CARACTERIZACIÓN, ADAPTACIÓN Y MEJORA DE NUEVOS SISTEMAS DE RECOLECCIÓN INTEGRALES PARA OLIVAR.

INTEGRAL OLIVE HARVESTING SYSTEMS: CHARACTERIZATION, ADJUSTMENT AND IMPROVEMENTS.

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TITULO: *Caracterización, adaptación y mejora de nuevos sistemas de recolección integrales para olivar*

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CARACTERIZACIÓN, ADAPTACIÓN Y MEJORA DE NUEVOS SISTEMAS DE RECOLECCIÓN INTEGRAL PARA OLIVAR

INTEGRAL OLIVE HARVESTING SYSTEMS: CHARACTERIZATION, ADJUSTMENT AND IMPROVEMENTS

Para optar al título de doctor con mención "Doctorado Internacional" por la Universidad de Córdoba.

To aim for the International Doctorate at University of Cordoba.

El doctorando:

Fdo: **Francisco José Castillo Ruiz**

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Prof. Dr. D. **Jesús Antonio Gil Ribes** Prof. Dr. D. **Sergio Castro García**

Córdoba, febrero de 2017

TÍTULO DE LA TESIS: CARACTERIZACIÓN, ADAPTACIÓN Y MEJORA DE NUEVOS SISTEMAS DE RECOLECCIÓN INTEGRAL PARA OLIVAR.

DOCTORANDO: FRANCISO JOSÉ CASTILLO RUIZ

INFORME RAZONADO DE LOS DIRECTORES DE LA TESIS

Los directores de la tesis Prof. Dr. Jesús A. Gil Ribes y Prof. Dr. Sergio Castro García, informan que el doctorando Francisco José Castillo Ruiz ha desarrollado los objetivos previstos para la realización de la presente Tesis Doctoral. Dicha tesis cumple las condiciones formales y académicas exigidas por la legislación vigente para optar al título de Doctor con mención "Doctorado Internacional" por la Universidad de Córdoba. El doctorando ha impartido la docencia universitaria correspondiente a la concesión de una beca de Formación del Profesorado Universitario (FPU) por parte del Ministerio de Educación, Cultura y Deporte (AP2012-4334). Además, ha realizado los trabajos de investigación y transferencia en 3 proyectos públicos, 5 contratos y convenios de investigación (art. 83 LOU), en 2 contratos privados de investigación en el extranjero y en el convenio de Compra Pública Pre-comercial "Mecaolivar". Este convenio ha sido concedido por el Ministerio de Economía, Industria y Competitividad (fondos FEDER) y cofinanciado por la Universidad de Córdoba y la Organización Interprofesional del Aceite de Oliva Español (IAOE).

El doctorando ha realizado 2 estancias de investigación con una duración de 3 meses cada una:

- *Dipartimento di Scienze Agrarie Alimentari e Ambientali* de la *Università degli Studi di Perugia* (Italia) entre agosto y noviembre de 2015.
- *Department of Engineering – Operations Management* de la *Aarhus Universitet* (Dinamarca) entre junio y septiembre de 2016.

La Tesis Doctoral se presenta por compendio de artículos con 3 publicaciones en las revistas *Sensors* (2 publicaciones) y *Spanish Journal of Agricultural Research*, ambas indexadas en *Journal Citation Report* (JCR) ® en el primer y segundo cuartil respectivamente. Además, la Tesis Doctoral se completa con 2 artículos en proceso de envío a revistas internacionales indexadas en el JCR ®.

La actividad investigadora desarrollada por el doctorando, además de lo expuesto anteriormente, ha dado lugar a la concesión de 3 patentes, 1 solicitud de patente, 3 artículos JCR, 7 publicaciones en revistas de divulgación y 22 comunicaciones presentadas en congresos nacionales e internacionales.

Finalmente, el doctorado ha participado en la elaboración de 2 proyectos de empresa que han dado lugar a la obtención de 3 premios y a la constitución de 1 empresa dedicada al asesoramiento, diseño y fabricación de maquinaria agrícola y sus componentes introduciendo innovaciones en el sector.

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

Web con información y publicaciones del doctorando:

https://scholar.google.es/citations?user=19vuFP8AAAAJ&hl=es

Córdoba, 1 de febrero de 2017

Firma de los directores

Fdo.:_ Prof. Dr. Jesús A. Gil Ribes   Fdo.: Prof. Dr. Sergio Castro García

MENCIÓN DE DOCTORADO INTERNACIONAL

Esta tesis cumple los requisitos establecidos por la Universidad de Córdoba en el artículo 35 de la normativa reguladora de los estudios de doctorado para la obtención de la mención de "Doctorado Internacional".

