution and for a unique year.

Table 1. Trial location, soil and weather condition characterization for the five places considered in the study.

	Carmona	Osuna	Trigueros	Córdoba	Jerez
Experimental Field					
Avg # cultivars per year	30	31	35	36	33
Avg sowing date	18-Mar	7-Mar	14-Mar	1-Mar	10-Mar
Range sowing date	1-Mar / 15-Apr	22-Feb / 17-Mar	3-Mar / 25-Mar	22-Feb / 9 Mar	9-Feb / 21-Mar
Avg yield (kg ha^{-1})	1600.7	1543.7	1763.6	1897.3	2284.2
Range yield (kg ha-1)	630.7 - 2722.5	588.1 - 2678.0	613.3 - 2990.4	1090.2 - 2890.0	1247.2 - 2718.2
Temporal yield variability; CV (%)	26	37	37	29	20
Avg cultivars variability; CV (%)	11	12	13	12	11
# analyzed years	15	14	11	10	13
Period	1987-2009	1987-2009	1996-2007	1987-1998	1987-2009
Soil					
Water holding capacity (mm m^{-1})	220	170	165	200	200
Depth (m)	1.8	2.2	2.1	2.3	2.2
Weather conditions					
Avg rainfall (Sept 1st – Week 26) (mm)	532	472.1	638	624.8	581.4
Range rainfall (Sept 1st – Week 26) (mm)	227.6 - 895.5	230.2 - 672.3	294.7 - 943.3	377.4 - 1002.9	304.0 - 862.2
Temporal rainfall variability; CV (%)	29	25	31	33	28
Avg maximum temp flowering (Weeks 24 to 27) (ºC)	37.3	36.8	36.5	36.2	34.5
Range maximum temp flowering (Weeks 24 to 27) (ºC)	30.3 - 39.5	28.8 - 42.3	32.4 - 39.1	30.3 - 40.0	28.4 - 37.4
Location					
Altitude (m)	140	163	74	120	34
Distance to sea (km)	95	86.1	24.6	132.1	20.4

1.3.1.3. Weather data

Weather data from five weather stations provided by the Spanish National Meteorology Agency (AEMET, in Spanish) were used in this study (Table 1). Some years were eliminated from the analysis due to a significant percentage of errors or missing data. Analyzing weather conditions across locations, Carmona, Osuna, Trigueros and Córdoba could be considered as in-land locations, while Jerez could be considered as a coastal location. Predictable future weather conditions for Southern Spain (van der Linden and Mitchell, 2009) are fully included in the range of weather data considered in this study (e.g. extreme conditions during 2005 with maximum temperatures of around 40ºC during flowering and annual rainfall during crop cycle lower than 250 mm), allowing the use of the proposed approach for climate change studies.

In order to consider the water availability for the sunflower crop and to decrease the uncertainty in the determination of the soil water content at sowing date, accumulated precipitation was considered from September 1st, and then, seasonal rainfall was defined as the rainfall collected from September 1st until August 31st of the next year.

1.3.2. Simplified optimized model (SOM) for yield estimation

A regionally calibrated empirical approach estimates sunflower yield under rainfed conditions using an empirical multiplicative function considering rainfall from the beginning of the season (fixed on September 1st) to flowering and the temperature during the flowering phase, previously determined as key climatic components for yield estimation (Almaraz et al., 2012).

The multiplicative function allows rain (f_{Rain}) and temperature (f_{Temp}) to affect the estimated yield independently, and thus, severe water or temperature stress could reduce (even lead to crop failure) yield, independently of the other component.

$$Y_{estimated} = Y_{\max} \cdot f_{Rain} \cdot f_{Temp} \qquad [1]$$

with

$$0 \le f_{Rain} \le 1 \text{ and } 0 \le f_{Temp} \le 1$$

where f_{Rain} is the reduction factor related to the insufficient rainfall, and f_{Temp} is the reduction factor related to high temperatures during the flowering period. Y_{max} is the maximum yield for the analyzed area, 3200 kg ha^{-1}, based on the complete RAEA-sunflower dataset. The functions f_{Rain} and f_{Temp} were selected to maximize the R^2 coefficients between estimated yield, and rain and temperature, respectively.

The optimization process consisted on the minimization of the root mean square error (RMSE) calculated considering the observed values and the estimated yield by SOM modifying the set parameters included in f_{Rain} and f_{Temp} using genetic algorithms (Goldberg, 1989). This procedure has the ability to search for the global optimum parameter set. For the optimization process an initial value for each parameter included in f_{Rain} and f_{Temp} was assigned. The procedure combines the set parameters in a similar way to the evolutionary process in the nature using recombination and/or mutation to generate new parameter datasets. This optimization process was carried out using Evolver 6 software (Palisade, 2013).

1.3.3. Simulation models

1.3.3.1. AquaCrop

AquaCrop has been developed by FAO and simulates attainable yields for the main extensive herbaceous crops as a function of water consumption, with a limited number of parameters. Aquacrop estimates biomass production from actual crop transpiration considering a daily time step requiring weather data (maximum and minimum temperature, reference evapotranspiration, rainfall and [CO_2]), soil data (water content at field capacity and permanent wilting point, curve number and hydraulic conductivity) and crop parameters

(Steduto et al., 2012), through a normalized water productivity parameter to determine crop yield. AquaCrop takes into account water stress response functions considering the reduction of canopy expansion rate, closure of stomata, acceleration of canopy senescence, and changes in harvest index. Other stresses considered by Aquacrop are the air temperature stress, soil salinity stress and mineral nutrient stress. These stresses are considered using threshold values and response stress functions fully described with Steduto et al. (2012). Although AquaCrop could consider the impact of heat stress on pollination, in the current study the proposed functions have been excluded due to they still require further studies of calibration and validation under semi-arid conditions.

In our study, regional calibration for sunflower was made based on previous studies (García-Vila and Fereres, 2012) and with the assistance of experts and farmers from the area.

1.3.3.2. Water balance model

A daily water-balance model was used to simulate water management at field-plot level based on FAO methodology (Allen et al., 1998). The components of the water balance model were: rainfall, soil evaporation, transpiration, run-off and deep percolation. Surface run-off was predicted from daily precipitation using the Soil Conservation Service curve number method (USDA-SCS, 1972). The amount of water above field capacity was computed as deep percolation. Crop evapotranspiration (ET_c) was calculated from reference evapotranspiration (ET_o) and dual crop coefficients. ET_o was obtained using the FAO Penman–Monteith method, and the basal crop coefficients and crop growth stages were determined from the methodology proposed by FAO (Allen et al., 1998), modified locally following local experience (Santos et al., 2008). Previous crop (wheat) management was regarded as to set the initial soil water content, considering the soil depleted at 1m depth at the end of the summer (September 1st). From this date considering rainfall and soil evaporation, soil water balance is daily computed until the sowing date. From sowing date water balance is daily updated considering additionally the water extraction carried out by the crop in the whole soil profile depth described in Table 1.

Finally, effective rainfall is defined as the water from rain that really could be used by the crops for transpiration, and was computed as rainfall minus deep percolation, surface run-off and variation in soil water content throughout the crop season.

1.3.3.3. Stewart function

In order to estimate crop yield, a production function approach proposed by Doorenbos and Kassam (1979) according to Stewart et al. (1977) has been considered. These authors presented the following linear relationship between relative yield and relative crop evapotranspiration:

$$\left(1-\frac{Y}{Y_{\max}}\right)=K_y\cdot\left(1-\frac{ET_c}{ET_{c\max}}\right) \qquad [2]$$

where Y is the calculated yield, Y_{max} is obtained from the regional analysis of the yields provided by the complete RAEA-sunflower dataset (here 3200 kg), K_y is the crop response factor adjusted according to local experience ($K_y = 1.2$; Lorite et al., 2005), ET_c the observed crop evapotranspiration and $ET_{c\ max}$ the measured ET when Y_{max} was obtained.

This approach has been previously successfully used (Raes et al., 2006; Santos et al., 2008) although it requires the computation of a simple water balance model in order to determine ET_c.

1.3.4. Statistical analysis

In order to judge the ability of the models to predict yield, four goodness-of-fit parameters were chosen: Root Mean Square Error (RMSE), Relative Root Mean Square Error (RRMSE), agreement index (*d*) and the coefficient of determination (R^2). Additionally tests of the significance of deviations of the functions for their intercepts and slopes have been included.

1.4 Results and Discussion

1.4.1. Simplified optimized model (SOM)

1.4.1.1. Components of the simplified model

Sunflower is particularly susceptible to high temperature stress as capitulum temperature can exceed air temperature during flowering and grain-filling periods (Ploschuk and Hall, 1995; Guilioni and Lhomme, 2006). Maximum temperatures detected in the current study (Table 1) coincide with the temperatures observed by Chimenti et al. (2001), Chimenti and Hall (2001) and Rondanini et al. (2003; 2006) that severely impacted sunflower yield by reducing floret differentiation, grain set and grain weight. Equally Rondanini et al. (2003; 2006) indicates that the magnitude of those impacts strongly depended on the timing of exposure. Additionally sunflower is susceptible to water stress generating a morphological adjustment, such as a marked senescence of basal leaves in response to water stress at anthesis (Connor and Jones, 1985). Sunflower affected by water stress during grain-filling showed an immediate decrease in gross CO_2 assimilation due to a loss of leaf area and decreased light use efficiency (Whitfield et al., 1989). However when water stress takes place on other growing stages as the vegetative period, water efficiency is improved (Piquemal et al., 1990).

Considering these studies, a weekly temporal analysis for effective rainfall, total rainfall and average maximum temperature was carried out by means of multiple attempts for determining the windows of time most appropriate for each function (see section 2.2.) that provided the best adjustments (minimum RMSE) between simulated and observed sunflower yield. Thus, accumulated rainfall (total and effective) from the start of the season (September 1st) until the 26th week of the year and, in the case of temperature, the period ranged between 24-27th weeks of the year were the time period when the functions for yield assessment showed the highest figures. This period roughly coincides with the flowering stage of sunflower in Southern Spain conditions. Impact of heat in earlier development phases was also analyzed and resulted on negligible effect. Previously, the period of flowering was identified as a crucial one for sunflower yield by Göksoy et al. (2004) in relation with water stress, and Moriondo et al. (2011) for high temperatures. Equally, Gimeno et al. (1989) observed that moderate temperatures during flowering contributed to higher sunflower yields, and Pereyra-Irujo and Aguirrezabal (2007) described lower sunflower yields in locations with higher temperatures during blooming and delayed sowing dates.

1.4.1.2. Calibration

In order to determine the response of sunflower yield to temperature and rainfall linear, bilinear, curvilinear and exponential functions, including inverse terms, were considered for Carmona, Osuna and Trigueros datasets. Fig. 1 describes those relationships showing the best goodness of fit with observed yield with accumulated rainfall from the beginning of the season (potential function for week 26), and average maximum temperature (polynomial of second order function for weeks 24-27). Rainfall impact on sunflower yield was not linear as described in Fig. 1 and was caused by the different effectiveness of the rainfall, and depends on the seasonal amount and rainfall pattern. Thus, when seasonal rainfall is abundant sometimes, water in the soil could exceed that useable by the crop (e.g. Grassini et al., 2009) and important losses by runoff and deep percolation will be produced. For this study conditions, yield increase with seasonal rainfall higher than 600 mm was negligible, the rest of the rainfall being lost.

The inclusion of different varieties, locations and years for the development of the functions described in Fig. 1, although generated useful trends adapted to different weather conditions, also generated significant scatter in the regressions, mainly caused by the wide variability in the variable dataset (soils, weather conditions, phenology, etc.). This huge variability in the dataset conditions ensured greater reliability in the calibration process, encompassing broad ranges of weather, field and crop conditions. However, as any approach based on calibration, the results obtained under conditions/locations other than those used for the calibration process must be used with caution.

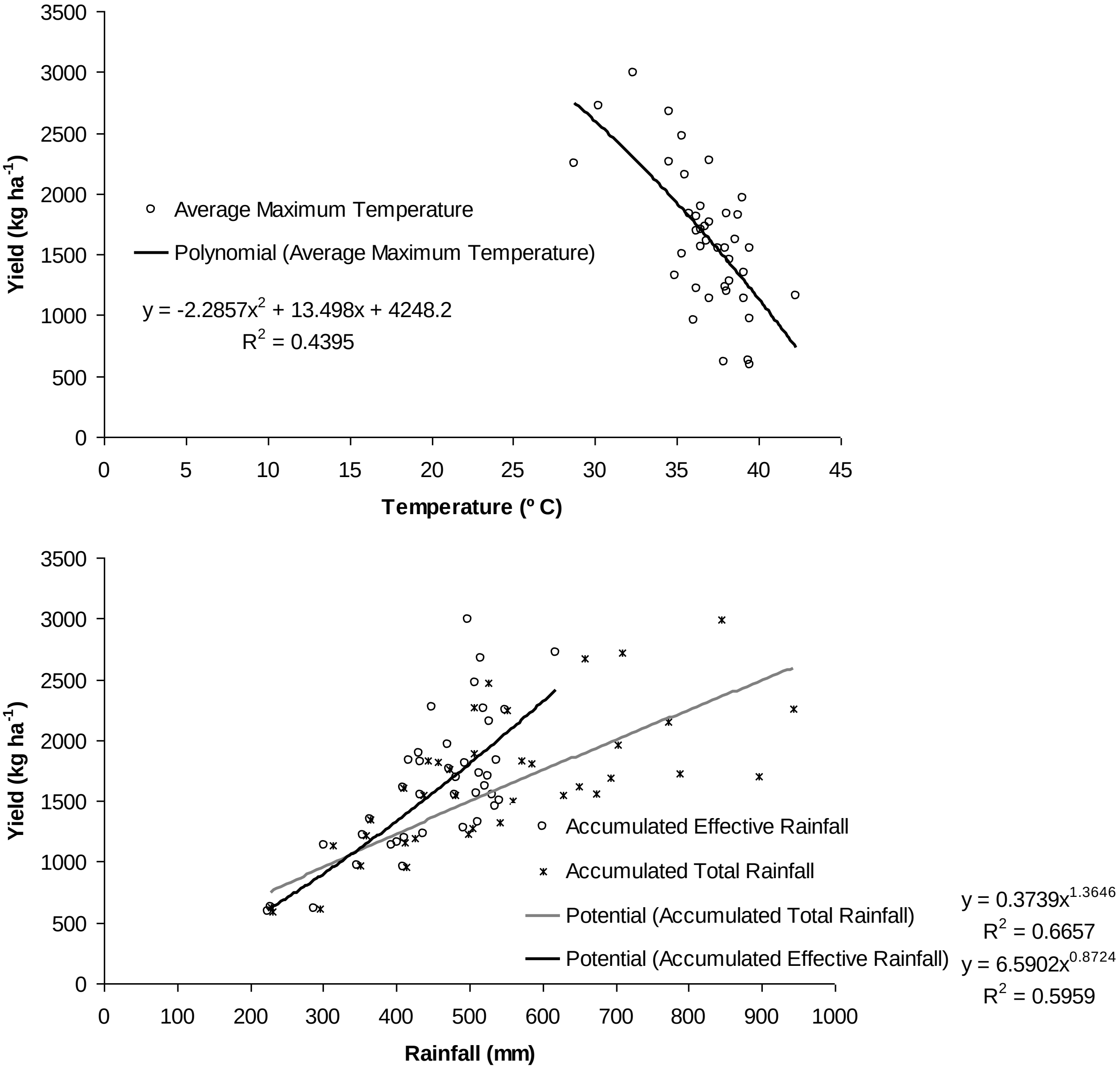

Figure 1. Relationship between maximum temperature at flowering with observed yield. Below, relationships between accumulative effective and total rainfall from the start of the season (September 1st*) until flowering with observed yield. For both graphs, Carmona, Osuna and Trigueros datasets were considered.*

In order to determine the set parameters for f_{Rain} and f_{Temp} functions (see section 3.1.1) a calibration process using the optimization procedure described in section 2.2., with the datasets from Carmona, Osuna and Trigueros locations, was carried out. The best results were considering the accumulated effective rainfall from the start of the season (fixed on September 1st) until week 26 (CER), computed using a simplified simulation model (see section 2.3.2.), and the average maximum temperature during flowering (T_M), and the equations obtained were:

$$f_{Rain} = 0.00236247 \cdot CER^{0.92295276} \quad [3]$$

$$f_{Temp} = -0.00122752 \cdot T_M^2 + 0.05119014 \cdot T_M + 0.54290904 \quad [4]$$

As the accurate determination of the effective rainfall required a significant amount of data (see section 2.3.2.), with a scant availability at a regional scale, a similar analysis was made only using the accumulated rainfall from the start of the season (TR), generating the following equations:

$$f_{Rain} = 0.03120514 \cdot TR^{0.50171429} \quad [5]$$

$$f_{Temp} = -0.0012944 \cdot T_M^2 + 0.05171429 \cdot T_M + 0.53781203 \quad [6]$$

The utility of these functions is limited to the range of weather data detected in the three datasets considered for calibration. Thus, for the calibration datasets the T_M value ranged from 28.8 to 42.3ºC and the TR value from 227.6 to 943.3 mm. With these ranges and considering the weather predictions for Southern Spain (van der Linden and Mitchell, 2009) the utility of this approach for climate change studies is assured.

1.4.1.3. Results

Thanks to the use of Córdoba and Jerez datasets for the validation of the SOM model, a wide range of rainfall and temperatures (Table 1) were considered. Thus average sunflower yield estimates made by the SOM model provided very accurate results. The average estimated yield was 1864 and 1927 kg ha^{-1}, considering the total rainfall (TR) and the effective rainfall (CER), respectively. These results implied an error around 11% with respect to the measured value (2116 kg ha^{-1}). The goodness-of-fit indicators were significantly improved compared with other methodologies: Considering CER+T_M, RMSE was 363 kg ha^{-1}, RRMSE equal to 17.2% and R^2 = 0.64, while considering TR+T_M, RMSE was 391 kg ha^{-1}, RRMSE was 18.5% and R^2 = 0.65 (Table 2). The comparison of the RRMSE with the inter-annual observed yield variability (CV_t equal to 24%; Table 2) confirmed that the results provided by SOM were very satisfactory.

Table 2. Goodness-of-fit parameters for SOM (considering CER+T_M and TR+T_M), AquaCrop, and Stewart function, considering the Cordoba and Jerez datasets. Additionally, results of tests of significance of deviations of the functions for each approach ($p<0.05$).

Approach	**Yield** (kg ha^{-1})	**CV_t**	**RMSE** (kg ha^{-1})	**RRMSE**	**d**	**R^2**	**Slope**	**P (slope)** *	**Intercept**	**P (intercept)** *	**Test** **
Observed	2116.0	0.24									a
SOM (CER+T_M)	1926.8	0.25	363.1	17.2	0.86	0.64	0.84	< 0.0001	499.6	0.0830	a
SOM (TR+T_M)	1864.1	0.24	390.9	18.5	0.84	0.65	0.90	< 0.0001	438.8	0.1285	a
AquaCrop	2168.1	0.50	835.1	39.5	0.69	0.47	0.31	0.0003	1438.5	0.0000	b
Stewart function	1869.8	0.23	489.3	23.1	0.71	0.35	0.69	0.0030	819.5	0.0516	a

* Probability of being different to 0
** “a” means that linear regression is not significantly different to line with slope equal to 1 and intercept equal to 0. “b” means that linear regression is significantly different to line with slope equal to 1 and intercept equal to 0.