Se han realizado dos estancias internacionales en países del Espacio Europeo de Educación Superior (EEES) distintos de España:

- Estancia internacional predoctoral de 3 meses desde el 3 de agosto de 2015 al 13 de noviembre de 2015 en la *Università degli studi di Perugia* (Italia) *Dipartimento di Szience Agrarie, Alimentari et Ambientali* supervisada por la profesora Dr. Daniela Farinelli.
- Estancia internacional predoctoral de 3 meses desde el 20 de junio de 2015 al 21 de septiembre de 2016 en la *Aarhus Universitet* (Dinamarca) *Department of Engineering - Operations Management*, supervisada por el investigador Dr. Dionysis Bochtis.

La tesis cuenta con el informe previo de al menos dos doctores externos con experiencia acreditada pertenecientes a alguna institución de educación superior o instituto de investigación dentro del EEES

- Arlindo Castro Ferreira Almeida: Associate professor, Department of Vegetal production and technology, Polytechnic Institute of Bragança, Escola Superior Agrária. Bragança, Portugal. acfa@ipb.pt
- Giuseppe Zimbalatti: Full professor, Department of agriculture, Mediterranea University of Reggio Calabria. Reggio Calabria. gzimbalatti@unirc.it

Finalmente, un doctor perteneciente a una institución de educación superior o centro de investigación del EEES participará en el el tribunal que evaluará la tesis doctoral.

Por último, la tesis se ha redactado en español y en inglés, y se presentará en ambos idiomas.

El doctorando

Francisco José Castillo Ruiz

TESIS POR COMPENDIO DE ARTÍCULOS

La presente tesis doctoral cumple el requisito establecido en el artículo 24 de la normativa de doctorado de la Universidad de Córdoba, para ser presentada como compendio de artículos. Está constituida por tres artículos publicados en revistas incluidas en los tres primeros cuartiles del *Journal Citation Report* ® (JCR) correspondiente al último año disponible, 2015. En particular, los artículos han sido publicados en revistas de los dos primeros cuartiles de dicho índice, por lo que cabe resaltar la apuesta por la calidad de los contenidos en la presente tesis doctoral. En todos los artículos indicados, el doctorando aparece como primer autor.

Publicaciones:

- Development of a telemetry and yield mapping system of olive harvester. 2015. F.J. Castillo-Ruiz, M. Pérez-Ruiz, G.L. Blanco-Roldán, J.A. Gil-Ribes, J. Agüera. Sensors, 15, 4001-4018. JCR ® 2015 con índice de impacto de 2,033; posición 12/56 (1º cuartil) en el área temática Instruments & Instrumentation.
- Analysis of fruit and oil quantity and quality distribution in high-density olive trees in order to improve the mechanical harvesting process. 2015. F.J. Castillo-Ruiz, F. Jiménez-Jiménez, G. L. Blanco-Roldán, R. R. Sola-Guirado, J. Agüera-Vega, S. Castro-García. Spanish Journal of Agricultural Research, 13 (2), 0209. JCR ® 2015 con índice de impacto de 0,76; posición 24/57 (2º cuartil) en el área temática Agriculture, Multidisciplinary.
- Olive crown porosity measurement based on radiation transmittance: an assessment of pruning effect. 2016. F.J. Castillo-Ruiz, S. Castro-Garcia, G.L. Blanco-Roldán, R.R. Sola-Guirado, J.A. Gil-Ribes. Sensors, 16, 723. JCR ® 2015 con índice de impacto de 2,033; posición 12/56 (1º cuartil) en el área temática Instruments & Instrumentation.

El doctorando:

Francisco José Castillo Ruiz.

Si piensas que eres demasiado pequeño como para marcar la diferencia, intenta dormir con un mosquito en la habitación

.

Proverbio africano

La verdadera ciencia enseña, por encima de todo, a dudar y a ser ignorante.

Miguel de Unamuno

La presente tesis doctoral ha sido financiada a través de la concesión de una beca de formación del profesorado universitario (FPU) por parte del Ministerio de Educación Cultura y Deporte.

Por otra parte, los trabajos realizados se han realizado gracias a la financiación del convenio de compra pública precomercial Mecaolivar, concedido por el Ministerio de Economía, Industria y Competitividad, y cofinanciado por la Interprofesional del Aceite de Oliva Español. Además se ha contado con la financiación a través de contratos OTRI de la Interprofesional del Aceite de Oliva Español y la Interprofesional de la Aceituna de Mesa.

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Deseo expresar mi más sincera gratitud a todas las personas que de una u otra forma han hecho posible la realización de esta tesis doctoral.

En primer lugar a mis directores de tesis D. Jesús A. Gil Ribes y D. Sergio Castro García, por el tiempo que han dedicado a mi formación como doctor y como docente, así como por la revisión del presente documento y de los artículos publicados.

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ABREVIATURAS / ABBREVIATIONS

Se han empleado las siguientes abreviaturas a lo largo de la tesis:

The following abbreviations are used in this thesis:

A/D: Convertidor analógico-digital / Analogue-to-digital converter

DGNSS: Sistema de navegación por satélite con correcciones diferenciales / Differential Global Navigation Satellite System

FRF or FDF: Fuerza de retención del fruto / Fruit retention force or fruit detachment force

FRF/FW or FDF/FW: Ratio que expresa la fuerza de retención del fruto por gramo de peso fresco / Fruit retention force by fruit fresh weight ratio

FW: Peso fresco del fruto / Fruit fresh weight

GIS: Sistema de información geográfica / Geographic Information System

GNSS: Sistema global de navegación por satélite / Global Navigation Satellite System

GSM: Sistema global para las comunicaciones móviles / Global System for Mobile

HD: Alta densidad / High density

HCP: Servidor / Host Control Platform

KML: Lenguaje de marcado basado en XML para representar datos geográficos / Keyhole Markup Language

MRMP: Sistema de seguimiento para maquinaria / Machine Remote Monitoring Platform

PAR: Radiación fotosintéticamente activa / Photosinthetically active radiation

RS-232: Estándar de comunicación 232 / Recommended standard 232

SD: Desviación estándar / Standard deviation

SE: Error estándar / Standard error

SHD: Superintensivo / Super high density

SMS: Servicio de mensajes cortos / Short Message Service

UTC: Tiempo universal coordinado / Universal Time Convention

RESUMEN

La presente tesis doctoral aborda el estudio conjunto de la recolección mecanizada y la poda del olivo para mejorar el uso de las cosechadoras, actuales y en desarrollo, por medio de la adaptación del árbol y el diseño de la plantación. Se han considerado tres de las principales tipologías de cultivo del olivo presentes en España: tradicional, intensivo y superintensivo. Las adaptaciones del árbol a la máquina se han centrado en el olivar tradicional, ya que apenas se realizan nuevas plantaciones de esta tipología de cultivo, mientras que, el diseño de plantación se ha estudiado para el olivar superintensivo, En caso del olivar intensivo se han tenido en cuenta ambos factores.

Para determinar la influencia del diseño de plantación sobre el funcionamiento de las cosechadoras de olivar se ha desarrollado un sistema de seguimiento remoto y una metodología de análisis de tiempos, junto con un monitor de rendimiento. Estos desarrollos han permitido la obtención y análisis de un gran volumen de datos para tres cosechadoras comerciales de olivar. En cuanto a la adaptación del árbol a las cosechadoras, se ha estudiado la distribución de la producción de aceite en la copa del árbol, tanto en calidad como en cantidad, para establecer las zonas prioritarias donde debe actuar un sistema de recolección mecanizada. Además, se han establecido tres tratamientos de poda para evaluar la adaptación del olivar tradicional a la recolección con cosechadoras, tanto actuales como en desarrollo. La caracterización de la estructura del árbol se ha completado con una metodología para evaluar la porosidad de copa basada en la radiación transmitida. Finalmente, a nivel de fruto se ha determinado el efecto que genera la aplicación de esfuerzos torsores en el pedúnculo del fruto, de cara a mejorar el porcentaje de derribo que podría obtenerse con una cosechadora en futuros desarrollos.