Studying the two field locations separately, for Córdoba, inland location, all the goodness-of-fit indicators were excellent. Thus, considering CER+$T_{M,}$ RMSE was 292 kg ha^{-1}, RRMSE 15.4% and R^2 = 0.73, respectively. However, the different weather conditions of Jerez compared with those of the Guadalquivir Valley (coastal location with different rainfall pattern, lower maximum temperatures and higher relative humidity; Table 1) produced validation results poorer (RMSE was around 410 kg ha^{-1}, RRMSE 17.9 and R^2 = 0.63). Similar results were found with TR+T_M approach.

Due to weather and soil conditions of Jerez, excellent yields were found even under dry conditions (Table 1), and then, as the SOM model was not calibrated with these data, the results showed a general slight underestimation for yield assessment (Fig. 2b). This fact shows the high robustness of the model under different conditions from it was calibrated, implying that the model, in spite of its simplicity, considers key components in the yield formation applicable in other areas apart from the used for calibration. These results fully agree with previous analyses carried out by Almaraz et al. (2008) and Moriondo en al. (2011), who determined significant correlations between rainfall during May and temperatures in flowering with yield for corn and sunflower, respectively. Comparing with previous analyses, it is required to highlight the large database considered in this study encompassing five locations during 13 years totalling more than 2000 experimental field measurements (Table 1). Thus, this study takes advantage of one of the most complete dataset for experimental data for sunflower under semi-arid conditions in the world, allowing to expand the current understanding for sunflower yield assessment generated previously using pot experiments in a single location (Chimenti and Hall, 2001; Rondanini et al., 2006), or considering limited statistical information at regional scale for a single year (Moriondo et al., 2011).

Considering other functions instead of those described in Figure 2, required the inclusion of additional calibration parameters and generated null or very small improvements for CER+T_M and TR+T_M respectively. Thus, for example using bilinear functions for rainfall and temperature RMSE was 401 kg ha^{-1}, RRMSE 19.0% and $R^2 = 0.60$ (Data not shown).

The differences between the two data requirement alternatives (CER and TR) were small, and both regression lines between observed and simulated yield were close to 1:1 (slopes were equal to 0.84 and 0.90 for CER+T_M and TR+T_M, respectively, with small intercepts) being not statistically different from the line 1:1 and intercepts = 0 ($p>0.05$) (Table 2). Comparing the results described in Table 2 and Fig. 2b, CER+T_M approach was the most accurate option (with the lowest RMSE and highest *d*), while TR+T_M alternative produced slightly worse results. This low data requirements has as disadvantage the generation of higher uncertainty in the yield assessment in those regions with different conditions that those where the model was calibrated, and then CER+T_M approach is recommended. The small improvement obtained when CER+T_M approach very likely was caused by the fact that effective rainfall ratio was similar for all locations. For shallower soils the impact on water balance components could be different (Sadras and Calviño, 2001): shallow soils will reduce the water stored, implying to be more independent of rainfall previous to the crop, and would require a specific calibration process or the consideration of the CER+T_M function.

In spite of these very satisfactory results, limitations of empirical models related with the simulation of foreseen changes in agronomic practices forced by climate change effects must be overcome, especially those related with sowing date or crop cycle length. These changes will affect to the flowering period (during weeks 24-27 under the current conditions) but not in the sensibility of sunflower to the heat and water stress. The new critical dates under future weather conditions and agronomic practices could be easily determined considering the growing degree days and photoperiod (Aiken 2005) to account for effects of temperature regimes on phenology, similarly as are considered in AquaCrop model (Steduto et al., 2012). With these new dates the proposed formulation is fully applicable for future scenarios analysis.

1.4.2. AquaCrop

Although average AquaCrop estimated sunflower yield for Cordoba and Jerez locations was similar to the observed average yield (2168 kg ha^{-1} vs. 2116 kg ha^{-1}; Table 2), the average yield camouflaged the real performance of the model, compensating clear under and overestimations (Fig. 2a). Thus, considering the goodness-of-fit parameters, RMSE was 835 kg ha^{-1}, RRMSE was 40% and $R^2 = 0.47$ (Table 2). The slope and intercept of the regression between observed and estimated sunflower yields (Fig. 2a), in spite of an acceptable R^2, deviated from 1:1 line ($P<0.05$), indicating that the results were not optimal, underestimating sunflower yield under dry conditions and in the opposite case, overestimating under wetter conditions due to the model simulating an excessive growth. For dry years canopy expansion simulated by AquaCrop was intensively affected by water stress, also influencing the harvest index (HI), not reaching its maximum. These impacts were respectively controlled by a water stress coefficient and by a threshold green canopy cover below which the HI can no longer increase (Steduto et al., 2012). From the analysis of the obtained results (Fig. 2a), calibration of these parameters must be improved, especially for dry conditions, for reducing the impact of the water stress on yield. During wet years errors arise due to the non-inclusion of fertilizer limitations in the models, but which does influence the actual yields. Using OILCROP-SUN, Villalobos et al. (1996) obtained similar results (RMSE = 800 kg ha^{-1}) and Rinaldi et al. (2003) for irrigated sunflower in Italy obtained very good simulated results (RMSE = 533 kg ha^{-1} and $R^2 = 0.74$) after a regional parameterisation process. Finally, Cabelguenne et al. (1999), using EPICphase, obtained results for sunflower with a RMSE of 1380 kg ha^{-1} and R^2 equal to 0.83.

In order to determine the degree of goodness of the soil parameter determination in the AquaCrop model, a sensitivity analysis for water holding capacity, WHC, soil depth and soil water content at the beginning of the simulation, SWC_i, was carried out. The most sensitive parameter was WHC, generating an estimated variation of around 36% in average yield, with changes of 20% in WHC. Changes in SWC_i affected simulated yield by around 23%, when SWC_i was modified by 20%. This lesser effect was caused by the null effect of this change on yield in rainy years. Finally, the effects of soil depth gain were much more limited; yield increases of around 11% when soil depth gains were 20%. These sensitivity analysis results agree with Olesen et al. (2000) and Alvarez (2009), who indicated that a correct soil characterization was vital in the ability of the models to reproduce accurately the observed yield.

The sensitivity analysis results generate serious concerns about the use of this type of model to analyze climate change yield impacts at a regional scale, where an accurate characterization of these (and other) parameters, even for experimental fields, is hard to achieve. Previous studies with similar models to AquaCrop have provided poor results for large-scale studies, most likely due to the above limitations. For example, Landau et al. (1998) detected that process-based models such as CERES-wheat, were not able to predict historical wheat yields in the UK, not even the average annual yields.

1.4.3. Stewart function

Taking into account the ET_c values calculated by a water balance model (see section 2.3.2), the results of the Stewart function provided an average yield estimation (considering Cordoba and Jerez datasets) equal to 1890 kg ha^{-1}, 11.6% lower than the average observed yield. RMSE was 489 kg ha^{-1} and RRMSE equal to 23% (Table 2). This underestimation is confirmed analyzing the results across the range of observed yields, with a linear correlation with slope = 0.69 and an intercept of 819.5 (Fig. 2a) although without statistically significant differences from line 1:1 (Table 2). However dispersion was elevated with $R^2 = 0.34$. In spite of previous analyses carried out by Katerji et al. (1998) found accurate averaged yield estimates for sunflower, the results described in Figure 2a depicts an excessive simplicity of the model and implies that some key components in the yield formation for sunflower, as impact of water stress on yield, are not correctly calibrated in this approach.

1.4.4. Comparison of models

In order to evaluate and compare AquaCrop, Stewart function and the empirical model SOM, observed sunflower yield for Cordoba and Jerez locations were considered taken into account some goodness-of-fit parameters described in Section 2.4. Although the results obtained with AquaCrop were acceptable compared with similar physically-based models (Villalobos et al., 1996; Cabalguenne et al., 1999) the SOM model highlights for the promising results in yield assessment previously described. Thus, comparing the SOM approach uniquely using effective rainfall and maximum temperatures (CER+T_M) or total rainfall and maximum temperatures (TR+T_M) with AquaCrop, SOM produced very satisfactory results (Table 2), reducing the RMSE in more than 56%, a very valuable improvement considering the great simplicity of the proposed approach and the acceptable results obtained with AquaCrop. Close to SOM results, the Stewart function, provided worse but also accurate results, demonstrating the high potential of this methodology for yield estimation.

Traditionally, complex models have been recommended for assessing yield due to their better adaptation to extreme weather and management conditions (Cabelguenne et al., 1999; Hansen and Jones 2000), rather than empirical models like SOM. Thus, AquaCrop approach includes a specific parameter and curve impact to consider the failure of pollination due to heat stress, affecting the harvest index and depending on timing and extent of stress (Steduto et al., 2012). However, further analyses are still required because the recommended maximum threshold temperature for sunflower and the impact curve shape require a calibration and validation process that until now has not been developed. This heat stress effect omission is one of the main causes of the described divergences between these approach results and the observed yields. Due to this, the results obtained in this study in quite different locations from those used for the calibration (such as Jerez) produced more reliable results with the SOM model than with AquaCrop (e.g. RMSE for SOM using CER+T_M in Jerez was 410 kg ha^{-1} vs. 916 kg ha^{-1} using AquaCrop), indicating that models requiring a high quality of data may not be the best option, as these models, like the empirical ones, also require an accurate local calibration process.

Thanks to the SOM model clear response functions as shown in Fig. 1a have been determined, providing key information about the sunflower crop under real field conditions, warning of the effect of heat stress on anthesis, providing useful information for researchers, technicians and farmers around the world. The large database considered in this study provided a high reliability level for the main conclusions of the study, providing critical information to modellers of the importance to consider the heat stress on yield formation, although local/regional calibration was still required to quantify the impacts for specific varieties and crop cycles.

Climatic change, in addition to changes in temperature or rainfall pattern, also forecast an increasing atmospheric [CO_2]. This fact is considered in AquaCrop approach but obviously in the SOM approach and in the Stewart function is omitted. However considering the results provided by AquaCrop model, changes in [CO_2] do not interact with temperature or water status, and then, the impact of application of different adaptation strategies (as advancing sowing date or using a shorter crop cycle length) could be evaluated using the SOM approach.

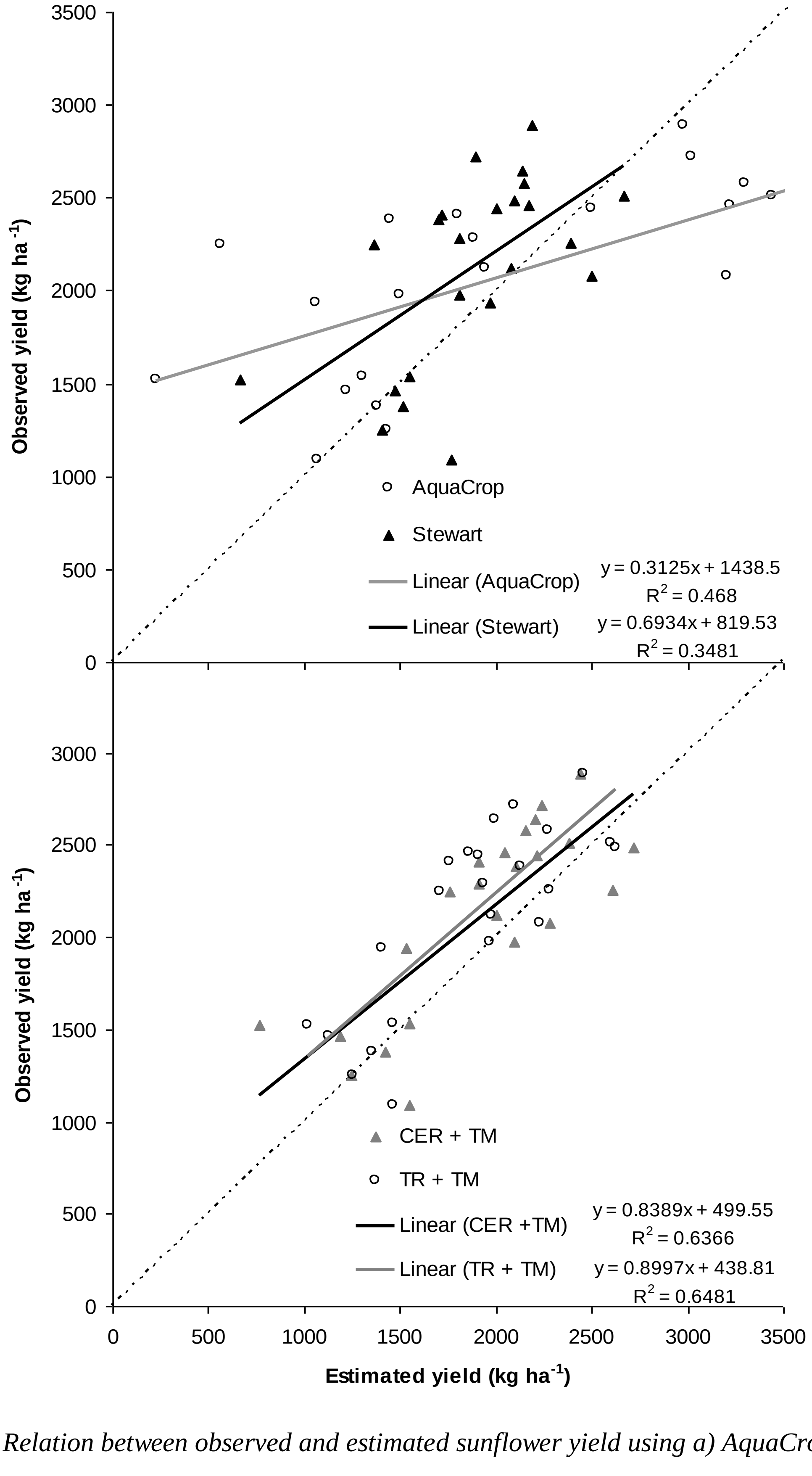

Figure 2. Relation between observed and estimated sunflower yield using a) AquaCrop model and Stewart function, and b) SOM model (considering CER+T_M and TR+T_M) considering Cordoba and Jerez datasets.

1.5 Conclusions

The main objective of this study was to carry out an evaluation of different well-known simulation models (AquaCrop and Stewart function) and a new simple empirical approach for assessing yield of rainfed sunflower under semi-arid conditions to analyze climate change impacts at a regional scale, where the data available are very limited.

In this study, it has been demonstrated that simple, empirical models using only weather/soil data and experimental field data, are able to provide accurate yield estimations even better than more complex models, detecting important components for crop yield assessment as the heat stress on flowering period. However empirical models have limitations related to their applicability in regions under climate/crop/soil conditions clearly different of those where the calibration was carried out. Additionally, a major limitation of the empirical models is the non-consideration of weather event dynamics effects on yield simulation. However, in rainfed summer crops such as sunflower, the crop cycle and the rainfall period slightly overlap, contributing to the very satisfactory results obtained. However, for those crops whose cycle overlaps the rain period (such as winter/spring crops), the results from empirical models are worse, and further analyses are required.

In all the crop simulation models, even in the most complex ones, some important processes are omitted. The findings described in this study related with high temperature effects on sunflower yield, constitutes a note of warning with respect to the use of functions or models which do not include a calibrated/validated high temperature response function, in those tools aimed to explore possible impacts of climate change. Possible tools for this estimation could be based on response functions considering cumulative heat-stress temperatures during critical periods. Other omitted process is the response of sunflower to water stress when it takes place on other growing stages of the plant different to flowering, and also is promoted to be included in crop simulation models. Finally, in commercial fields there are important yield-limiting factors that have not been considered here, producing an overestimation in simulated yields. This fact constitutes the basis of future analyses on the sunflower yield gap under semi-arid conditions.

The consideration of simple models as SOM in climate change studies must cope with the limitations caused by the no-consideration of changes in crop varieties, response to variations in [CO_2] or possible interactions between [CO_2], high temperatures and water/nutrient stresses. However, even for the most complex models, these topics have a high level of uncertainty due to the limited available datasets for calibration and validations of these processes. In spite of these limitations, regionally calibrated empirical models can be used as excellent decision tools for studying climate change, yield gap, benchmarking, risk management and farm planning, avoiding the restrictions of more complex models with higher data requirements.

1.6 Acknowledgements

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Capítulo 2: Yield response of sunflower to irrigation and fertilization under semi-arid conditions

2.1 Abstract

Until recently, irrigation of traditionally rainfed crops such as sunflower in the semi-arid regions of southern Spain was limited to supplementary irrigation given the very limited water supply. This was primarily due to a poor understanding of the irrigation management of this crop. However, thanks to irrigation and N-fertilization research carried out between 2012 and 2014 in southern Spain, functions of sunflower yield response to irrigation and N-fertilization have been determined, thus identifying the optimal irrigation and fertilization scheduling to optimize both yield and water productivity. The study found that irrigation volumes of around 60-80% of the optimum and N-fertilization doses of around 100 and 150 units of N, depending on if stressed or non-stressed conditions were found, provided the maximum yield.

Significant interactions between irrigation and N-fertilization supply were demonstrated, as N crop status also depended on the water stress conditions, with N deficiencies detected when water supply was limited, demonstrating the utility of using the nutritional crop status for combined fertilization and irrigation recommendations. Likewise, sowing date affected the yield response of sunflower to water supply, with early sowing dates resulting in higher yields (an increase of around 11.4% compared to traditional sowing dates) due to the mitigation of heat and water stress during the flowering period.

Irrigation practices for sunflower under semi-arid conditions have demonstrated significant benefits, especially with limited rainfall supply. However these practices must be combined with N-fertilization practices in order to maximize input efficiency. Optimized irrigation and fertilization practices for sunflower must therefore be encouraged as a way to achieve a similar performance as traditional irrigated crops.

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2.2 Introduction

Historically, rainfed agriculture has formed the economic foundations for vast areas of Southern Europe. This type of agriculture is characterized by low inputs and low yields, and is severely affected by droughts as the sole source of water is the generally limited rainfall (Valverde et al., 2015). Similarly, fertilization is very limited since farmers in these areas normally apply little or no fertilizer. These restrictions in input supply lead to a huge year-over-year variability in yield, mostly linked to annual rainfall (García-Lopez et al., 2014). Traditionally, this rainfed agriculture stems not only from the unavailability of water for irrigation but also the farmers' supposition that to apply water resources to wheat, olive or sunflower crops is not economically viable as water applied to other crops could potentially generate a higher profit (García-Vila et al., 2008; Lorite et al., 2012; 2013).

In recent years, the profitability of irrigated agriculture has fallen significantly, with irrigation water productivity values very close to the profitability thresholds, especially for traditionally irrigated crops such as maize (Lorite et al., 2012; 2013). Consequently, in some irrigation districts the amount of available water is higher than the irrigation demand (Lorite et al., 2012), due to a clear lack of alternatives for obtaining profitable crop patterns. Faced with this new situation, the consideration of new irrigated crops such as biomass crops or almond/walnut orchards, or even watering traditionally rainfed crops, are some of the alternatives that are currently being contemplated in many irrigated areas of southern Europe.

Sunflower (*Helianthus annuus* L.) is an oilseed plant grown in Spain since the 1960s and is characterized by its adaptability to a wide range of environments. The sunflower is nowadays the most important oilseed crop in Spain and in recent years there has been a significant increase in the area under cultivation. In the European Union (EU), 4.32 million ha of sunflowers were planted in 2012 with a production of 7.23 million Mg. In Spain, 753,000 ha were cultivated in 2012 (200,000 ha in Andalusia) and sunflower has subsequently become an important component of the crop rotation systems in the rainfed areas located in the south.

Only around 10% of the total surface area planted with sunflower was cultivated using irrigation, with an average yield of 2,200 kg per ha, while the remaining 90% is cultivated using rainfed systems with average yields of around 700 kg per ha (MAGRAMA, 2012).

Compared to other crops, sunflower is well-adapted to sub-arid environments (Stone et al., 2002; Moroke, 2002) due to its ability to extract water from deeper soil layers with the pronounced development of the root system under water stress (Connor et al., 1985; Fereres et al., 1993). However, sunflower is particularly sensitive to water stress (Osman and Talha, 1975; Unger 1983; Göksoy et al., 2004) and heat stress from early flowering to the achene filling stage (Ploschuk and Hall, 1995; García-López et al., 2014).Previous studies have therefore shown that substantial yield increases are achieved through irrigation (Unger, 1982; Connor et al., 1985; Cox and Jolliff, 1986; Sadras et al., 1991; Stone et al., 1996; Karam et al., 2007). Likewise, nitrogen fertilization is a critical component of sunflower yield production (Zubriski and Zimmerman, 1974; Yousaf et al., 1986; Sarmah et al., 1994). Thus, a rational mineral nutrition is needed for the crop to reach optimum growth and high yields (Andrade et al., 2000) since N plays an important role, either directly or indirectly, in processes such as growth and leaf senescence and in determining yield components (Merrien, 1992).Previous studies have shown that N deficiency in sunflowers reduces vegetative and generative growth, induces premature senescence (Narwal and Malik, 1985; Tomar et al., 1999) and leads to a fall in yield due to reductions in crop leaf area and therefore, a lower uptake of solar radiation (Massignam et al., 2009). On the other hand, excess N-fertilization may shift the balance between vegetative and reproductive growth toward excessive vegetative development, thus delaying crop maturity (Hocking et al., 1987), increasing the susceptibility of the plant to a number of diseases (Seassau et al., 2010) as well as producing a reduction in the accumulation of seed oil (Steer et al., 1986; Ozer et al., 2004).

In order to address the level of crop fertilization, the use of Critical Nitrogen Dilution Curves (CNDC) has been proposed. These curves reflect the critical concentration of N in the aboveground biomass and are unique for a species or group of species (Andrade el al., 1996). There are specific CNDC for many crops such as wheat (Justes et al., 1994; Ziadi et al., 2010), maize (Plénet and Lemaire, 1999) and cotton (Xiaoping et al., 2007). However, until recently, no specific CNDC for sunflowers existed and those that did were based on analogies with other C3 species (Merrien, 1992; Reau et al., 2001; Gonzalez-Dugo et al., 2010). Consequently, the equation developed by Merrien (Merrien 1992) has been used as a reference to determine the nutritional status of sunflower (Sosa et al., 1999; de Caram et al., 2007). Finally, Debaeke et al. (2012) recently proposed a sunflower-specific CNDC as an alternative to the Merrien's equation as a following comprehensive field experiments in Argentina, Australia, France, Italy and Spain.

Although irrigation and fertilization are key factors for sunflower production, studies combining both factors are not very common (Muriel et al., 1980; Alvarez de Toro, 1987), with the majority focusing on the assessment of irrigation (Rinaldi, 2001; Göksoy et al., 2004; Sezen et al., 2011) or fertilization impacts on yield (Reau et al., 2001; Ozer et al., 2004; Massignam et al., 2009), but with both factors examined separately. To fill this gap, a three-year experiment involving different irrigation schedules and fertilization strategies was carried out. These experiments revealed the effect of different irrigation volumes and fertilization treatments and their possible interactions on sunflower seed yield, oil content, and the other yield components.

2.3 Material and Methods

2.3.1. Field experiments

The experiments were carried out during the 2012, 2013 and 2014 growing seasons, between the months of March and September, at the "Alameda del Obispo" experimental farm located near the city of Cordoba, southern Spain (latitude 37º 51' 42" N, longitude 4º 48' 0" W). For both 2012 and 2013, a single trial was carried out, while in 2014 two identical trials were carried out, the only difference being their sowing dates. Phenology of the crop for each trial and year is detailed in Table 1.

Table 1. Crop phenology for each treatment

	2012	**2013**	**2014-D1**	**2014-D2**
Sowing date	30/03/2012	04/11/2013	28/01/2014	14/03/2014
Emergence	13/04/2012	25/04/2013	14/02/2014	25/03/2014
Flowering	18/06/2012	26/06/2013	17/05/2014	31/05/2014
End grain filling	16/07/2012	25/07/2013	13/06/2014	07/03/2014
Harvest	16/08/2012	15/09/2013	16/07/2014	08/04/2014

The climate in Cordoba is considered to be semi-arid, with the rainy period concentrated between autumn and spring, and with a very hot, dry summer season. Weather conditions during the time period under analysis are summarized in Table 2, highlighting the high temporal heterogeneity in annual rainfall (from 314 to 915 mm). Temperature pattern during flowering was influenced by sowing date.

The soil is a deep sandy loam, with a Typic Xerofluvent classification. Soil analyses were carried out each year, just before planting, to determine the amount of available nitrogen in the soil. Depending on the year and the experimental site, available nitrogen ranged from 5.2 kg ha^{-1} (2014-D1) to 25.69 kg ha^{-1} (2012), with intermediate values for the rest of the trials (5.6 kg ha^{-1} for 2014-D2 and 16.9 kg ha^{-1} for 2013; Table 2). Irrigation water was extracted from an alluvial aquifer with connection with wells from nearby mountains with stable values of nitrates and nitrate as nitrogen (NO_3^-N) of around 32 and 7.2 ppm, respectively.

All trials were arranged as split-plots on randomized block designs, with four replications, where irrigation levels were the main plots and N fertilizer dosages were the sub-plots. Experimental plots consisted of 8 rows with a North-South orientation, 10 m long, 70 cm apart, 25 cm between plants within rows, and with a plant population of around 55.000 plants per hectare. All experiments were seeded with Bosfora cultivar (Syngenta).

Table 2. Weather conditions, water and heat-stress impact (f_Rain and f_Temp) calculated according to the methodology used by García-Lopez et al. (2014) and initial N conditions for each treatment. FL and EGF indicate flowering and end of grain filling periods respectively.

	2012	**2013**	**2014-D1**	**2014-D2**
Rainfall (mm)	314,2	915,4	510	510
f_Rain	0,56	0,96	0,71	0,71
ET_o (mm)	1485,4	1314,8	1406,1	1406,1
ET_o (FL-EGF) (mm)	220,7	220,3	165,6	187,6
Max. Temperature on FL (ºC)	34,5	34,4	24,8	30,3
f_Temp	0,81	0,82	1,04	0,94
Available N at beginning (kg ha^{-1})	25,69	16,9	5,2	5,6

The irrigation method consisted of a drip system with one meter drip emitter spacing. Optimal irrigation scheduling was based on a water balance approach described later in Section 2.2. For each year and trial different irrigation schedules were considered, providing between 24% and 124% of the optimal irrigation requirements (67 mm for IR1 / 2014-D1 and 521 mm for IR3 / 2013, respectively; Table 3), and three levels of N fertilizer (0 u.N. ha^{-1}, 75 u.N. ha^{-1} and 150 u.N. ha^{-1}, for N1, N2 and N3 treatments, respectively). Combining the four designed trials, different irrigation volumes were used in order to evaluate crop behavior under a full range of water availability conditions. Nitrogen fertilizer in granulated form was manually applied in the sowing lines when the sunflower plants had four true leaves, at a rate depending on the fertilization treatment. Calcium ammonium nitrate was used as the source of N.

Table 3. Water balance components, performance indicators (ratio between current and optimal irrigation, and between current and optimal water supply) and measured yield for each trial. SWC_f *refers to the soil water content at the end of the crop cycle and* $K_{s\text{-}FG}$ *is the stress coefficient from flowering (FL) to end of grain filling (EGF).*

	IR1	**IR2**	**IR3**	**Rainfed**	**Optimal**
2012					
Effective rainfall (mm)	263,8	263,8	263,8	263,8	263,8
Irrigation volume (mm)	145,7	235,4	325,9	0	508
Irrigation vs. Optimal Scheduling	0,29	0,46	0,64	0	1
(Rainfall+Irrigation) vs. Optimal Supply	0,53	0,65	0,76	0,34	1
Transpiration (mm)	156	224,3	321,1	131,4	475,9
SWC_f (%)	96,3	92,4	91	97,3	88,1
$K_{s\text{-}FG}$	0,24	0,43	0,65	0,17	1
Yield (kg ha^{-1})	1333	1982	2622	293	
2013					
Effective rainfall (mm)	599,9	599,9	599,8	615,9	599,9
Irrigation volume (mm)	211,9	368,9	521,3	0	419
Irrigation vs. Optimal Scheduling	0,51	0,88	1,24	0	1
(Rainfall+Irrigation) vs. Optimal Supply	0,8	0,95	1,1	0,6	1
Transpiration (mm)	379,5	492,86	636,69	335,23	597,81
SWC_f (%)	94,46	88,46	74,9	95,36	85,62
$K_{s\text{-}FG}$	0,69	0,91	1	0,59	1
Yield (kg ha^{-1})	2168	2647	3285	1375	
2014-D1					
Effective rainfall (mm)	451,3	451,3	451,3	451,3	451,3
Irrigation volume (mm)	67	134,1	201,1	0	276,2
Irrigation vs. Optimal Scheduling	0,24	0,49	0,73	0	1
(Rainfall+Irrigation) vs. Optimal Supply	0,71	0,8	0,9	0,62	1
Transpiration (mm)	280,5	340,77	396,08	251,7	465,63
SWC_f (%)	92,83	92,71	88,33	93,13	86,87
$K_{s\text{-}FG}$	0,45	0,64	0,83	0,39	1
Yield (kg ha^{-1})	2259	2576	2992	1876	
2014-D2					
Effective rainfall (mm)	451,3	451,3	451,3	451,3	451,3
Irrigation volume (mm)	92,2	184,4	276,6	0	265,4
Irrigation vs. Optimal Scheduling	0,35	0,69	1,04	0	1
(Rainfall+Irrigation) vs. Optimal Supply	0,76	0,89	1,02	0,63	1
Transpiration (mm)	249,39	323,15	402,66	222,46	425,45
SWC_f (%)	93,34	91,83	87,75	92,91	88,36
$K_{s\text{-}FG}$	0,45	0,81	0,99	0,42	1
Yield (kg ha^{-1})	1960	2559	2880	1546	

In each trial and replication, seed yield, seed oil content and some yield components were determined by harvesting around 120 plants from the two central rows of the trials to avoid crop border effects. Equally, for each trial and replication six individual plants were harvested to estimate other plant variables and other yield components such as head diameter (HD), total plant weight (TW), seed number (SN), seed weight (SW), and hundred seed weight (W100). Seed oil content was estimated using Nuclear Magnetic Resonance (NMR spectroscopy). Finally, for determining the nutritional status of the sunflower crop two plants were harvested for each treatment and replication.

2.3.2. Crop water requirements and irrigation scheduling

A water balance approach formed the basis of irrigation scheduling at field scale (Allen et al., 1998; Lorite et al., 2004). A daily water balance was calculated for each field trial, with rainfall and irrigation as inputs, and superficial runoff, deep percolation, soil evaporation and crop transpiration as outputs. Superficial runoff was determined using the curve number methodology defined by SCS (SCS, 1972). The water balance was grounded in a cascade approach defining the deep percolation as the excess of water that the root zone is not able to store (when soil water content exceeds the field capacity). In order to determine soil evaporation, a water balance for the superficial soil layer was calculated, and the methodology proposed by Allen et al. (1998) was applied.

A key component of the irrigation scheduling is the accurate determination of crop water requirements using crop coefficients (Allen et al., 1998). In this study the methodology proposed by Allen et al. (1998) to determine crop basal coefficients (K_{cb}) was used. This methodology requires the determination of crop ground cover and crop height for each field throughout the crop cycle. To determine crop ground cover, aerial digital pictures of the crop were used. These pictures were obtained with variable temporal frequency, depending on the crop stage, and at least six dates per experiment were considered. Based on these pictures, sunflower crop ground cover for each field was determined using the GreenCropTracker software (Pattey and Liu, 2010). For crop height determination, field measures were made on the same date as the ground cover estimation. Daily K_{cb} values were based on available images and using an interpolation technique based on a spline function (Santos et al., 2008; Trezza et al., 2013). These daily values and the reference evapotranspiration (ET_o) provided the potential transpiration of the crop, the key component when determining crop irrigation water requirements.

Weather data and ET_o were collected by an automated weather station located near the experimental fields, which formed part of the Agroclimatic Weather Network of Andalusia (Gavilán et al., 2006).

The water balance was initialized on 1st September of each year, and the soil profile was considered to hold on 20% of the total soil storage. This value was determined taking into consideration the previous crop (rainfed wheat) and the weather conditions.

Water stress affects the crop as water stored in the root zone falls below a certain threshold. This threshold is defined by Allen et al. (1998) as the fraction of the total available soil water in the root zone that the crop can extract without suffering water stress (p), and for sunflower it was set at 0.6 (Lorite et al., 2005). In order to consider the impact of water stress on crop transpiration, the daily stress coefficient K_s defined by Allen et al. (1998) was determined for each trial (Table 3).

Once the water balance had been developed, effective rainfall was calculated as water from rainfall that was accessible to the crop (i.e. rainfall minus runoff and deep percolation; Table 3). Equally, optimal irrigation scheduling was defined as that which avoided stress throughout the crop cycle but without generating over-irrigation. Thus, water stress was avoided until grain filling, by maintaining the K_s coefficient equal to 1 from flowering to grain filling (Table 3), since in terms of water shortage flowering is the most critical stage for yield (Karam et al., 2007). In addition, and in order to avoid over-irrigation at the end of the crop cycle, optimal irrigation scheduling was defined to ensure that water stored in the soil at the end of the crop cycle did not exceed 20% of the maximum water storage. Irrigation events were programmed three times per week, with rates ranging between 4.2 and 17.9 mm per day, depending on the irrigation treatment.

At least two irrigation schedules per experiment were defined considering sustained deficit irrigation (SDI) by reducing the length of watering time for each irrigation event obtained from the optimal irrigation scheduling. SDI generates water deficit that increases progressively as the season advances and allows plants to adapt to water deficit (Fereres and Soriano, 2007). The use of irrigation water with nitrates could generate differences in N supply between irrigation treatments. In this study, this additional N supply was considered when fertilization impact was evaluated.

Water productivity (WP) is defined as the ratio between yield and available water for the crop (effective rainfall plus irrigation). Similarly, irrigation water productivity (IWP) is defined as the ratio between the increase of yield caused by irrigation and the irrigation applied. Yield for rainfed conditions was simulated considering the field experiments for each year. WP and IWP have frequently been applied in the past to evaluate the irrigation management at field and irrigation district scale (Tolk and Howell, 2012; Lorite et al., 2012; Droogers and Kite, 2001).

2.3.3. Nitrogen Nutrition Index (NNI)

In order to determine the nutritional status of the sunflower crop, during the 2012, 2013 and 2014 seasons, Nitrogen Nutrition Index of the crop (NNI) was estimated at different stages of the crop development. NNI is defined (Lemaire and Gastal, 1997) as:

$$NNI = \frac{[N]_a}{[N]_{critical}} \qquad [1]$$

where $[N]_a$ is the actual N content of the plant, estimated using the Kjeldahl "classic" method (Page et al., 1982), and $[N]_{critical}$ is the critical N concentration required to reach the maximum growth rate in shoot dry matter prior to anthesis. Previous studies determined NNI index for sunflower crop in different areas of Argentina (Diaz-Zorita, 2002; de Caram et al., 2007) with satisfactory results.

In order to determine NNI for each treatment and stage, two plants were randomly selected from each plot during six reproductive stages of the crop (Schneiter and Miller, 1981): R1 (the terminal bud forms a miniature head rather than a cluster of leaves), R2 (the immature bud elongates 0.5 to 2 cm above the nearest leaf attached to the stem), R3 (the immature bud elongates more than 2 cm above the nearest leaf), R4 (the inflorescence begins to open), R5 (beginning of flowering and can be divided into sub-stages depending on the percentage of the head area that has completed or is flowering), and R6 (flowering is complete and the ray flowers are wilting). Following R6, the plant changes the composition of dry matter producing a redistribution of N, mainly moving it from the leaves and stems to the head, and giving way to the oil phase synthesis (Merrien et al., 1986). The sampled plants were dried in an oven at 70° until constant weight in order to determine the total dry matter (DM) per plant.

Once DM values for each crop reproductive stage were obtained, $[N]_{critical}$ was determined by applying two different methodologies. The first one considered the Merrien´s equation defined in Merrien (1992) as:

$$CNDC_M = \frac{281.5}{(DM_P + 52.6)} \qquad [2a]$$

where DM_P is dry matter per plant. When turned into a power function and taken on a density of 5.5 plant m^{-2}, it becomes:

$$CNDC_M = 4.23 \cdot DM^{-0.49} \quad [2b]$$

where DM is total dry matter per hectare. Debaeke defined a similar formula (Debaeke et al., 2012):

$$CNDC_D = 4.53 \cdot DM^{-0.42} \quad [3]$$

In this study, and in order to detect which procedure is best suited for determining CNDC, both functions have been considered.

In contrast to crops such as durum wheat, which must reach an NNI of 1 to maximize both yield and protein concentration, and NNI > 1 or NNI < 1 indicates excess or deficiency of N, respectively (Debaeke et al., 2006), for sunflower crop NNI levels between 0.8 – 0.9 at anthesis are enough to maximize grain yield and oil concentration (Debaeke et al., 2012). Excessive levels of N induce yield losses by predisposing the crop to disease, maturation delays, excessive lowering of oil content or broken stems (Ozer et al., 2004; Seassau et al., 2010).

2.4 Results

2.4.1. Crop response to irrigation

With respect to the irrigation scheduling carried out for each treatment and year (Table 3), key components of the water balance such as crop transpiration (T), water content at the end of the crop cycle (SWD_f) and crop water stress between flowering and end of grain filling ($K_{s\text{-}FG}$) were determined. Average $K_{s\text{-}FG}$ ranged between 0.24 (2012/IR1) to 1.00 (2013/IR3; Table 3), with 2012 registering the lowest values. Crop transpiration was associated with $K_{s\text{-}FG}$ and ranged between 156 mm (2012/IR1) and 637 mm (2013/IR3). Lesser differences between treatments and years were determined for SWD_f, ranging between 74.9% (2013/IR3) and

96.3% (2012/IR1) of total available water in the soil.