Actualmente, el olivar superintensivo cuenta con un sistema de cosecha muy eficiente y con una alta capacidad de trabajo, aunque sensible a distintos parámetros de diseño de la plantación como son el ancho de calle de servicio o la longitud de línea de árboles. Al igual que el olivar superintensivo, las explotaciones intensivas requieren una adaptación del árbol a la cosechadora, mientras que el sistema de derribo se diseña para obtener una mayor eficiencia en aquellas zonas de la copa de mayor interés, como la zona exterior y superior del árbol. Del mismo modo, el olivar tradicional requiere una adaptación importante de la estructura del árbol para mejorar la eficiencia de la cosechadora. La adaptación de la estructura del árbol no ha influido en la producción de frutos en el periodo estudiado. Sin embargo, en algunos casos se ha producido una reducción de la producción de frutos en zonas de la copa que son difícilmente accesibles para algunos sistemas de derribo, como ocurre con la producción de las ramas interiores. Todo ello, a pesar de que la aplicación de diferentes tratamientos de poda si ha generado diferencias en la porosidad de la copa y, por lo tanto, en la radiación transmitida. Por último, se ha determinado que es recomendable generar giros superiores a 180º en los frutos para facilitar su desprendimiento, variando los resultados en función de la variedad.

Palabras clave: *Olea europaea* L, Recolección mecanizada, poda, arquitectura de copa, sacudidor de copa, vibrador de troncos.

SUMMARY

This doctoral thesis addresses the related studies of mechanised olive harvesting and pruning of olive trees, in order to improve their use by present and developing harvesters, through the adaptation of the tree and the layout of the orchard. In the research, the three main orchard categories currently in use in Spain have been considered: traditional, intensive and super high density olive orchards. On one hand, the adaptation of the tree to the harvester by pruning has been focused in traditional orchards, since very few new orchards are planted in this way. On the other hand, orchard layout was mainly considered for super high density orchards: whilst for intensive orchards, both factors were studied.

A remote tracking system, a time elements methodology and a yield monitor were developed for the study of olive harvesters. Using these devices, a large data set from three olive harvesters was gathered and analysed. This data set was used to assess the influence of orchard layout on harvesting performance. Regarding the adaption of the tree to the harvesting system, the distribution of olive oil yield in the tree canopy has been studied – regarding quality as much as quantity – in order to establish a system to increase harvesting efficiency. Furthermore, three pruning treatments were tested, in order to evaluate the adaptation of traditional olive trees to different harvesting systems. A methodology for the measurement of olive tree crown porosity was developed and tested, based on radiation transmittance, in order to describe olive tree structure. Finally, the effects of twisting forces on fruit stalks were assessed in order to improve harvesting efficiency for further harvester developments.

Currently, super high density olive orchards have an efficient and highly effective harvesting system, although this is influenced by orchard layout, mainly alley width and row length. The adaptation of trees to the harvester is required by both super high density and intensive olive orchards. Furthermore, the fruit detachment system should be designed to obtain high harvesting efficiency in those canopy areas which are more productive to harvest, such as the outer canopy and upper canopy. In the same way, traditional olive trees require important adaptations in order to increase harvesting efficiency, although it was found that debris production is not related to pruning treatments. Tree pruning did not influence the total fruit yield, although in some cases, fruit distribution has been modified by pruning, reducing yield within the inner canopy, which is more difficult to reach with some harvesting systems. Despite this, crown porosity and thus radiation transmittance were affected by pruning treatment. Finally, it was found that it is advisable to apply stalk twisting angles over 180 º in order to improve fruit detachment process although different cultivar behaviour was observed.

Keywords: *Olea europaea* L, mechanical harvesting, pruning, canopy structure, canopy shaker, trunk shaker.

CAPÍTULO 1. INTRODUCCIÓN Y JUSTIFICACIÓN.

Presentación y marco de la tesis doctoral

La presente tesis doctoral, ha sido desarrollada en la Universidad de Córdoba (España) dentro de las actividades del Grupo de Investigación AGR-126 “Mecanización y tecnología rural”. Los trabajos realizados se han enmarcado en la línea de investigación “Mecanización y recolección del olivar”. Se han incluido datos desde la campaña de recolección 2010/11 hasta 2015/16, incluyendo datos de olivar almazara y de aceituna de mesa. Además, se han estudiado conjuntamente las operaciones de recolección y poda, con el objetivo de realizar la adaptación de los árboles a distintos sistemas de recolección mecanizada. Esta adaptación junto con la adecuación del diseño de plantación a la cosechadora y de la máquina al cultivo, es recomendable para el éxito de la mecanización de la recolección en olivar.

Importancia del olivar

La Unión Europea (UE) es la principal productora a nivel mundial de aceite de oliva y aceituna de mesa. En el periodo 2009/10 - 2014/15, la UE ha producido casi el 70 % del total del aceite de oliva mundial, con una media ligeramente superior a 2 millones de toneladas anuales. En el mismo periodo, España ha producido más del 60 % del aceite de oliva europeo, aportando de media 1,3 millones de toneladas. En cuanto a la producción de aceituna de mesa, la UE supone más del 30 % del total a nivel mundial con 0,8 millones de toneladas, mientras que España ha aportado casi el 70 % del total de la producción europea con 0,5 millones de toneladas (COI, 2015).