In the 2012 season, average yield ranged between 1333 kg ha^{-1} (IR1) and 2622 kg ha^{-1} (IR3), corresponding to three different irrigation treatments that ranged from 146 mm to 326 mm respectively (Table 3). The measured yield for 2012 provided the lowest values for the whole dataset due to the deficit irrigation volume applied (Table 3) that coincided with the high temperatures during the flowering period (Table 2). Thus, optimal irrigation requirements for 2012 were equal to 508 mm, depicting a clear deficit irrigation scheduling, especially for IR1 and IR2 (the ratio between irrigation applied and optimal irrigation was 0.29 and 0.46, and $K_{s\text{-}FG}$ was equal to 0.24 and 0.43, respectively; Table 3). For the 2013 season, the highest yield, close to 3300 kg ha^{-1}, was obtained with IR3 treatment, applying the highest volume of irrigation (521.3 mm, 24% more than the optimal irrigation requirements; Table 3), but without any detectable impact of the heat stress on yield. During the 2014 season with an early sowing date, yield ranged between 2259 kg ha^{-1} and 2992 kg ha^{-1} with irrigation volumes varying between 67 mm and 201 mm; for late sowing date, crop yield ranged between 1960 kg ha^{-1} and 2880 kg ha^{-1} with irrigation volumes varying between 92 mm and 277 mm (Table 3).

Significant differences in yield, oil yield and seed weight (SW) among IR1, IR2 and IR3 irrigation treatments, were determined for all the years (Table 4). For head diameter (HD), total plant weight (TW) and hundred seed weight (W100), significant differences for IR1 and IR3 treatments were also determined for all the years (Table 4). These differences indicate that the increase of yield when irrigation supply increases is mainly due to the increase of SW (46.7% from IR1 to IR3 treatments), although the increase of number of seeds per head (NS) also contributed (19.1%). Equally, carrying out a four-experiment combined ANOVA, the interaction Year x Irrigation was significant for yield and oil content (Table 5), meaning a different rate of variation on the response of these two variables to the different water dosages.

Table 4. Yield, % of oil, oil yield and other components (head diameter, HD, total plant weight, TW, seed number, SN, seed weight, SW, and hundred seed weight, W100) for each irrigation treatment. Same letter for each season indicates non-statistically significant differences.

Year	**Treatment**	**Yield** (kg ha^{-1})	**% Oil** (%)	**Oil yield** (kg ha^{-1})	**HD** (cm)	**TW** (g)	**SN** (seeds head^{-1})	**SW** (g)	**W100** (g)
2012	**IR1**	1333 (c)	41.2 (b)	550 (c)	12.3 (c)	89.4 (c)	660 (b)	26.4 (c)	3.8 (c)
	IR2	1982 (b)	43.2 (a)	855 (b)	12.7 (b)	106.2 (b)	698 (a)	33.9 (b)	4.7 (b)
	IR3	2622 (a)	43.3 (a)	1136 (a)	15.6 (a)	158.7 (a)	720 (a)	49.5 (a)	6.9 (a)
2013	**IR1**	2168 (c)	47.3 (a)	1025 (c)	15.1 (c)	143.1 (c)	863 (c)	47.9 (c)	5.5 (b)
	IR2	2647 (b)	47.7 (a)	1264 (b)	17 (b)	213.5 (b)	986 (b)	65.6 (b)	6 (ab)
	IR3	3285 (a)	45.1 (b)	1484 (a)	19.4 (a)	320.5 (a)	1123 (a)	81 (a)	7.2 (a)
2014-D1	**IR1**	2259 (c)	45.5 (b)	1030 (c)	15.2 (c)	132.7 (c)	856 (b)	43.4 (c)	4.9 (c)
	IR2	2576 (b)	46.8 (b)	1202 (b)	16.6 (b)	161.7 (b)	914 (b)	54.1 (b)	5.7 (b)
	IR3	2992 (a)	49.4 (a)	1470 (a)	18.4 (a)	196.8 (a)	1026 (a)	69.4 (a)	6.7 (a)
2014-D2	**IR1**	1960 (c)	49.6 (a)	974 (c)	14.6 (b)	135.5 (b)	1021 (a)	49.3 (c)	4.8 (b)
	IR2	2559 (b)	49.3 (a)	1261 (b)	15.8 (ab)	160.1 (b)	1051 (a)	62.2 (b)	5.9 (a)
	IR3	2880 (a)	48.4 (a)	1394 (a)	17.4 (a)	219.6 (a)	1196 (a)	79.2 (a)	6.6 (a)

Integrating the different trials (Table 3), yield and yield component response to several parameters such as stress, water or irrigation applied was determined (Fig. 1 and Table 6). Yield relationship with crop water stress (considering averaged $K_{s\text{-}FG}$ parameter), with the percentage of optimal water requirements, and with the percentage of optimal irrigation requirements generated logarithmic curves with R^2 equal to 0.85, 0.85, and 0.69 respectively (Table 6). Thus, for the three regression curves, slope was reduced as $K_{s\text{-}FG}$ or % of water/irrigation applied increased, obtaining asymptotic curves to a yield value of around 3200 kg ha^{-1}.

When analyses were divided according to the sowing date, a different behavior for treatments with early sowing date (2014-D1) and late sowing date (2012, 2013 and 2014-D2) was observed (Fig. 1). Thus, analyzing yield and yield components separately, higher values for early sowing date for all water stress conditions ($K_{s\text{-}FG}$), and irrigation supply treatments were found (Fig. 1).

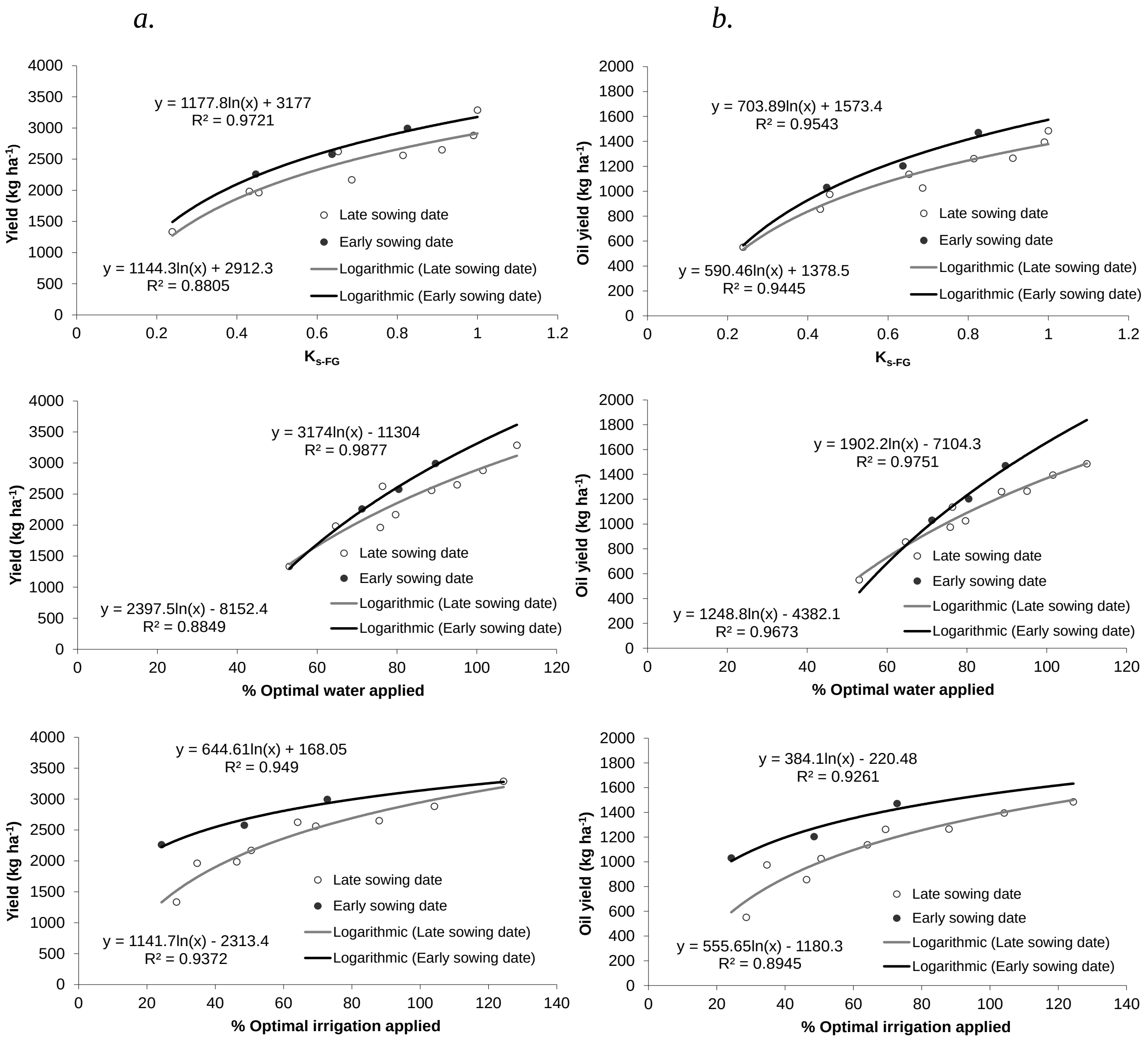

Figure 1. (a) Relationship between yield and $K_{s\text{-}FG}$, percentage of optimal water applied, and percentage of optimal irrigation applied, for early and late sowing date treatments; (b) relationship between oil yield and $K_{s\text{-}FG}$, percentage of optimal water applied, and percentage of optimal irrigation applied, for early and late sowing date treatments.

Water productivity (WP) ranged between 0.27 kg m^{-3} (2013/IR1) and 0.46 kg m^{-3} (2014-D1/IR3; Table 7). The lowest values were detected for 2013 (0.28 kg m^{-3}) due to the high rainfall (620 mm), and the highest values for 2014-D1 (0.44 kg m^{-3}) as a result of appropriate water management. Analyzing by treatments, IR1 generated the lowest WP values, especially for 2012, due to the limited water supply that generated considerable yield reductions. On the contrary, IR3 generated the highest WP values, the increase in WP obtained with IR3 during 2012 compared with IR1 and IR2 treatments (Table 7) being especially significant. Irrigation water productivity (IWP) ranged between 0.34 kg m^{-3} (2013/IR2) and 0.72 kg m^{-3} (2012/IR2), with low values for the 2013 season due to the high levels of irrigation applied. Equally, the high IWP values for 2012 were caused by the low levels of rainfall and show the value of the irrigating sunflower, especially during dry seasons. For WP and IWP, early sowing dates generated higher values compared to late sowing date treatments, especially under deficit irrigation strategies (Tables 3 and 7).

*Table 5. ANOVA for year, irrigation and N-fertilization factors for yield, % of oil, oil yield and rest of components (head diameter, HD, total plant weight, TW, seed number, SN, seed weight, SW, and hundred seed weight, W100). * significant p<0.05, ** significant p<0.01, and n.s. indicates not significant.*

	Yield	% Oil	Oil yield	HD	TW	SN	SW	W100
Year	**	**	**	**	**	**	**	n.s.
Irrigation	**	*	**	**	**	**	**	**
Year x Irrigation	*	**	n.s.	n.s.	**	n.s.	n.s.	n.s.
N Fertilization	**	**	**	**	**	**	**	**
Year x N-Fertilization	**	**	**	**	**	**	**	**
Irrigation x N-Fertilization	n.s.	n.s.	n.s.	**	n.s.	n.s.	*	*
Year x Irrigation x N-Fertilization	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.

2.4.2. Crop response to nitrogen fertilization

Analyzing the N-fertilization impact on sunflower, significant differences in yield response for N1, N2 and N3 treatments were detected in all the trials except for the 2012 season (Table 8). Yield increases when fertilization was raised from N1 to N3 ranged from 2.5% (2012) to 122% (2014-D1; Table 8). For 2012 no-response was obtained by using different N-fertilization dosages, most likely due to the clear irrigation deficit in that year (Table 3). For the rest of the treatments, significant differences in yield and yield components were detected when N-fertilization increased (Table 8), highlighting the reduction in % Oil when N-fertilization level increased (reductions of around 3% for the four trials from N1 to N3; Table 8). The yield increase when N-fertilization was carried out was mainly caused by increases in NS (around 32.6% for 2013 and 2014 treatments when N-fertilization changed from N1 to N3; Table 8), although W100 and TW also showed significant increases (of around 20.7% and 59.5%, respectively). On the other hand, the interaction Year x N-fertilization was significant for all the characters studied, including all the yield components (Table 5); this implies different responses on the rate of change of those variables to the N supply, depending on the year, namely the different environmental conditions other than those fixed by the experiment.

NNI, using the methodology developed by Debaeke et al. (2012) (NNI_D) increased as N-fertilization levels increased (Fig. 2). The response to N-fertilization lead to an increase of around 32% for N2 and around 63% for N3 compared with N1 treatment. For 2012, response was especially low (22% and 32%, respectively) due to limited irrigation supply and high initial N levels (Table 2). The response was much more evident during the 2014 trials as the initial levels of N were especially low (Table 2).

NNI_D values at the R6 stage revealed deficiencies for all the treatments in N-fertilization for IR1 and IR2, when N1 and N2 fertilization were considered (NNI_D-R6 for IR1/N1, IR2/N1, IR1/N2 and IR2/N2 were equal to 0.48, 0.52, 0.63 and 0.70, respectively; Fig. 2). However for N3 treatments NNI_D-R6 increased significantly, to values of around 0.91, and for R3/N3 the maximum NNI_D-R6 value was obtained (of around 1.10), indicating excess N-fertilization.

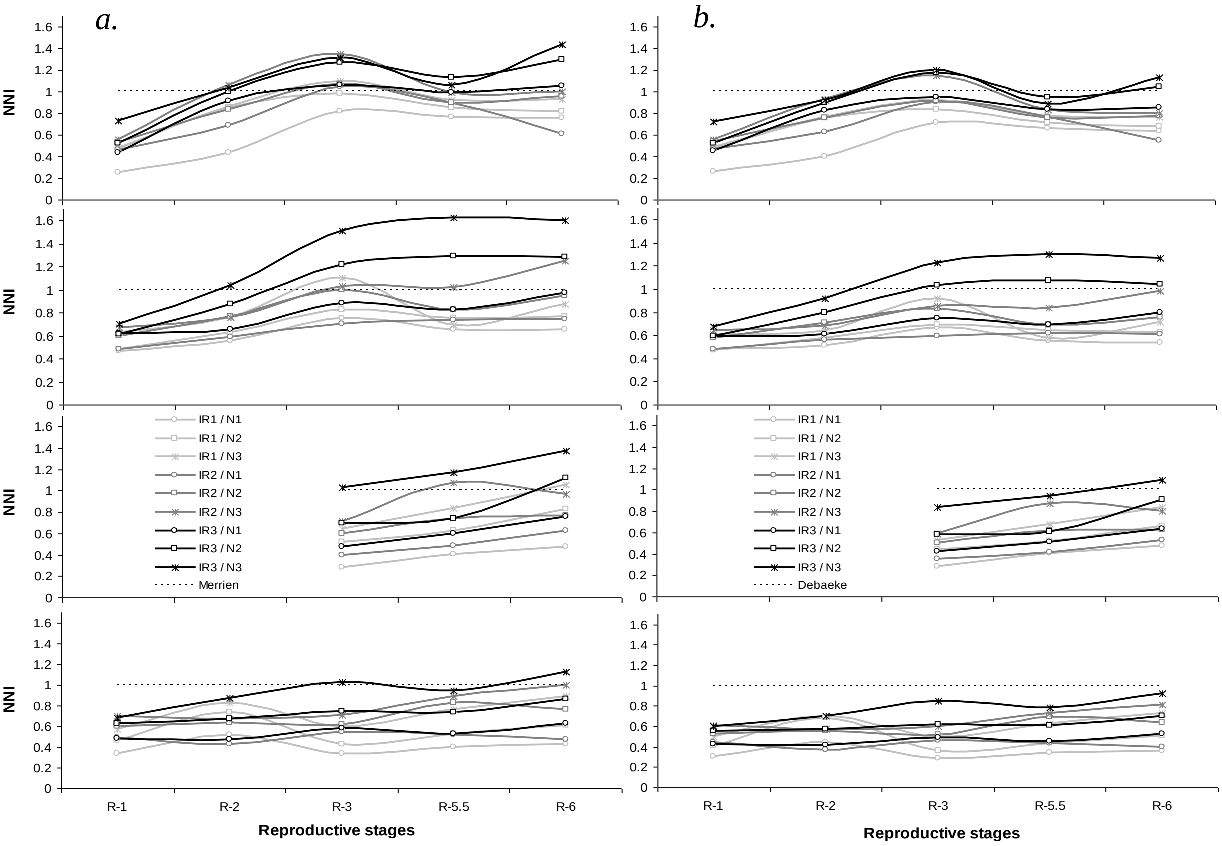

Figure 2. NNI values throughout the sunflower crop cycle for each treatment according to a) Merrien and b) Debaeke methodologies.

When NNI_D-R6 and yield values for the whole dataset were compared, logarithmic function provided non-optimal fitting (R^2=0.45), as a huge yield variability was determined for a specific NNI_D-R6 value (Fig. 3). This was caused by external factors, such as heat and water stress, which reduced the yield. Looking at Fig. 3, NNI_D-R6 values higher than 0.8 do not generate additional increments in potential yield, with fertilization efficiency falling above this threshold. When relationships of NNI_D-R6 with yield by year were considered, different performance levels were found (R^2 was equal to 0.52, 0.79, 0.86 and 0.77 for 2012, 2013, 2014-D1 and 2014-D2, respectively), indicating that under non-severe-stress conditions, annual relationships could provide accurate yield estimations. When relationships between NNI_D-R6 and oil yield were determined, R^2 values were lower (R^2=0.32) as additional factors affecting the harvest index are not included in the function. However, annual relationships and thresholds defined for yield are just as valid for oil yield (Fig. 3).

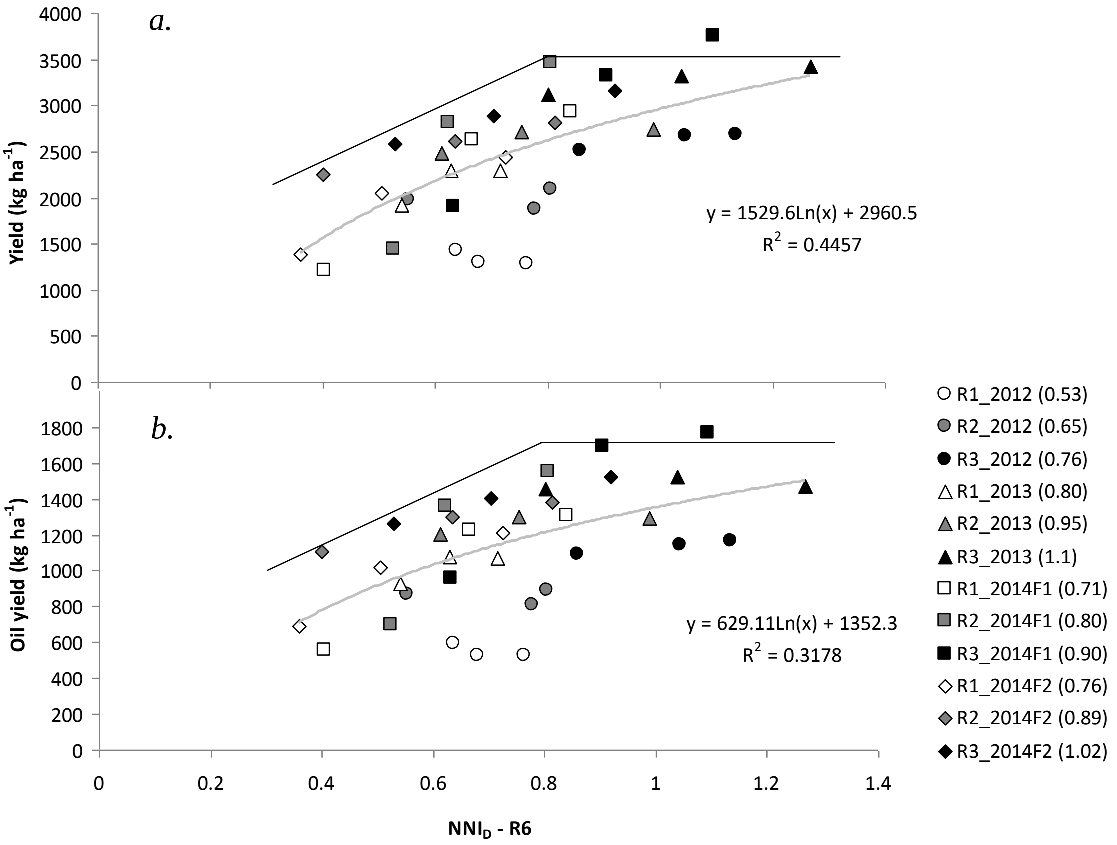

Figure 3. (a) Relationship between yield and NNI$_D$-R6, and (b) between oil yield and NNI$_D$-R6, including results for the four trials considered in the study. Grey curves indicate logarithmic function and upper black lines the envelope of each relationship. In the legend, in parenthesis, the ratio between rainfall+irrigation and optimal supply for each treatment.

2.4.3. Interaction between irrigation and fertilization

Correlating observed oil yield with N supply (including N-fertilization, available N in the soil at the beginning of the crop season and NO_3-N in the irrigation water) a clear effect of irrigation supply was detected. Thus, for correctly irrigated experiments (ratio between water supply and optimum higher than 0.70) yield increased as N supply increased following a polynomial function providing maximum yields for N supply around 150 kg ha^{-1}, with yield reductions for higher N supply (Fig. 4a). However, when severe deficit irrigation was present (R1 and R2 during_2012) yield was not affected by the increase in N-supply (Fig. 4a), and then, values lower than 100 kg ha^{-1} could be an acceptable N supply recommendation.

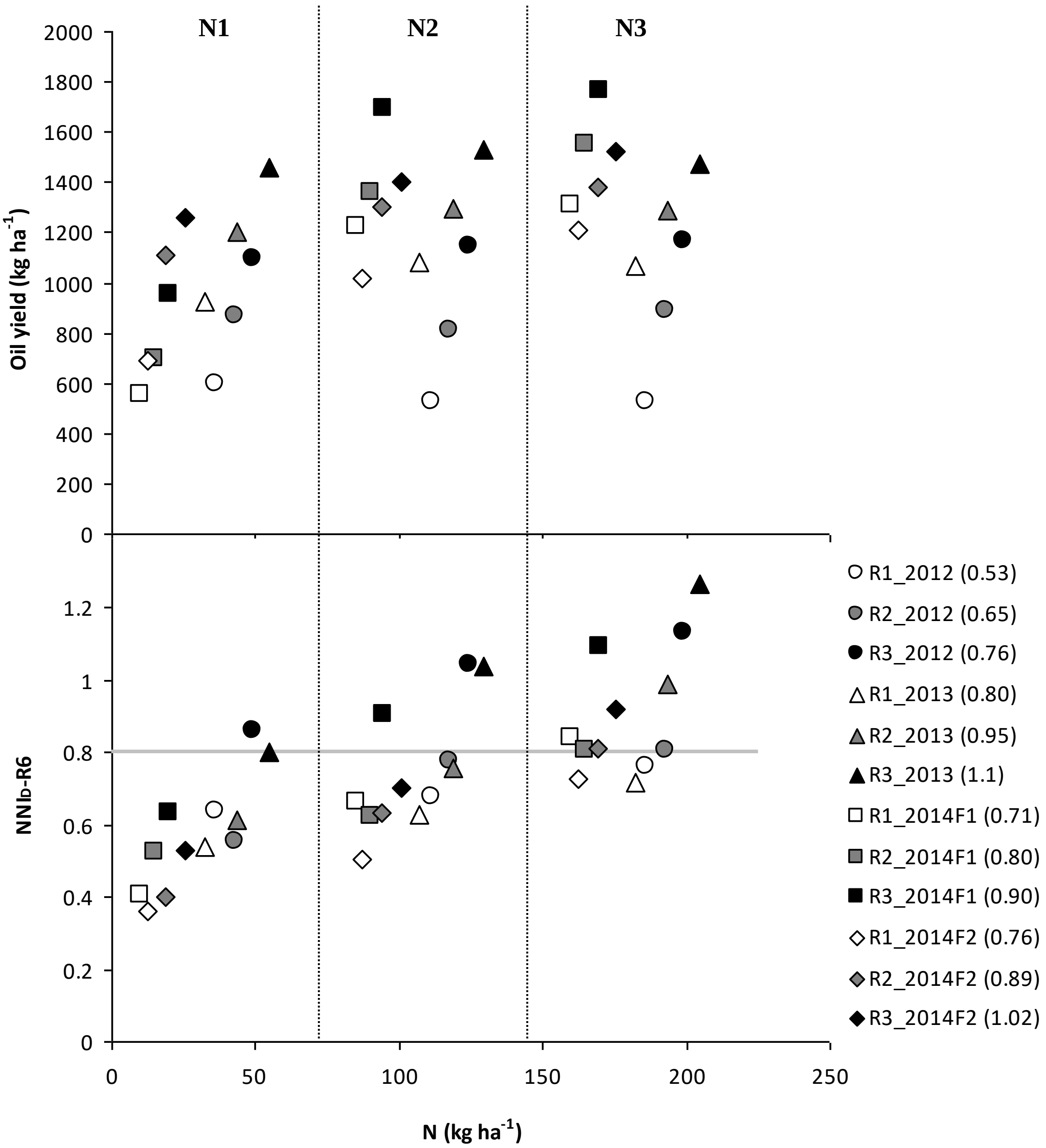

Figure 4. Correlation between N-supply and oil yield (a) and NNI$_D$-R6 (b) for each irrigation treatment considered in the study. In the legend, in parenthesis, the ratio between rainfall+irrigation and optimal supply for each treatment.

Analyzing the nutritional status with NNI for the four trials considered, a significant influence of water stress on yield was revealed (Fig. 3). Thus, yield response to NNI was clearly reduced when water stress was elevated. Thus, the R3-2012 treatment had elevated NNI$_D$-R6 values but yield was clearly under the envelope curve due to water stress; for R3-2013 and R3-2014F1 treatments, without severe water stress, yields were located nearby the envelope curve (Fig. 3). Similarly, evaluating the interaction between NNI and N supply, in addition to the increase in NNI_D-R6 values when N supply increased, NNI_D-R6 also increased as the volume of irrigation applied increased (Fig. 4b). On the other hand, high N-fertilization doses with deficit irrigation schedules generated low NNI_D-R6 values (for example, NNI_D for R1_during 2012, 2013 and 2014F2 was lower than 0.8 in spite of the N-fertilization dosage close to 200 kg ha^{-1}; Fig. 4b). Similarly, for a same amount of N supply, high differences in nutritional status of sunflower were determined (for example for a N supply around 100 kg ha^{-1}, NNI_D-R6 ranged from 0.5, i.e. severe deficiency, to 0.9, i.e. over fertilization) depending on the irrigation supply.

In spite of these relationships, the interaction Irrigation x N-Fertilization was not significant for the core variables (yield, oil content and oil yield; Table 5), meaning that the rate of variation (slope) of the effect of the N doses is similar, regardless of the irrigation supply received by the crop. Equally, analyzing NNI during the R6 growing stage, the ANOVA for each season confirm these results, showing no significance for the interaction Irrigation x N-Fertilization (data not shown), which is coherent with the results for yield and oil content.

2.5 Discussion

By using different irrigation schedules, different levels of water stress were generated and then, yield response of sunflower to different water/irrigation supply and water stress was accurately determined. Thus, logarithmic functions with a high level of fitting (R^2 values around 0.85; Table 6) confirm the excellent response of sunflower to irrigation and are in line with previous studies carried out by Connors et al. (1985), Cox and Jollif (1986) and Alvarez de Toro (1987). For water supply, the relationship with yield was similar, with significant reductions in crop yield when irrigation water supply was reduced to 60% of the optimal irrigation water requirements (Fig. 1). Equally, the clear yield response to water stress during the flowering-maturation period confirms the importance of this period for sunflower crops, with significant yield reductions when average $K_{s\text{-}FG}$ values during the flowering-maturation period dropped below 0.6 (Fig. 1). García-Lopez et al. (2014) confirmed similar yield reductions for rainfed sunflower when water and thermal stress during flowering was detected, and Göksoy et al. (2004), Karam et al. (2007) and Rinaldi (2001) also determined the flowering stage as the period most sensitive to water stress.

Table 6. Regression equations and coefficient of determination (R^2) for each yield component considering water stress during flowering-end grain filling period ($K_{s\text{-}FG}$), % of optimal water supply (rainfall + irrigation), and % of optimal irrigation applied.

	Avg. $K_{s\text{-}FG}$ coefficient (x)	**% of Optimal water supply (x)**	**% of Optimal irrigation applied (x)**
Yield (y) (kg ha^{-1})	$y=1142.3Ln(x)+2973.4$ $R^2=0.848$	$y=2430.6Ln(x)-8234.9$ $R^2=0.847$	$y=875.47Ln(x)-1090.5$ $R^2=0.6944$
Oil Yield (y) (kg ha^{-1})	$y=598.22Ln(x)+1417.2$ $R^2=0.8907$	$y=1280.3Ln(x)-4485.1$ $R^2=0.900$	$y=436.71Ln(x)-623.33$ $R^2=0.6617$
% Oil (y) (%)	$y=3.8963Ln(x)+48.224$ $R^2=0.3646$	$y=8.6134Ln(x)+8.5765$ $R^2=0.3931$	$y=1.7649Ln(x)+39.285$ $R^2=0.1043$
Head diameter (y) (cm)	$y=4.3009Ln(x)+17.855$ $R^2=0.7663$	$y=9.6434Ln(x)-26.505$ $R^2=0.8498$	$y=3.2205Ln(x)+2.8596$ $R^2=0.5989$
Total Weight (y) (gr)	$y=117.56Ln(x)+224.86$ $R^2=0.6633$	$y=276.94Ln(x)-1046.3$ $R^2=0.812$	$y=104.06Ln(x)-249.66$ $R^2=0.7245$
Seed Number (y) ( )	$y=307.93Ln(x)+1070.3$ $R^2=0.5881$	$y=749.37Ln(x)-2364.5$ $R^2=0.7683$	$y=221.16Ln(x)+34.661$ $R^2=0.4229$
Seed Weight (y) (gr)	$y=36.506Ln(x)+72.252$ $R^2=0.852$	$y=81.135Ln(x)-305.51$ $R^2=0.9514$	$y=29.105Ln(x)-62.167$ $R^2=0.7549$
Seed Weight 100 (y) (kg)	$y=2.1637Ln(x)+6.7381$ $R^2=0.8029$	$y=4.4116Ln(x)-13.647$ $R^2=0.7363$	$y=1.7625Ln(x)-1.3797$ $R^2=0.7426$

In spite of the excellent response of sunflower to irrigation, the optimal strategy must be based on suboptimal irrigation schedules according to on Fig. 1 and Table 6, where the slope functions fall significantly as the percentage of optimal water/irrigation requirements increases. The analysis, in keeping with Connors et al. (1985), concluded that irrigation water supply of around 60% of the optimal irrigation requirements was the optimal strategy given that values above this resulted in very limited yield increases. Similar conclusions were obtained when water productivity was considered. Thus, due to low IWP values obtained in this study (Table 7), IWP could be lower than the threshold of profitability for the irrigation practice to be considered profitable. This threshold for conditions in southern Spain was fixed at around 0.138 € m^{-3} (Lorite et al., 2012) and subsequently, irrigation schedules applied during the 2013 season generated IWP values below this profitability threshold (IWP was equal to 0.13 € m^{-3}), suggesting a reduction in the irrigation volumes is required. However IWP for the rest of the trials provided satisfactory values (0.40 € m^{-3} for 2012 and around 0.17 € m^{-3} for 2014; Table 7), with similar IWP values to those determined for traditional irrigated crops such as maize, cotton or sugar beet (0.26 € m^{-3}, 0.53 € m^{-3} and 0.56 € m^{-3}, respectively; Lorite et al., 2012). These results indicate that a moderate irrigation practice for sunflower provides similar advantages in terms of water productivity to irrigation for traditional irrigated crops, especially in dry seasons. In summary, the percentage of irrigation supply for sunflower crop must range between 60% and 80% of the optimal (defined by the irrigation schedule that avoids water stress throughout the crop cycle), which translates to around 2000 - 2500 m^3 ha^{-1} for the semi-arid conditions of southern Spain. This strategy would enable farmers to save water for other crops with higher water productivity, as per the irrigation scheme proposed by Lorite et al. (2007) for southern Spain. Rinaldi (2001) coincides with these values, determining volumes of around 2000 m^3 ha^{-1} to obtain the highest profitability.

Table 7. Water productivity (WP) and irrigation water productivity (IWP) for each trial considered in the study.

	IR1	IR2	IR3
2012			
WP (kg m^{-3})	0,33	0,4	0,44
WP (€ m^{-3})	0,18	0,22	0,25
IWP (kg m^{-3})	0,71	0,72	0,71
IWP (€ m^{-3})	0,4	0,4	0,4
2013			
WP (kg m^{-3})	0,27	0,27	0,29
WP (€ m^{-3})	0,09	0,1	0,1
IWP (kg m^{-3})	0,37	0,34	0,37
IWP (€ m^{-3})	0,13	0,12	0,13
2014-D1			
WP (kg m^{-3})	0,44	0,44	0,46
WP (€ m^{-3})	0,14	0,14	0,15
IWP (kg m^{-3})	0,57	0,52	0,55
IWP (€ m^{-3})	0,19	0,17	0,18
2014-D2			
WP (kg m^{-3})	0,36	0,4	0,4
WP (€ m^{-3})	0,12	0,13	0,13
IWP (kg m^{-3})	0,45	0,55	0,48
IWP (€ m^{-3})	0,15	0,18	0,16

When the dataset was broken down according to sowing date, the functions for early sowing date always generated higher yields. This is especially true in cases of low irrigation supply, when yields obtained for treatments with late sowing dates are significantly reduced (Fig. 1). The analysis of these functions shows the advantages of earlier sowing date for sunflower, especially when water availability is limited. Previous studies show that the use of earlier sowing dates for sunflower resulted in a simultaneous increase of leaf area duration and water uptake during the critical periods of the crop (Gimenez and Fereres, 1986; Gimeno, 1989), increasing the number of seeds per area without decreasing its weight, thus producing higher crop yields (Flagella et al., 2002; Barros et al., 2004).

The excellent coefficients of determination obtained for $K_{s\text{-}FG}$, % of water and irrigation supply vs. yield relationships (around 0.85, 0.85 and 0.69, respectively; Table 6 and Fig. 1) indicate the potential use of these functions for modeling sunflower yield, although this would require a prior process of regional validation under different weather conditions. These irrigation supply-yield relationships were asymptotic curves to a yield of around 3200 kg ha^{-1}, value considered as the maximum attainable yield for sunflower for the analyzed area, and coincides with maximum yields in previous studies carried out in the Andalusia region (García-Lopez et al., 2014).

Table 8. Yield, % of oil, oil yield and other components (head diameter, HD, total plant weight, TW, seed number, SN, seed weight, SW, and hundred seed weight, W100) for each N-fertilization treatment. Same letter for each season indicates non-statistically significant differences.

Year	**Treatment**	**Yield** (kg ha^{-1})	**% Oil** (%)	**Oil yield** (kg ha^{-1})	**HD** (cm)	**TW** (g)	**SN** (seeds $head^{-1}$)	**SW** (g)	**W100** (g)
2012	**0 N**	1971 (a)	43 (a)	852 (a)	13.4 (a)	119.6 (a)	669 (a)	36.9 (a)	5.3 (a)
	75 N	1946 (a)	42.3 (a)	828 (a)	13.5 (a)	119.1 (a)	705 (a)	37 (a)	5.2 (a)
	150 N	2020 (a)	42.3 (a)	861 (a)	13.5 (a)	115.7 (a)	702 (a)	35.9 (a)	5.1 (a)
2013	**0 N**	2507 (b)	47.7 (a)	1195 (a)	15.3 (c)	170.2 (c)	878 (b)	52 (c)	5.6 (c)
	75 N	2774 (a)	47 (ab)	1301 (a)	17.1 (b)	225.4 (b)	950 (b)	62.7 (b)	6.3 (b)
	150 N	2820 (a)	45.5 (b)	1277 (a)	19 (a)	281.5 (a)	1144 (a)	79.7 (a)	6.8 (a)
2014-D1	**0 N**	1523 (c)	47.7 (a)	736 (b)	14.5 (c)	115.1 (c)	749 (c)	40.1 (c)	5.1 (b)
	75 N	2921 (b)	48.6 (a)	1425 (a)	17.1 (b)	173.8 (b)	955 (b)	58.2 (b)	6 (a)
	150 N	3382 (a)	45.5 (b)	1542 (a)	18.6 (a)	202.2 (a)	1091 (a)	68.5 (a)	6.2 (a)
2014-D2	**0 N**	2073 (b)	49.2 (a)	1020 (b)	14.8 (c)	147 (b)	985 (b)	51.5 (c)	5.2 (b)
	75 N	2520 (a)	49.1 (a)	1239 (a)	15.9 (b)	172.1 (b)	1084 (ab)	64.4 (b)	5.9 (a)
	150 N	2807 (a)	48.9 (a)	1371 (a)	17.2 (a)	202.1 (a)	1200 (a)	74.8 (a)	6.2 (a)

An additional advantage of irrigation practices for sunflower cultivation was the decrease of canopy temperature. Some studies on rainfed sunflower indicated the importance - in terms of yield - of temperature during the flowering stage (Ploschuk and Hall, 1995; Guilioni and Lhomme, 2006; García-Lopez et al., 2014), with significant yield reduction when heat stress occurred during flowering. Sowing date and irrigation practices are factors that affected the impact of heat stress; similar maximum temperatures during flowering were detected in 2012 and 2013 (Table 2), however significant yield reductions were only found for 2012, whereas 2013/IR3 recorded the maximum yield of the whole dataset (Table 3). This fact represents an additional benefit of irrigation, as irrigation during flowering stage mitigates the negative impact of high temperature on the crop (for 2013/IR3 a yield reduction of around 20% caused by heat stress was estimated by the approach developed by García-Lopez et al., 2014). Other studies have confirmed the alteration of canopy temperature by the use of irrigation at local and regional scale (Steiner et al., 1983; Mahmood et al., 2006; Lobell et al., 2008), due to the increase of soil moisture and latent energy flux reducing the sensible heat flux for near-surface heating, even for drip irrigation and for tall crops (Nainanayake et al., 2008).