En nuestro país, el cultivo del olivar tiene una gran importancia económica y social, habiéndose estimado que este cultivo genera una actividad económica media valorada en 1,866 millones de € por año (periodo 2007 - 2012) y la generación de empleo se estima en 46 millones de jornales al año (MAPAMA, 2016). Además, el cultivo del olivar se adapta en ocasiones a condiciones marginales, en suelos pobres y zonas montañosas, existiendo escasas alternativas a dicho cultivo. Por último esta actividad económica presenta un fuerte arraigo y una gran importancia patrimonial, ambiental y sociocultural en las regiones mediterráneas (EUROSTAT, 2012).

A nivel regional, el olivar destaca por su importancia en Andalucía, donde ocupa 1,52 millones de hectáreas, lo que supone más del 30 % de la superficie agraria útil de toda la región y una generación de 19 millones de jornales anuales (CAPDR, 2015). La distribución de la superficie de olivar no es homogénea, concentrándose entorno a un eje virtual que atraviesa Andalucía desde el noreste al centro de la región, lo que suele reflejarse en el término “eje del olivar”. A lo largo de dicho eje, el olivar tiene una gran importancia en numerosos municipios, en los que representa casi un monocultivo (Fig. 1).

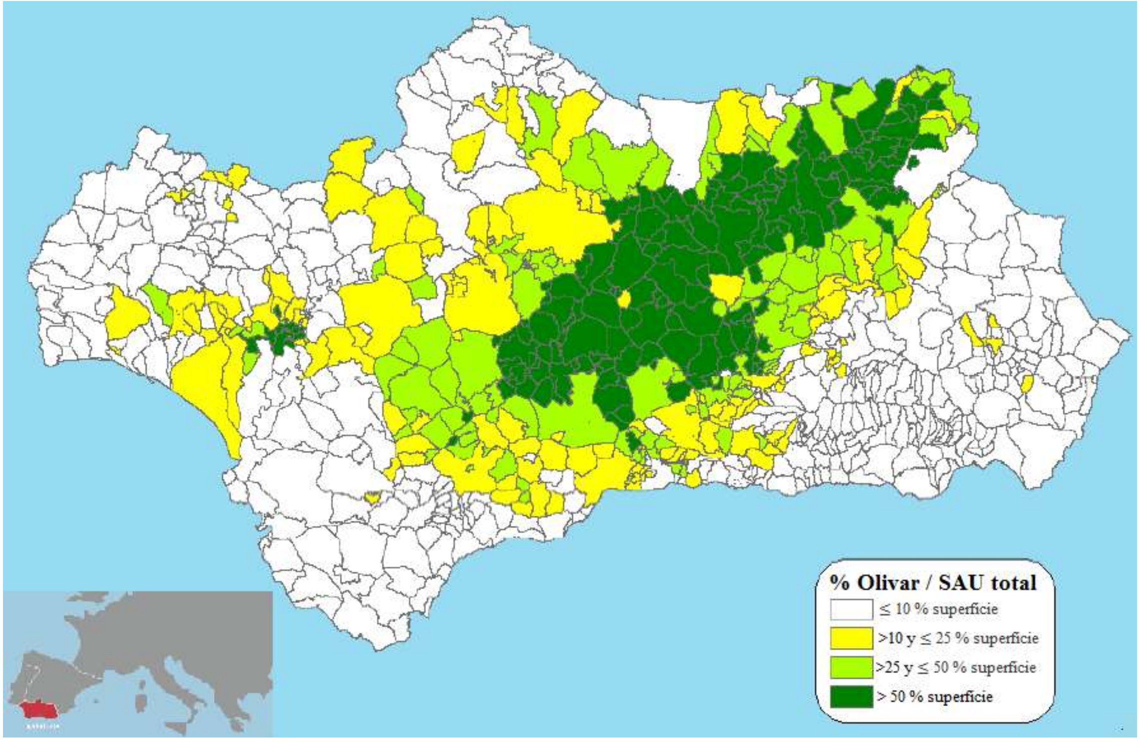

Fig. 1. Distribución de la superficie de olivar en Andalucía a nivel municipal en porcentaje respecto a la superficie agraria útil (SAU). (CAPDR, 2015).

Mecanización del olivar

La recolección es la operación que supone un mayor porcentaje de los costes de cultivo en olivar, siendo la poda la tercera operación más costosa en las explotaciones de secano (AEMO, 2012). Debido a esta circunstancia, es recomendable incidir sobre los costes de ambas operaciones, ocupándose en primer lugar de los costes de recolección, con el objetivo de incrementar la competitividad del sector.

El olivar es un cultivo mediterráneo que tradicionalmente ha requerido una alta cantidad de mano de obra para realizar las distintas labores, si bien, en los últimos años el olivar está sufriendo un proceso de mecanización que ha mejorado notablemente la competitividad del sector (Gil-Ribes, Blanco-Roldán & Castro-García, 2009). Sin embargo, el nivel de mecanización y tecnificación actual no es comparable al de otros cultivos como los cereales o la vid en espaldera. Además, dentro del sector, el uso de la mecanización no afecta por igual, siendo diferente para explotaciones con una u otra estructura del árbol.

El olivar tradicional de varios troncos (Fig. 2) representa una tipología de cultivo a día de hoy obsoleta, ya que cuando estos árboles fueron plantados, estaban adaptados a la recolección manual, con troncos inclinados que disminuyen la altura de las ramas fructíferas, facilitando el acceso a la producción por parte de operarios a pie. La adaptación de esta tipología de plantación a la recolección mecanizada ha sido muy reducida, incluyendo pocos cambios más allá del aumento de la altura de las ramas bajas para facilitar la visibilidad del tronco por parte del conductor.

Fig. 2. Olivar tradicional de varios troncos.

La adaptación de la cosechadora al cultivo para el que está diseñada es un paso necesario para mejorar la eficiencia de recolección. Ambos pasos son necesarios para la doble adaptación que se requiere en el proceso de mecanización de un cultivo. Dos ejemplos opuestos son la recolección del olivar tradicional, que se realiza fundamentalmente mediante la adaptación de la máquina, mientras que en el caso del olivar superintensivo, el éxito de la operación de recolección se basa en la adaptación del cultivo a la cosechadora. Lo ideal sería que ambos procesos se desarrollasen simultáneamente para mejorar la eficiencia y la capacidad de recolección.

Cuando se trabaja en el desarrollo de cualquier producto, en este caso maquinaria agrícola, es recomendable enfocarlo hacia un segmento de mercado determinado. En el caso de la maquinaria agrícola en general y del olivar en particular, actualmente el mercado está escindido en dos segmentos principales: Por un lado la agricultura más moderna y puntera en manos de grandes corporaciones empresariales, empresas de servicios o grandes agricultores. Este tipo de consumidor final demanda un producto que cuente con un alto grado tecnológico, de automatización de procesos, así como de toma y gestión de datos. Por otro lado está la agricultura familiar y en países en vías de desarrollo, que cuenta con menores recursos, pero que también representa un segmento umportante de la demanda. Un ejemplo aplicado al olivar son los vibradores y sacudidores de ramas portados por un operario a pie, y que a día de hoy son una pieza fundamental en la recolección del olivar en explotaciones pequeñas, de difícil topografía, o en el norte de África (Cicek, Sumer, & Kocabiyik. 2010).

La línea de trabajo llevada a cabo por el Grupo de Investigación AGR-126 inicia el camino para establecer un liderazgo por parte de España y la UE, no sólo en el sector de producción de aceite de oliva y aceituna de mesa, sino también en el sector de la fabricación de maquinaria para la recolección de olivar. Este liderazgo debe forjarse a través de la innovación constante, del ensayo y mejora continua de la maquinaria. Es necesario poner en relieve que el desarrollo de un producto tan complejo como una cosechadora de olivar puede requerir largos periodos de tiempo. Sirva como ejemplo, la puesta a punto y adaptación de las cosechadoras cabalgantes para la recolección de olivar en seto, que ha requerido un largo proceso de mejora contínua y prueba en campo.

Justificación de la tesis doctoral

La adaptación de la estructura del árbol y el diseño de plantación a las cosechadoras de olivar es una cuestión de gran importancia que incide en la competitividad del sector productor de aceite de oliva. Para evitar la pérdida de competitividad de los olivareros europeos y españoles es recomendable reducir los costes de producción mediante la tecnificación y mecanización integral del cultivo. En el caso del olivar, el primer objetivo debe ser la mecanización de la recolección, que supone la mayor partida en la cuenta de costes. Una de las posibles vías para maximizar la eficiencia y reducir el coste de la recolección en olivar, es la adaptación de los árboles a la cosechadora mediante la poda y la adaptación del diseño de plantación a la cosechadora empleada.