There was a statistically significant trend of increasing yield and other yield components as the N-fertilization level increased, except for the 2012 season. This result is in line with previous studies (Zubriski and Zimmenman 1974; Blamey and Chapman 1981; Steer et al., 1986; Scheiner and Lavado, 1999; Halvorson et al., 1999; Ruffo et al., 2003; De Giorgio et al., 2007; Oyinlola et al., 2010). However this trend was less clear than the response for water/irrigation supply (Tables 4 and 8), and the differences in yield and yield components among N-treatments were not significant for some treatments and years (for example only for 2014 trials were there significant differences in oil yield between the N1 and the rest of the treatments). Analyzing seed oil concentration (% Oil) N-fertilization caused a consistent decline in % Oil of sunflower plants as a consequence of increased protein content in the seed (Blamey and Chapman, 1981; Steer et al., 1986), and subsequently, the highest oil concentration was detected with N1 treatments. Finally, the increase in yield when N-fertilization increased was mainly caused by the increase in NS - in line with Steer et al. (1984), Connor and Hall (1997), and Lopez Pereira et al. (1999), all of which concluded that SN was the yield component most significantly correlated with grain and oil yields.

As the correlation between NNI_D-R6 and observed yield values did not provide a clear fitting as factors as heat or water stress affected, this type of relationship does not then seem to be of use for yield modeling but could be utilized to determine potential yield depending on N status (using NNI_D-R6). However, in order to determine optimal N-fertilization dosage, the consideration of irrigation supply is particularly relevant. Similar levels of fertilization generated different NNI_D-R6 values depending on water supply (Figs. 4b). Consequently, there is a need to consider beforehand the amount of water for irrigating the crop to determine optimal fertilization levels. Thus, if water supply meets the crop water requirements, total N supply around 150 kg ha^{-1} would be required under the weather and field conditions detected in this study, and then, for some treatments, considering N in the soil at sowing and in the water irrigation, no additional fertilization was required (for R3_strategy during 2012 and 2013 NNI_D-R6 values for N1 were equal to 0.86 and 0.80, respectively; Fig. 4). Previous studies determined a wide range of optimum N-fertilization under irrigated conditions, ranging from 75 kg ha^{-1} and even lower (Zheljazkov et al., 2012) to requirements close or even higher than 200 kg ha^{-1} (Zubillaga et al., 2002; Ruffo et al., 2003; Gholinezhad et al., 2009; Sincik et al., 2013), confirming the necessity to consider additional factors for determining N-fertilization recommendations. On the other hand, if severe water stress is foreseen, acceptable values of NNI_D-R6 will only be obtained using high levels of N-fertilization; thus, in N3 experiments NNI_D-R6 values were equal to 0.72 for 2013-IR1 and 2014-D2-IR1 (Fig. 4b). However in spite of these acceptable NNI_D-R6 values, N-fertilization under these water stress conditions did not generate increase in yield (Figs. 3 and 4a).

Alternatively, a low N-fertilization supply may not be the cause of a low NNI_D-R6, since a limited water supply has a similar effect in terms of NNI_D-R6. Confirming these results, Merrien et al (1998) determined a very low utilization of the applied fertilization in sunflower compared to other crops such as wheat, and Blanchet et al. (1987) concluded that in spite of a high N-fertilization, a weak response could be detected when water is a limiting factor. Thus, under rainfed conditions optimal N recommendations were lower than for irrigated (Sincik et al., 2013) due to the limited impact on yield of increases in N-supply under severe water stress (Gholinezhad et al., 2009).

The consideration of new approaches, such as the one proposed by Debaeke et al. (2012), for determining the nutrient status of sunflowers has provided more reliable figures than traditional approaches, such as that proposed by Merrien et al. (1992), which has been extensively used in South America to diagnose the nutritional status of sunflower crop (Diaz-Zorita, 2002; de Caram et al., 2007). Thus, analyzing the NNI values calculated using both methodologies, significant differences appeared between approaches (Fig. 2). Debaeke et al. (2012) warned of underestimations in the detection of N deficiency when the methodology developed by Merrien (1992) was used. Thus, in this study, IR3/0N treatment showed elevated NNI-R6 values using Merrien’s approach (1.06 and 0.98, for 2012 and 2013, respectively) indicating over-fertilization in both seasons, a questionable conclusion as no fertilization was carried out. However, when considering Debaeke’s approach, results for NNI-R6 were equal to 0.86 and 0.80 for 2012 and 2013 - values that are still high but more reasonable.

Significant uncertainties have been detected in the development of this study, especially for those components related with N-fertilization with limited fertilization and irrigation supply. Thus, the effect of N and irrigation supply in the absorption of N by the crop generated significant knowledge gaps due to the complexity of the involved processes. The consideration of correlations between yield and nutrient crop status reduced significantly the uncertainty as the correlations were carried out considering real N absorbed by the plant. In this study the conclusions related with the interaction irrigation-N fertilization were confirmed using NNI studies, providing a solid scientific base for carrying out N-fertilization recommendations to farmers and technicians.

2.6 Conclusions

Irrigation of traditionally non-irrigated crops such as sunflower under semi-arid conditions has proved useful. Correct irrigation practices produced higher yields, due to the reduction of water stress and by the mitigation of heat stress during flowering, and higher water productivity values. Furthermore, sub-optimal irrigation scheduling (with around 60-80% of the optimal irrigation schedules) is recommended, especially under limited rainfall conditions. Similar to the beneficial effects of irrigation on sunflower crop, early sowing dates has a mitigating effect on heat and water stress. In our study, an earlier sowing date (around 45 days in advance) led to an increase in sunflower yield of around 11.4 %.

Similar benefits of N-fertilization were demonstrated for sunflower, although crop water status is of critical importance as a clear interaction between yield response to water and fertilization was shown. Thus, the response of sunflower yield to N-fertilization is affected by water stress, and consequently treatments with deficit irrigation had a much smaller response to N-fertilization. The NNI index has proved to be an excellent tool for determining the N-fertilization status of the crop, leading to agronomic practices that generated higher N fertilization levels in the crop, and confirmed N-fertilization recommendations of around 100 and 150 kg ha^{-1} for stressed and non-stressed sunflower fields, respectively.

The integration of irrigation and N-fertilization treatments and the analysis of the nutritional status of the crop for each treatment have provided guidelines to improve irrigation water management and fertilization for sunflower crops in the semi-arid conditions of southern Spain. However, in spite of the satisfactory results of this study, further studies about the interaction between irrigation and fertilization supply and other agronomic practices such as sowing date, crop cycle or planting density are still required.

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Capítulo 3: Improving the sustainability of farming systems under semi-arid conditions by enhancing crop management

3.1 Abstract

Under semi-arid conditions, water is the most limiting factor for ensuring the sustainability of Mediterranean agriculture. Proper management of practices such as irrigation, fertilization, and changes in sowing date and sowing density can contribute decisively to efficient water management in these agricultural systems. Thus, the aim of this study was to assess the effect in terms of yield and profit of combining those agricultural practices, and subsequently to define strategies for the sustainable intensification of semi-arid agricultural systems in southern Spain. The study focused on sunflower as a representative crop.

Sustainable intensification practices were evaluated through a series of experiments, revealing the prominent role played by water availability in their performance. Thus, high sowing density provided much more satisfactory yield results compared to the traditional sowing density, and it was observed that this yield increase was related to water availability: higher yield increases (around 27%) were obtained with deficit irrigation strategies than under severe deficit irrigation or rainfed conditions (around 16%). Other intensification strategies such as support irrigation and early sowing date also generated satisfactory yield increases (around 45% and 30%, respectively). Finally, interactions between irrigation and fertilization indicated that under limited water availability, very low N-fertilization rates were required. All these results led to the conclusion that the combination of high sowing densities, early sowing date, deficit irrigation and limited fertilization constitutes an innovative intensification strategy for sunflower under semi-arid conditions.

An economic analysis of the proposed agricultural practices also revealed a clear connection between water availability and optimized management of sowing density, sowing

date and fertilization. These results confirmed that technical advisory services provided to farmers should focus on integrated site-specific crop management, especially under semi-arid conditions with severely limited water availability.

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3.2 Introduction

Rainfed agriculture plays a significant role in the agricultural systems of Southern Europe. This type of agriculture is mainly based on specific low-input cultivation techniques for wheat, sunflower and legume crops that allow efficient and effective use of limited soil moisture. Agriculture is one of the sectors most vulnerable to the impact of global climate change (Tingem et al., 2009) and rainfed systems are especially vulnerable to changes in weather conditions (Valverde et al., 2015). The General Circulation Models (GMCs) of the Intergovernmental Panel on Climate Change (IPCC) have predicted strong warming over western and southern Europe during summer, especially in the southwestern parts (France, Spain and Portugal), increases in mean summer temperatures (exceeding 6ºC by the end of the century) and substantial decreases in summer precipitation in southern and central Europe (IPCC, 2014). Furthermore, heat waves and droughts are predicted to occur more often due to the combined effect of warmer temperatures and less precipitation (Lotze-Campen, 2011).

Spain has a total of 17 M ha of farmland, of which only 3.5 M ha are cultivated under irrigation while the rest are rainfed crops. In these rainfed systems, sunflower is a relevant crop. Globally, the European Union is the third largest sunflower producer in the world behind Ukraine and Russia (MAPAMA, 2016). Spain ranks fourth or fifth in terms of EU countries' sunflower yield, depending on climatological factors, mainly drought. By cultivated area, it lies in third place behind Romania and Bulgaria. In 2016 in Spain, around 730,000 ha was dedicated to sunflower cultivation, and in Andalusia, the region with the largest cultivated area, this crop was cultivated on around 260,000 ha, of which only 5% was cultivated under irrigation (MAPAMA, 2016).

Consequently, the sunflower crop in its traditional production areas, such as the Guadalquivir Valley in Andalusia, will be exposed to severe impacts of climate change related to water shortages and high temperatures (Debaeke et al., 2017), especially when these climatic conditions happen during the critical periods of the crop cycle, from early flowering to the achene filling stage (García-López et al., 2014). In addition to these impacts, the scarcity of available adaptation strategies for rainfed agriculture could be a limiting factor for the future economic sustainability of agricultural systems cultivated with sunflower. Throughout history, farmers have responded to changes in the environment by adopting new crop cultivars and by adjusting their cultural practices (Gala Bijl and Fisher, 2011). At the farm level, examples of these adaptations include alterations in planting and harvest dates, changes in cropping sequence, better water management in irrigation systems, optimized use of fertilizers, and adoption of improved tillage practices (Adam et al., 1998).

In addition to the concerns related to climate change, the productivity of rainfed sunflower under Mediterranean conditions is currently low (Figueiredo et al., 2017) and is strongly dependent on water availability and the water use efficiency of the crop (Barros et al., 2004; Soriano et al., 2004). Water is by far the most limiting factor for rainfed sunflower production, although other factors such as temperature during flowering stage (García-Lopez et al., 2014), fertilization (García-Lopez et al., 2016), sowing date and sowing density may show an influential interaction with water supply (Diepenbrock et al., 2001; Barros et al., 2004). Thus, the abovementioned limiting factors relating to future climate change will require combining production intensification strategies with strategies aimed at improving the efficiency of the systems. These practices have recently been integrated under the term sustainable intensification (Gadanakis et al., 2015; Kumar et al., 2018).

The implementation of efficient deficit irrigation practices is one of the main sustainable intensification actions proposed for sunflower systems in southern Spain (García-Lopez et al., 2016) although the irrigation of low-income crops such as sunflower is not yet common (Lorite et al., 2012). Equally, proper management of sowing density is one of the most widely-recommended agricultural practices to achieve an increase in crop productivity (Escalante-Estrada et al., 2008; Jia et al., 2018). Thus, an appropriate number of individual plants per unit area may enable a better use of water and nutritional resources. Increasing density reduces biomass and yield per plant but biomass production and seed yield per unit area are higher (Vega-Muñoz et al., 2001). The optimum sowing density for sunflower is influenced by several factors such as temperature, soil fertility, water availability and genotype (Villalobos et al., 1994; Diepenbrock et al., 2001). In recent years, the need to increase yields, and thereby to improve crop productivity and profitability, has encouraged an increase in sowing density. This practice has been promoted in response to the negative trend in sunflower yields in Andalusia since the late 80s (García-Ruiz et al., 2008). This decline may have been caused by the sudden appearance of sunflower broomrape (*Orobanche cumana Wallr*) in traditional areas of cultivation, which led to the substitution of older varieties that were highly productive but also very susceptible to the parasite (García-Ruiz et al., 2008). Therefore, seed companies' primary objective has been to quickly breed broomrape-resistant varieties, leaving yield and oil content as a lower priority.

Another agricultural practice in semi-arid Mediterranean environments is the implementation of early sowing dates (Nouri et al., 2017), allowing the crop to benefit from moderate temperatures at the end of the crop cycle (García-Lopez et al., 2014) and from late winter rainfall, reducing the volume of water required to sustain the yield (Sarno et al., 1992; Soriano et al., 2004; García-Lopez et al., 2016). Conversely, the delay in sowing date shortens the growing cycle, decreasing the amount of radiation intercepted during the growing season and thus, the total dry matter at harvest (Andrade, 1995; Sunderman et al., 1997). Therefore, to maximize the use of natural resources, the selection of an appropriate sowing date is a critical issue since it ensures good seed germination, as well as the timely appearance of seedlings and the optimum development of the root system. Equally, a suitable sowing date allows the critical periods for oil yield and its components to overlap with the part of the growing season when the most environmental resources are available (Balalic et al., 2012). The practice of winter sowing for sunflower in Andalusia was first developed in the 1980s. Studies carried out during that period in the region, such as Gimeno et al., (1989), showed clear increases in yield, of up to 30% over the usual yield for the area. However, this shift in the sowing date was not put into practice by the farmers because of the difficulty in carrying out proper weed control. Weed interference increases the risk of crop yield losses, despite the technological progress made in weed control (Korres, 2016). An advance in the sowing date resulted in a greater abundance of winter weeds, which in the conventional spring sowings are easily controlled by land tilling prior to planting. Under these circumstances the sowing density is key to effective inter-row tillage: the distance between the sowing lines must be at least 65 cm, which entails densities from around 60,000 plants/ha. This is a critical requisite, as in the past it was not feasible to integrate an early sowing date with high sowing density. With the appearance in recent years of herbicide-resistant cultivars (Clearfield and ExpressSun technology), a clear opportunity to solve those limitations has been identified, but new research studies are needed to be able to take advantage of these opportunities.

Finally, correct fertilization coordinated with the irrigation supply constitutes an essential factor for optimal crop management (Debaeke et al., 2006; Sinha et al., 2017), and represents a useful sustainable intensification technique, especially in systems affected by severe water stress (García-López et al., 2016).

Despite their low profitability, extensive crops play an important role in the agriculture systems of southern Europe. However, while previous studies have described a significant number of agronomic practices for increasing the crop sustainability of extensive crops such as maize (Welde and Gebremariam, 2016) or wheat (Abolpour, 2018), few studies have done so for sunflower.

Given the new challenges described above, and in order to fill the gap in the literature specifically regarding sunflower, the main objective of this study was to evaluate different sustainable intensification strategies for Mediterranean agricultural systems cultivated with sunflower. The strategies analyzed were increases in sowing density, changes in the sowing dates, and limited irrigation and fertilizer supply; furthermore, the interaction between these strategies was also assessed, in order to determine whether these new crop management approaches have a positive influence on the economic sustainability of these agricultural systems.

3.3 Materials and methods

3.3.1. Field experiments with sustainable intensification practices

Four sustainable intensification practices related to sowing date and density, irrigation, and fertilization management (Fig. 1), and their interactions with water availability, were evaluated through a study conducted during six growing seasons (from 2012 to 2017) in three experimental fields located at “IFAPA-Alameda del Obispo” (Córdoba), “IFAPA-Tomejil” (Carmona) and “IFAPA-Rancho de la Merced” (Jerez de la Frontera), in Andalusia, southern Spain (Fig. 2). The climate in Córdoba and Carmona, both located in the Guadalquivir Valley, is considered semi-arid, with the rainy period concentrated between autumn and spring, and with a very hot, dry summer season. Different weather conditions are found in Jerez, which is located on the coast, with a different rainfall pattern, lower maximum temperatures, and higher relative humidity.

At the “IFAPA-Alameda del Obispo” experimental farm, located near the city of Córdoba (latitude 37º 51´ 42´´N, longitude 04º 48´ 0´´W) two trials were carried out during the 2012 and 2013 seasons, aimed at evaluating the interaction between fertilization and irrigation supply. In addition, during the 2016 and 2017 seasons, two trials were run to evaluate the interaction between sowing density and irrigation supply (Table 1). The 2012 and 2013 trials are fully described in García-Lopez et al. (2016). The 2016 and 2017 trials were arranged as strip-plot designs with four replications, where irrigation rates were the main plots and sowing density were the sub-plots. Experimental plots consisted of 4 rows with a North-South orientation, 10 m long, 70 cm apart and two distances between plants within rows (20 and 15 cm), resulting in plant populations of around 70,000 (D2) and 95,000 (D1) plants/ha, respectively. Both trials were seeded with LG-5537 HO cultivar (Limagrain). For the irrigation treatments, a drip irrigation system with 75 cm drip emitter spacing was used. Two strategies were considered in these treatments: providing around 15% and 40% of the full irrigation requirements of the crop for R1 and R2 strategy, respectively. Thus, for each year and trial different irrigation scheduling was used, providing 82, 246, 123 and 232.5 mm for the trials CO-2016-R1, CO-2016-R2, CO-2017-R1 and CO-2017-R2, respectively, representing 12.8, 38.5, 19.9 and 37.7 % of the full water requirements. Full irrigation scheduling was based on a water balance approach described later in Section 3.3.2.