La importancia de los trabajos realizados queda patente tanto por el peso del sector al que se dirige, como por el interés mostrado por el sector de producción de aceite de oliva y de aceituna de mesa a través de la Interprofesional del Aceite de Oliva Español, y de la Interprofesional de la Aceituna de Mesa. El sector de fabricación de maquinaria agrícola también ha mostrado un gran interés como indica el alto grado de participación en las licitaciones convocadas dentro del convenio Mecaolivar. Cabe resaltar, que estos trabajos están enmarcados dentro de la estrategia del grupo de investigación AGR-126, que pretende mantener o aumentar la competitividad del olivar español, a través de la innovación y el desarrollo de nuevos sistemas de recolección. Finalmente, el aumento de la competitividad, debe posicionar al olivar español, junto con el resto de países de la UE para poder ofrecer un producto de calidad a un coste similar o menor al que pueda obtenerse en terceros países. Todo ello permitirá mantener un olivar rentable y sostenible, desde el punto de vista social, económico y medioambiental.

El interés despertado por la actividad del doctorando y del Grupo de Investigación AGR-126 ha alcanzado también el plano internacional. Este interés ha quedado patente a través de la visita de la Profesora Daniela Farinelli dentro del programa Erasmus+ junto con otros investigadores y olivareros nacionales e internacionales durante la fase de demostración de los prototipos del convenio Mecaolivar. También se han establecido contactos con la Universidad de Perugia (Italia), Universidad de Aarhus (Dinamarca), Universidad de California Davis (EE.UU.) y con la Universidad de Reggio Calabria (Italia). En el ámbito privado, los trabajos del Grupo de Investigación han generado interés a nivel internacional a través de contactos establecidos con la fundación Basilis (Grecia) y con una empresa de Arabia Saudí dedicada a la explotación de olivar.

Trabajos realizados dentro de la tesis doctoral.

La presente tesis doctoral se ha desarrollado gracias a la concesión de una beca dentro del programa nacional de formación del profesorado universitario (FPU), que ha permitido la ejecución de los trabajos y ensayos de la presente tesis. Además se ha contado con el apoyo financiero de numerosos contratos privados financiados por la Interprofesional del Aceite de Oliva Español (IAOE) y por la Interprofesional de la Aceituna de Mesa, y financiación pública concedida por el Ministerio de Economía, Industria y Competitividad a través del convenio de compra pública precomercial Mecaolivar, financiado con fondos FEDER y cofinanciado por la IAOE.

Los trabajos del Grupo de Investigación AGR-126 "Mecanización y tecnología rural" para desarrollar un sistema de recolección integral para olivar comenzaron con el proyecto agentes del conocimiento "Sistemas avanzados de recolección integral del olivar tradicional" (2008-000448 Pl45120). Posteriormente se han desarrollado diferentes prototipos para la recolección de distintas tipologías de olivar. En una primera fase se diseñaron y ensayaron varias versiones de un sistema sacudidor de copa para la recolección de olivar tradicional e intensivo (Sola-Guirado, 2016), empleando para ello la financiación recibida a través de contratos OTRI. Posteriormente se han desarrollado distintos prototipos en colaboración con varias empresas del sector, dentro del convenio de compra pública precomercial Mecaolivar. En esta fase, se han desarrollado y ensayado dos cosechadoras para olivar tradicional basadas en la sacudida de copa, tres cosechadoras para olivar intensivo basadas en la vibración del tronco y dos prototipos de vibrador de troncos con automatización de diferentes procesos, y sistemas para reducir la incidencia del descortezado. Dentro del mismo proyecto se ha desarrollado una línea de investigación para desarrollar y ensayar distintos sistemas de poda que permitan adaptar los árboles a los sistemas de recolección en desarrollo.