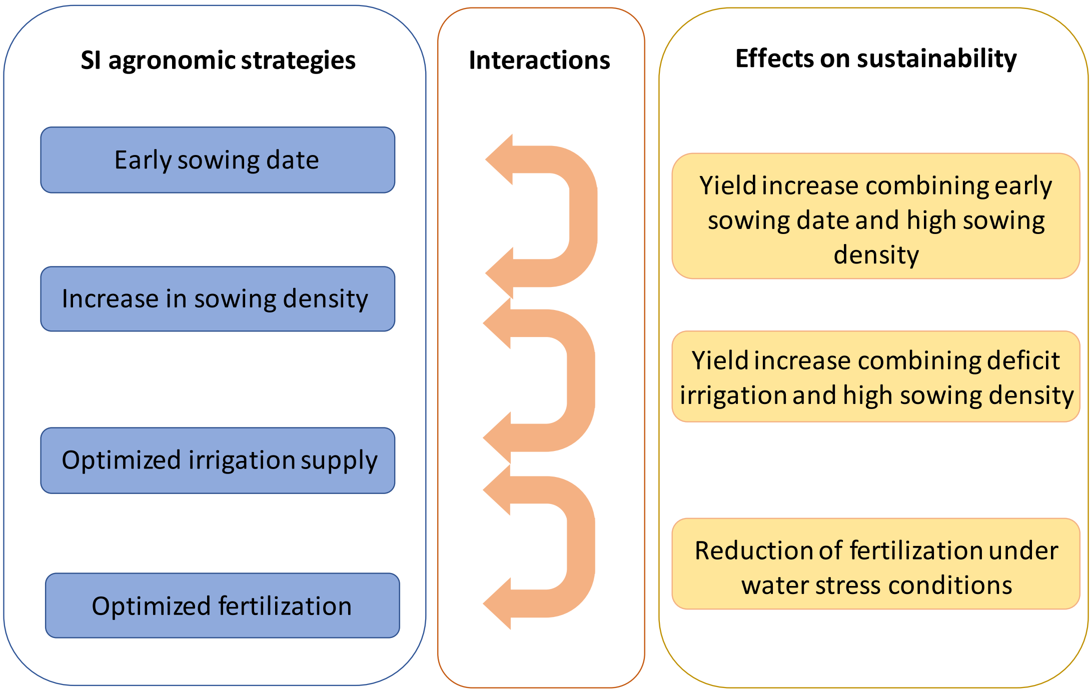

Figure 1. Sustainable intensification agronomic strategies, interactions between them, and effects on the sustainability of sunflower-based agricultural systems in southern Spain

The other six trials were carried out under rainfed conditions: one located in “IFAPA-Rancho de la Merced” experimental farm situated near the city of Jerez de la Frontera (Cádiz) (latitude 36º 38´33´´N, longitude 06º 00´ 48´´W) in 2015, and five located in “IFAPA-Tomejil” experimental farm situated near the city of Carmona (Seville) (latitude 37º 24´ 07´´N, longitude 05º 35´ 10´´W) in 2014, 2015 and 2017 (Table 1). All of them were arranged as strip-plot designs with four replications, where the main factor was sowing density and the secondary factor was varieties. In addition, in 2015 and 2017 in the trials carried out in "IFAPA-Tomejil", two different sowing dates were used per year: conventional sowing dates (S2) and winter sowing dates (S1; Table 2). Experimental plots consisted of 4 rows (70 cm apart) or 6 rows (40 cm apart), 10 m long and 25 cm between plants within rows, obtaining approximate densities of 60,000 (D2) and 100,000 (D1) plants per hectare, respectively. For the trial conducted in 2014 and the three trials carried out in 2015, three cultivars were used: one hybrid resistant to race F of sunflower broomrape (*Orobanche cumana* Wallr), one hybrid resistant to Pulsar40 herbicide (based on Clearfield technology) and one hybrid resistant to Granstar50 herbicide (based on ExpressSunTM technology). The Clearfield technology consists of hybrids with resistance to herbicides of the imidazolinone family and the ExpressSunTM technology involves hybrids that are tolerant to a herbicide of the sulfonylureas family. Lastly, for the two trials of 2017, only two varieties were used, the hybrid resistant to the race F sunflower broomrape and the hybrid with Clearfield technology.

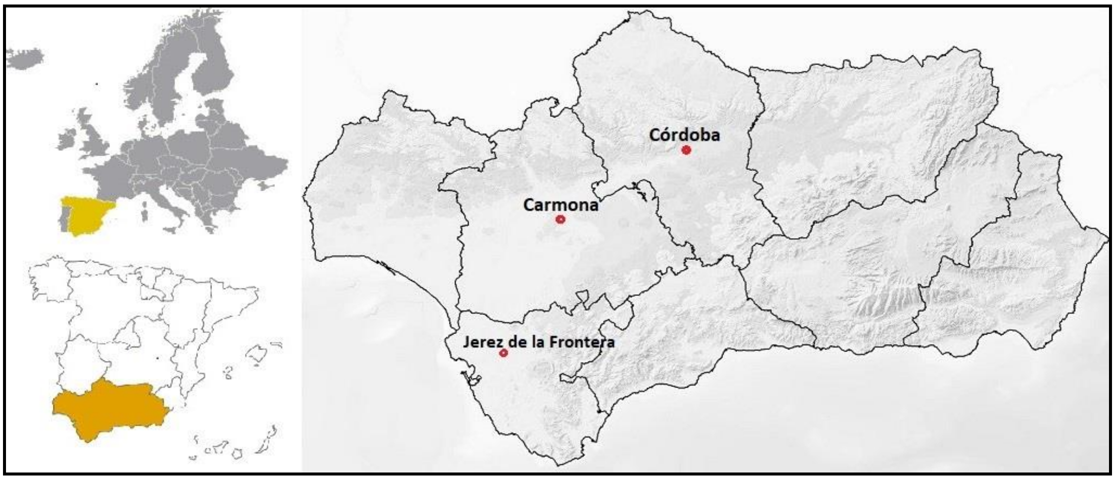

Figure 2. Location of the three experimental fields in the study

Table 1. Weather conditions (rainfall, annual reference evapotranspiration, ET_o, seasonal reference evapotranspiration from flowering to end of grain filling, ET_o (F-EGF), maximum temperature during flowering, and mean maximum temperature from flowering to end of grain filling for each trial.

Year	Location	Code Trials	Rainfall	ET_o	ET_o (F-EGF)	Max T^a (F)	Mean T^a max (F-EGF)
			(mm)	(mm)	(mm)	(ºC)	(ºC)
2014	Tomejil	TO-2014-R0	389.3	1348.9	131.9	39.8	31.7
2015	Jerez	JE-2015-R0	688	1145.6	174.9	36.6	29.4
2015	Tomejil	TO-2015-S1-R0	387.2	1269.4	183.8	40.7	32.6
2015	Tomejil	TO-2015-S2-R0	387.2	1443.2	148.3	37.1	31.7
2016	Córdoba	CO-2016-R0/R1/R2	518.5	1314.3	166.4	41.7	35.3
2017	Tomejil	TO-2017-S1-R0	456.9	1240.8	176.1	39.1	32.8
2017	Tomejil	TO-2017-S2-R0	456.9	1396.5	182.9	42.9	36.7
2017	Córdoba	CO-2017-R0/R1/R2	541.6	1290.2	162.1	42.4	35.2

In each trial and replication, phenology stages were identified (Table 2) by periodical visits to experimental fields. In addition, seed yield and seed oil content were assessed by harvesting all the plants from the two central rows of the trials to avoid crop border effects. Seed oil content was estimated using Nuclear Magnetic Resonance (NMR) spectroscopy.

Table 2. Crop phenology for each trial

Year	Location	Code Trials	Sowing date	Emergence	Flowering (50%)	End grain filling	Harvest
2014	Tomejil	TO-2014-R0	5 Mar	23 Mar	29 May	17 June	31 July
2015	Jerez	JE-2015-R0	13 Jan	28 Jan	9 May	6 June	5 Aug
2015	Tomejil	TO-2015-S1-R0	26 Jan	12 Feb	11 May	5 June	14 July
2015	Tomejil	TO-2015-S2-R0	11 Mar	31 Mar	25 May	14 June	3 Aug
2016	Córdoba	CO-2016-R0/R1/R2	30 Mar	15 Apr	18 June	10 July	18 Aug
2017	Tomejil	TO-2017-S1-R0	31 Jan	15 Feb	17 May	11 June	8 July
2017	Tomejil	TO-2017-S2-R0	16 Mar	3 Apr	12 June	2 July	27 July
2017	Córdoba	CO-2017-R0/R1/R2	2 Mar	13 Mar	28 May	19 June	3 Aug

3.3.2. Crop water requirements, irrigation scheduling and fertilization

Irrigation scheduling and crop water stress assessment for each irrigated trial were computed using a water balance approach based on Allen et al. (1998) and previously described in García-Lopez et al. (2016). Thus, using a cascade approach, a daily water balance was computed for each field including rainfall and irrigation as inputs and superficial runoff, deep percolation, soil evaporation and crop transpiration as outputs (Lorite et al., 2004).

A key component of crop water stress and irrigation scheduling is the accurate assessment of crop water requirements using crop coefficients (Allen et al., 1998). In this study, the methodology for assessing crop basal coefficients (K_{cb}) entailed assessing crop ground cover by means of overhead digital pictures using the GreenCrop Tracker software (Pattey and Liu, 2010). These pictures were taken with variable temporal frequency, depending on the crop stage (Table 2). Daily K_{cb} values were calculated based on the available images and using an interpolation technique based on a spline function (Santos et al., 2008; Trezza et al., 2013). These daily values and the reference evapotranspiration (ET_o) provide the crop transpiration, the key component for assessing crop water requirements. Weather data and ET_o were collected by automated weather stations located near the experimental fields, which form part of the Agroclimatic Weather Network of Andalusia (Cruz-Blanco et al., 2015).

The water balance was initialized on 1st September of each year, considering the soil water content equal to 20% of the total soil storage, taking into account the previous crop and the weather conditions (García-Lopez et al., 2016). Full irrigation scheduling was defined as that which avoided stress throughout the crop cycle but without generating over-irrigation. This was achieved by ensuring that the water stored in the soil at the end of the crop cycle did not exceed 20% of the maximum water storage (García-Lopez et al., 2016).

Finally, based on experimentation described in García-Lopez et al. (2016), a positive correlation between yield (*y*) and N-supply (*x*) was found when the ratio of rainfall plus irrigation supply to optimal water supply to avoid crop water stress (RWS) was higher than 0.75 ($y = 2045.8x^{+0{,}053}$ and $y = 1898.3x^{+0{,}0721}$ for RWS equal to 0.76 and 0.95, respectively). However, the correlation was negative for RWS values around 0.5 ($y = 1839.1x^{-0{,}072}$ for RWS equal to 0.53).

3.3.3. Scenarios

Simulation scenarios were conducted to examine economic components related to irrigation and sowing density, fertilization and irrigation, and sowing date and sowing density under rainfed conditions. In these studies, the profitability of sunflower is defined according to sunflower price, seed costs and irrigation water/fertilizer supply and cost. Depending on the source and availability of irrigation water and N-fertilization, cost can vary widely. In the first study, profit was calculated depending on sowing density (71,000 and 95,000 seeds/ha), irrigation supply (rainfed, severe deficit and non-severe deficit irrigation) and water cost ranging between 6 and 14 cents/cubic meter. In addition, a fixed cost of 145 € per 150,000 seeds was set, and 150 €/ha for other costs such as soil management, fertilization, etc. For both irrigated and rainfed systems, three sunflower prices were considered based on previous and future projections: 200, 350 and 500 €/ton. In the second study, sunflower profit was calculated considering irrigation supply (severe, deficit and full irrigation) and cost (6 cents/cubic meter), and fertilizer supply (10, 50, 100 and 150 N-units/ha) and costs (1.8 and 3.6 €/N-unit), with an additional fixed cost of 100 €/ha, and sunflower price equal to 350 €/ton. Yield functions were developed based on the results obtained in the experimental trials under irrigation in “IFAPA-Alameda del Obispo” and under rainfed conditions in “IFAPA-Tomejil”.

Thresholds of profitability are defined as the irrigation water cost generating no profit; a higher cost would generate economic losses, implying that irrigation is not advisable.

Table 3. Observed yield and oil content for each experiment in the study. Same letter for each trial indicates non-statistically significant differences.

Experiment code	**Yield** (kg/ha)		**%OC**		**Irrigation supply** (m^3/ha)
	D1	**D2**	**D1**	**D2**	
TO-2014-R0	1714 a	1171 b	47.5 a	46.8 a	0
TO-2015-S1-R0	1445 a	1422 a	46.0 a	47.3 a	0
TO-2015-S2-R0	1284 a	1001 b	42.5 a	43.4 a	0
JE-2015-R0	3311 a	2624 b	50.4 a	49.9 a	0
TO-2017-S1-R0	1612 a	1531 a	42.4 a	43.0 a	0
TO-2017-S2-R0	1161 a	1191 a	40.2 a	40.7 a	0
Avg. Rainfed Experiments	**1754.5**	**1490**	**44.7**	**45.2**	
CO-2016-R2	2327 a	1885 b	45.8 a	45.0 a	2462
CO-2016-R1	1834 b	1371 c	40.6 b	40.1 b	820.8
CO-2016-R0	1364 c	1268 c	41.4 b	41.4 b	0
CO-2017-R2	2180 a	1668 bc	48.6 a	46.4 b	2325.6
CO-2017-R1	1734 b	1711 b	47.9 ab	46.5 b	1231.2
CO-2017-R0	1666 bc	1365 c	43.8 c	44.1 c	0
Avg. Irrigated Experiments	**1850.8**	**1544.7**	**44.7**	**43.9**	

3.4. Results

3.4.1. Interactions between sowing density and sowing date under rainfed conditions

Average yield increased by 17.8% (from 1490 to 1755 kg/ha) with the highest sowing density (D1; 100,000 plants/ha) relative to D2 (60,000 plants/ha) (Table 3). Breaking results down by location, experiments located in Jerez (JE) showed the highest yields of all the rainfed trials (R0): the highest sowing density (D1) produced over 3,300 kg/ha, an increase of 26% compared with the lower density (D2), with this difference being statistically significant (Table 3). Experiments in Tomejil (TO) also showed differences between the two densities for seed yield, with D1 achieving a yield around 12.5% higher than D2, being statistically significant for TO-2014 and TO-2015-S2. On the other hand, seed oil content revealed no significant differences between densities in any of the tests carried out in both locations during the three seasons (Table 3).

Equally, sowing date had a great impact on yield, resulting in average yields of 1502.4 and 1159.3 kg/ha for early (S1) and traditional sowing dates (S2), respectively (Table 3). Increases in seed yield were observed with early planting dates for the two years tested, reaching 25.5 and 33.7%, respectively, although significant differences were only found in 2017 (Table 3). Similarly, significant differences in oil content were found in the two trials, with S1 registering increases of 8.4 and 5.4%, respectively, over S2 (Table 3).

When evaluating the effect of sowing density with different sowing dates on yield, increases in yield were found when sowing density was increased for both early sowing date (S1) and late sowing date (S2), although the increases were higher with S2. Thus, the increase using D1 compared with D2 was equal to 3.5 and 11.5% for S1 and S2, respectively. However, the highest yields were found with D1/S1 strategies, and the lowest with D2/S2 (Table 3).

3.4.2. Interactions between sowing density and irrigation supply

The volume of irrigation supply had a positive effect on yield under deficit irrigation (R2) and severe deficit irrigation (R1) compared with rainfed experiments (R0). Thus, average yields increased by 17.4 and 42.3% with R1 and R2 irrigation treatments, respectively, compared to R0 (Table 3). Yield differences between R2 and R0 were significant in 2016 and 2017, but no significant differences in yield between R1 and R0 were found. Analyzing seed oil content (% OC), this increased when irrigation supply increased. Thus, % OC was 42.7, 43.8 and 46.4% for rainfed, R1 and R2, respectively (Table 3). Deficit irrigation treatment (R2) showed a significantly higher oil content than for R0 in both years, whereas differences between R1 and R0 resulted in significant differences only for 2017 trials (Table 3).

In deficit and severe deficit irrigated trials, sowing density had a significant impact on yield. Thus, yield increased with high density sowing (1851 vs. 1545 kg/ha, for D1 and D2, respectively). However, this effect of sowing density on yield was influenced by the water availability (Table 3). The yield increase from traditional sowing density (D2) to high (D1) was equal to 15.1, 15.7 and 26.9% for R0, R1 and R2, respectively. Oil content showed a similar pattern, albeit with smaller differences between treatments. Thus, oil content increased under high density sowing (D1) (44.7 vs. 43.9% for D1 and D2, respectively) and was affected by the water availability, with the highest increase (around 4.1%) registered for R2 and the lowest for R0 (Table 3).

3.4.3. Effect of the interactions between sowing density, sowing date and irrigation supply on profit

The evaluation of the profit curves under different irrigation strategies and sowing densities for the current sunflower price (350 €/ton) revealed two clear patterns. High density (D1) generated curves with a positive slope, especially when the irrigation supply was above 1000 m^3/ha and when the irrigation water cost (IWC) was not high. However, the opposite trend was found when traditional plant population (D2) was considered (Fig. 3a). These differences are of critical importance to profit, as the slope of the curves indicates whether or not a specific irrigation strategy is suitable. If the slope is positive (e.g. with D1, an irrigation supply of around 1500 m^3/ha with IWC < 10 cents/m^3; Fig. 3a) the profit increases and so the irrigation practice can be considered appropriate. If the slope is negative (e.g. with D2, an irrigation supply of around 1500 m^3/ha with IWC = 10 cents/m^3; Fig. 3a) the profit decreases and so the irrigation practice cannot be recommended.

The profit values and the threshold of profitability are clearly affected by the sunflower price, with clear differences in terms of the recommended irrigation practice depending on this value (Fig. 3). Thus, under the weather/soil conditions of the Guadalquivir Valley in southern Spain, and with a sunflower price (SP) of 350 €/ton, the threshold of profitability for sunflower (the upper limit for irrigation water costs to be profitable) with a limited irrigation supply (below 1000 m^3/ha) was around 9 and 8 cents/m^3 for D1 and D2, respectively. For a non-severe deficit irrigation supply (irrigation between 1000 and 2500 m^3/ha) the threshold was around 12 and 6 cents/m^3 for D1 and D2, respectively (Fig. 3a). However, with SP = 200 €/ton, the irrigation supply below 1000 m^3/ha was not profitable with any sowing density, and between 1000 and 2500 m^3/ha it was only profitable for D1, with a threshold equal to 7 cents/m^3 (Fig. 3b). Finally, with SP = 500 €/ton and limited irrigation supply, the threshold was 14 and 11 cents/m^3 for D1 and D2, respectively, and for non-severe deficit irrigation supply equal to 16 and 8 cents/m^3 for D1 and D2, respectively (Fig. 3c).

Economic analysis of profit patterns under rainfed conditions with different sunflower prices (SP), sowing dates and sowing densities (Fig. 4) revealed a negligible impact of sowing density on profit compared with the effect of sowing date. Thus, for SP = 350 €/ton, the average profit ranged between 78.4 and 198.5 €/ha for S1 and S2, respectively, and between 134.8 and 142.1 for D2 and D1, respectively. This profit is reduced (even registering negative values) when SP decreases to 200 €/ton and increases (up to values of around 400 €/ha) when SP reaches 500 €/ton, with the pattern described above remaining constant (Fig. 4).

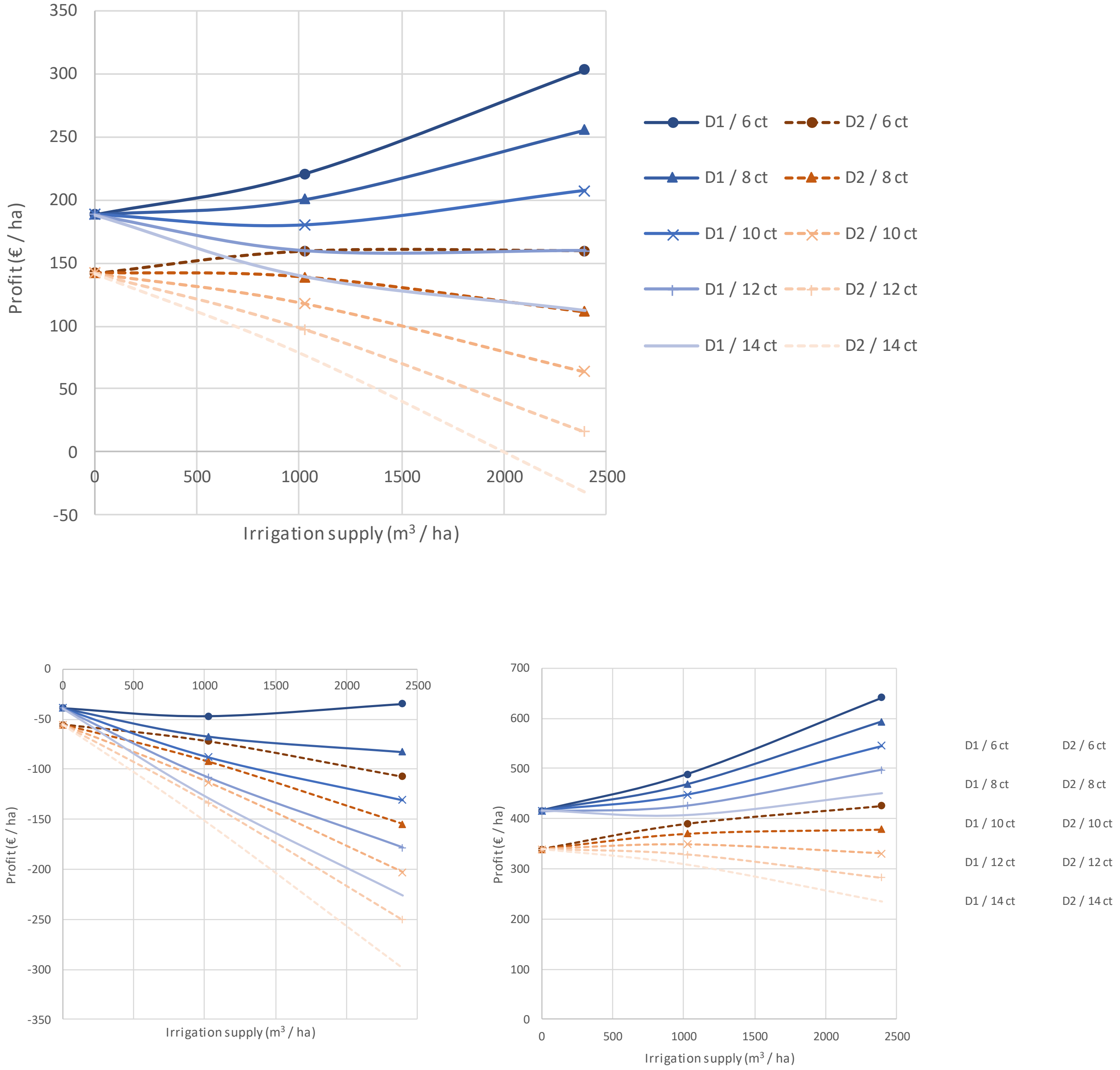

Figure 3. Simulated profit (€/ha) depending on irrigation supply, sowing density and water cost (using irrigated trials) for sunflower price equal to 350 €/ton (a), 500 €/ton (b) and 200 €/ton (c)

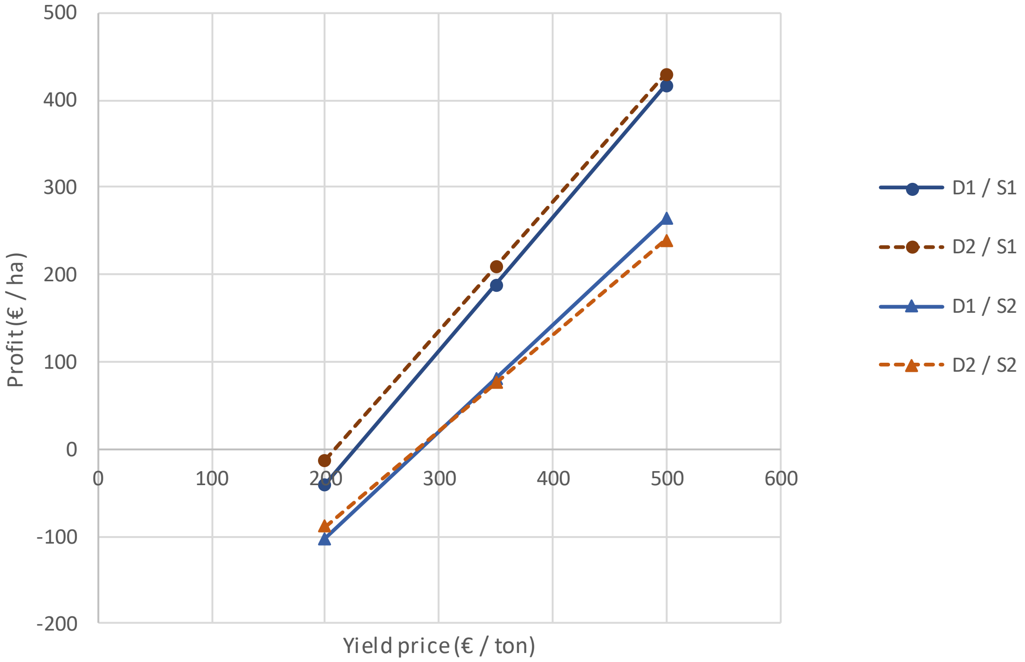

Figure 4. Simulated profit (€/ha) depending on sunflower price, sowing density, and sowing date (using rainfed trials)

3.4.4. Effect of the interactions between fertilization and irrigation supply on profit

In the economic evaluation of irrigation and fertilizer supply, under severely limited water supply the optimal N-supply was very small, even for low fertilization costs; the maximum profit was obtained with 10 N-units (Fig. 5). However, when water supply was close to the level required to avoid crop water stress (RWS around 1) and the N-fertilization cost was low (around 1.8 €/N-unit), the N-rate that maximized the profit was around 50 N-units/ha (Fig. 5). For all other water supply and fertilization cost scenarios, the recommendation was to supply the lowest N-rates (Fig. 5). When N-fertilization costs were high, the combination of irrigation and fertilization rates that maximized sunflower profit was deficit irrigation (RWS=0.76) together with very limited N-fertilization (10 N-units/ha). With low N-fertilization costs, the recommendation was similar, requiring deficit irrigation (RWS=0.76) with N-fertilization of between 10 and 50 N-units/ha (Fig. 5).

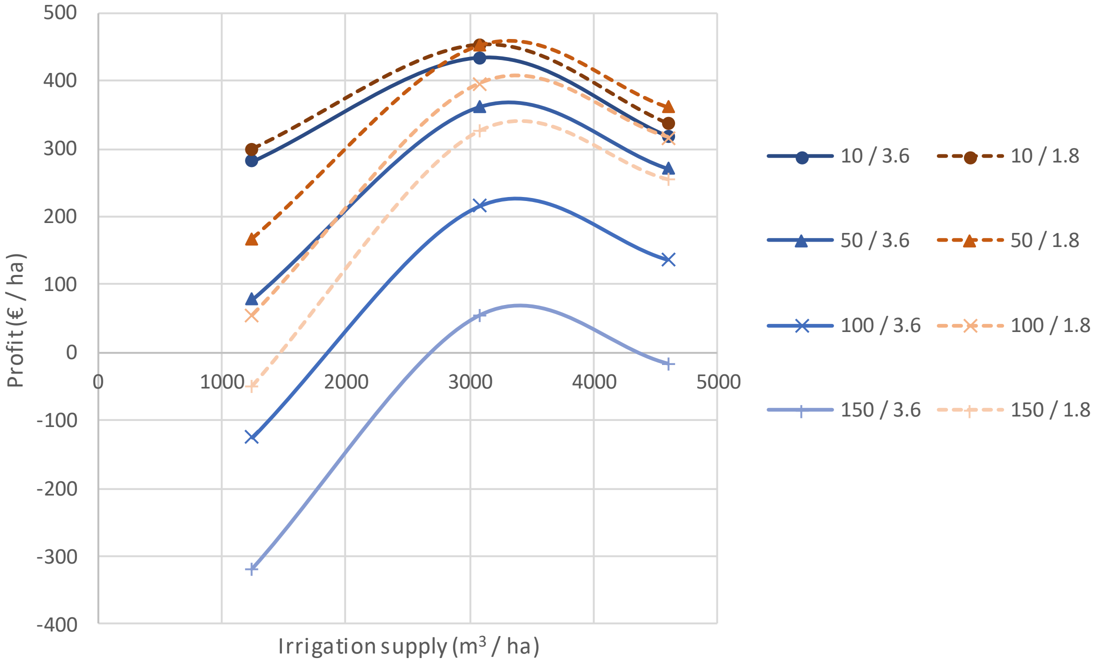

Figure 5. Simulated profit (€/ha) depending on irrigation supply, N fertilization rate (10, 50, 100 and 150 N-units/ha), and fertilization cost (3.6 and 1.8 €/N-unit) for sunflower price equal to 350 €/ton

3.5. Discussion

Several sustainable intensification practices specific to sunflower crop have been evaluated in this study; namely, increasing sowing density, bringing forward the sowing date, and implementing efficient deficit irrigation and limited fertilization strategies. This study complements previous studies uniquely focused on the optimization of deficit irrigation and N fertilization (Garcia-Lopez et al., 2016) and provides an innovative approach to identify intensification strategies for sunflower. The evaluation and integration of these intensification strategies is the result of the search for improved agricultural practices to overcome some of the drawbacks of traditional practices regarding unsustainable water use and nitrogen misuse, which have high economic and environmental costs (Jury and Vaux, 2005). To date, the most common intensification practice carried out in agricultural systems with limited water availability in southern Spain has been the application of support irrigation strategies for traditional rainfed crops such as wheat or sunflower (Lorite et al., 2012). In our study, the analysis of irrigation for sunflower— even though the full irrigation requirements were not met—produced very satisfactory results, with a significant increase in the yield of around 42% compared to the yield under rainfed conditions. These results agree with those obtained by Connor et al. (1985), Cox and Jolliff (1986) and García-Lopez et al. (2016). However, the main limitation for implementing this intensification practice is the lack of available water resources for irrigation in many agricultural areas in southern Spain. Thus, the increase in sowing density emerges as an optimal intensification practice; it is an easy, cost-effective measure in any agricultural area cultivated with sunflower. Based on the results of this study, increases in yield of around 19% on average confirm the virtues of this practice. However, this increase was not equal under rainfed and under irrigated conditions, indicating that the success of this agricultural practice depended on favorable water conditions. Thus, under rainfed (R0) and severe deficit irrigation (R1), the yield increase was around 17%, but with an efficient deficit irrigation strategy the increase reached 27%. This multiplier effect of other agronomical practices implies an additional advantage of the irrigation, even if it does not meet full water requirements. Additional advantages of irrigation were related to the decrease in canopy temperature, reducing the impact of heat stress on yield in crops such as sunflower (Ploschuk and Hall, 1995; Guilioni and Lhomme, 2006; García López et al., 2014), wheat and maize (Siebert et al., 2017), or preventing water stress during critical stages such as flowering (Rinaldi, 2001; Göksoy et al., 2004).

In line with the different behavior detected in this study depending on the irrigation supply, previous studies evaluated the effect of different sowing densities on sunflower yield and seed oil content, finding that the optimal plant population depended on the environmental conditions (Radford, 1978; Fernández et al., 1980; García Ruiz et al., 1980; Barros et al., 2004; McMaster et al., 2012; Ion et al., 2015). Thus, in those studies, the highest yields were reached for intensive plant populations but requiring favorable growing conditions; conversely, an increase in sowing density under less favorable growing conditions even led to a reduction in yields. Thus, optimal plant populations vary greatly across environments. The higher the potential yield according to the environment, the higher the plant population should be. In our rainfed trials, this trend can be clearly perceived, since both tests carried out in Tomejil during 2017 (S1-2017 and S2-2017) and the early sowing trial in 2015 (S1-2015) show very similar yield values for both densities, even detecting higher yields for lower densities (S2-2017). Evaluating the climatic conditions for these trials, very high average maximum temperatures—especially during the S2-2017 trial—and low rainfall were found in critical periods for the crop, hindering pollination and grain filling and, therefore, affecting the yields. In the opposite case, also in Tomejil, during the 2014 and 2015-S2 trials, higher density led to significant differences of 46% and 28%, respectively; both trials registered the lowest average maximum temperatures of the historical series of the trials. Similarly, the trial located in Jerez had an acceptable amount of rain and milder maximum temperatures in the critical periods, showing high yields, with higher density generating a significant difference of 26%. Moreover, the results obtained for irrigated trials confirm that the effect of increasing sowing density is enhanced when climatic conditions are satisfactory, obtaining higher yields as consequence of increasing sowing density.

Another sustainable intensification practice feasible under rainfed conditions and moderate winter temperatures is related to the advance in sowing date. Distinguishing between results from early and traditional sowing dates, the early ones produced between 25.5 and 33.7% more seed yield, and a significant increase in seed oil content of approximately 8.5 and 5.5% compared with traditional sowing dates. These results agree with those obtained by Unger (1980), Jones (1984), Gimeno et al. (1989), Flagella et al. (2002), and Barros et al. (2004). Some authors found that early sowing dates produced even greater differences;

Soriano et al. (2004) obtained increases in seed yield of up to 52% by bringing the sowing date forward from March to December. Likewise, Sheoran et al. (2015) concluded that a delay in the sowing date drastically reduced the crop yields to the tune of 33-37% in seed yield and 39-42% in oil yield in comparison to earlier sowing dates. Moreover, the benefit of early planting dates is strengthened by the results obtained with the herbicide-resistant varieties (Clearfield technology), which register a similar performance in terms of seed yield and even significantly higher than the hybrids widely cultivated in Spain (sunflower hybrids resistant to race F). When interactions between sowing date and sowing density were evaluated under rainfed conditions, only small increases in yield were associated with increases in sowing density, underlining the critical role of water availability on the outcomes of other agronomical practices.

Under irrigated conditions, the promotion of sustainable intensification practices must involve an efficient use of irrigation water. In this way, water losses can be avoided while also generating a positive economic value associated with irrigation, which for some crops such as sunflower is not always possible. However, only a few studies have evaluated irrigation management for crops such as sunflower; moreover, some of these studies have found that the application of irrigation for these crops could generate negative incomes even if yield increased compared to rainfed conditions (Lorite et al., 2012; García-López et al., 2016). As our study has proved, the profitability of irrigated sunflower will depend on the sunflower price and the irrigation water costs, but the role of sowing density is very relevant. Thus, under specific circumstances, the only way to obtain positive profits is by employing efficient deficit irrigation strategies; however, the yield must also be increased through some other additional intensification practice such as increasing sowing density. Equally, the combination of irrigation strategies that prevent severe water stress with high sowing density contributes to raising the profitability of sunflower. Lastly, an additional sustainable intensification strategy considered was the optimization of the N-fertilization. Again, the role of water availability was decisive, with the response to N-fertilization changing depending on water availability. Thus, N-rate reduction generated positive effects on root growth under rainfed conditions, improving drought resistance (Wang et al., 2019). These results confirm the need to develop integrated sustainable intensification strategies adapted to local conditions and including economic components (Webber et al., 2018).

Intensification techniques have been considered as a strategy to increase the economic sustainability of agricultural systems (Struik et al., 2017); however, using such strategies also helps to reduce the amount of irrigation and fertilization required, thereby increasing the environmental sustainability of these systems. Thus, in our study, non-maximum rates of irrigation and fertilization were required to maximize sunflower profit, confirming the results obtained by Sinha et al. (2017) and Wang et al. (2019). In addition to the resulting economic benefits, water savings and reductions in nitrate pollution were also achieved, making this an excellent sustainable intensification strategy.

The agronomic practices considered in this study, such as efficient irrigation and fertilization scheduling, increases in sowing density or the promotion of early sowing dates, have previously been independently evaluated (Barros et al., 2004; García-Lopez et al., 2014; 2016), but their combination has not been addressed thus far. This study has tried to close that gap. Thus, traditionally, the advisory services provided to farmers have been focused on irrigation, fertilization, or cultivar selection (Lorite et al., 2012). However, under current conditions of low agricultural profitability, more integrated advice is required, including the optimization and coordination of agronomic factors such as irrigation, fertilization, sowing date and sowing density. In this study, the individual effects of well-known agricultural practices have been confirmed; moreover, the critical role of water availability in the satisfactory performance of intensification practices has been identified. This component is often overlooked, and so even when improved agricultural practices (such as modifications in sowing date, sowing density or fertilization) have been correctly implemented, the outcome may not be as expected. The results of ecophysiological mechanisms related to drought, sowing density or sowing date are well known, even for crops such as sunflower (Diepenbrock et al., 2001; Hussain et al., 2018). For sunflower, however, the effects/interactions of these mechanisms when different agricultural practices are combined are unknown. This study constitutes the basis for assessing the effects of integrating different agricultural practices on physiological mechanisms such as radiation use efficiency or the stomatal response to water stress, with the ultimate aim of developing mechanistic crop models to be used under future climate conditions. Thus, under disturbing climate change scenarios, where water availability for crops will be a limiting factor, boosting water use efficiency will be critical. To achieve this, recent studies have emphasized the need to integrate management techniques (Farooq et al., 2019). Thus, this study provides a first step in the promotion of intensification strategies in traditional rainfed crops such as sunflower, a topic that has not been widely analyzed to date. However, additional experimental studies integrating different sowing dates, density, fertilization and irrigation strategies are still required. Similarly, experimental work under different climate and agronomic conditions is necessary to provide more general recommendations to farmers cultivating sunflower under semi-arid conditions.

Finally, by combining experimentation based on a wide range of agronomical practices and water availability with the development and analysis of economic scenarios, this study provides an innovative tool for analyzing the performance of integrated intensification strategies for sunflower. Equally, performing the analysis under different economic scenarios extends the applicability of this study to other regions and weather conditions, making it useful for analyzing the sustainability of a wide range of agricultural systems today and in the future.

3.6. Conclusions

Through the concept of sustainable intensification, this study evaluated a number of agronomical practices for traditional sunflower cultivation systems, such as deficit irrigation strategies, optimized fertilization practices related to water availability, the use of high sowing densities and the application of early sowing dates. Analyzing individually the effects of each proposed agricultural practice on yield revealed that efficient deficit irrigation was the practice reporting the greatest benefits in terms of crop performance, obtaining yield increases of 42% compared with rainfed fields. However, fertilization required adequate water supply, high sowing densities, and favorable weather conditions to achieve yield increases. An appropriate combination of agronomical practices enhanced the positive results on sunflower yield and profitability. Thus, coordinating deficit irrigation strategies with high sowing densities resulted in yield increases of around 70% compared with rainfed systems and traditional sowing densities. Similarly, the combination of high sowing densities with early sowing dates generated performance increases of approximately 40% compared to traditional techniques. Finally, the interaction between fertilization rate and water availability resulted in significant N-fertilization savings when irrigation/rainfall supply was very limited. All these results emphasize the vital importance of proper water management for the sustainability of agricultural systems under semi-arid conditions. Economic analyses under a wide range of scenarios confirmed the optimal performance when sowing density, deficit irrigation and N-fertilization strategies were coordinated. Equally, profitability thresholds relating to yield harvest price and irrigation water costs were reduced when deficit irrigation and high sowing density were integrated.

However, despite the evident improvements in yield, crop profitability and sustainability generated by the correct coordination of intensification measures described and evaluated in this study, their use has not been widely applied by farmers in southern Spain.

Thus, an effort to promote advisory services and technology transfer to farmers and technicians is required to increase the sustainability of these agricultural systems.

3.7. Acknowledgements

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