La estructura y resultados de la tesis se han presentado en un orden secuencial, siguiendo el orden en el que se han realizado los trabajos y ensayos, se han obtenido los resultados y se han publicado en revistas de alcance internacional. Los trabajos realizados son:

- Se ha llevado a cabo el seguimiento remoto de cosechadoras integrales de olivar en plantaciones intensivas y superintensivas para determinar la capacidad de trabajo y rendimiento, evaluando el efecto que tienen sobre estos parámetros distintos factores de diseño de la plantación.
- Se ha caracterizado el patrón de fructificación del olivo, evaluando la cantidad y calidad del aceite en distintas zonas de la copa, y la posibilidad de realizar una cosecha mecanizada de dichas zonas con distintos sistemas de recolección comerciales y en desarrollo.
- Por un lado, se ha evaluado cómo afectan tres tratamientos de poda a la estructura de los árboles, principalmente atendiendo a la porosidad de la copa, o densidad de estructuras de sustento, foliares y productivas (hojas, tallos, brotes...), y a la producción de biomasa obtenida.
- Por otro lado, también se ha evaluado la influencia de los tratamientos de poda en la recolección mecanizada con sacudidores de copa para analizar la adaptación del árbol a la máquina. En esta fase se ha determinado el porcentaje

de derribo, la incidencia del sistema de recolección en los daños realizados al árbol, y el efecto de la poda sobre la producción exterior e interior del árbol.

- Se ha estudiado como evoluciona la respuesta del pedúnculo del fruto frente a la aplicación de un esfuerzo torsional a lo largo del proceso de maduración. Dicho ensayo se ha realizado en cuatro variedades de olivo: ‘Arbequina’, ‘Frantoio’, ‘Maurino’ y ‘Leccino’ dentro de la estancia en el Departamento de Ciencias Agrarias, Alimentación y Medio Ambiente de la Universidad de Perugia, en colaboración con la profesora Daniela Farinelli y el doctor Sergio Tombesi.

Producción científica y técnica de la tesis doctoral

Los resultados de la presente tesis doctoral se reflejan el las tres publicaciones científicas realizadas en revistas internacionales con alto índice de impacto JCR ® (*Sensors* y *Spanish Journal of Agricultural Research*), dejando enviados otros dos trabajos para su publicación. Por otro lado se han realizado diversas publicaciones en revistas de divulgación (Agricultura, Interempresas, Vida Rural y Olimerca), y se han llevado a cabo numerosas ponencias y exposición de pósters en diferentes congresos nacionales e internacionales, tanto de ámbito científico, como en el ámbito del sector productor de aceite de oliva y aceituna de mesa. Además, se ha participado en distintas acciones encaminadas a la transferencia del conocimiento adquirido al sector, como la elaboración de un manual para la recolección mecanizada de la aceituna de mesa (actualmente en edición por Interaceituna), o la organización de una demostración pública de la maquinaria desarrollada para la recolección del olivar y la aplicación de tratamientos fitosanitarios, en colaboración con el Ministerio de Agricultura y Pesca, Alimentación y Medio Ambiente y la Consejería de Agricultura, Pesca y Desarrollo Rural.

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CAPÍTULO 2. ANTECEDENTES

Se ha hecho una revisión de la bibliografía y estado de la técnica actual de forma global a los trabajos que han dado lugar a la tesis doctoral. Para ello se han descrito las distintas tipologías de olivar, que condicionan el método de cosecha empleado, los sistemas de recolección integrales disponibles en la actualidad, y los sistemas de poda que adaptan el árbol a uno u otro sistema de recolección.

Tipologías de olivar

El olivar es un cultivo muy diverso, que puede realizarse empleando densidades de plantación muy diferentes y estructuras del árbol formadas a través de sistemas de poda muy variados. Además, las plantaciones de olivar pueden situarse en ambientes y relieves muy diferentes, lo que da lugar a una gran variedad de tipologías de cultivo, que condicionan directamente la recolección y la maquinaria empleada. La clasificación de las distintas tipologías de cultivo puede atender a diferentes criterios, como la densidad de plantación (ESYRCE, 2013), o a una combinación entre densidad de plantación, rendimientos, topografía y estructura del árbol (AEMO, 2012). Esta última clasificación divide el olivar en tres categorías diferentes y dos subcategorías:

- Olivar tradicional: se trata de parcelas con amplios marcos de plantación, 10 – 12 m de distancia entre árboles (80 – 150 árboles/ha), con una estructura del árbol formada con 2 ó 3 pies y un rendimiento relativamente bajo (4.000 – 10.000 kg/ha), aunque depende mucho de las condiciones edafoclimáticas (Fig. 3).
    - Olivar tradicional no mecanizable: son explotaciones que se sitúan en zonas con pendiente superior al 20 % o en parcelas demasiado pequeñas o de difícil acceso para su mecanización. Este tipo de explotaciones supone el 24 % de la superficie de olivar en España.
    - Olivar tradicional mecanizable: se sitúa en zonas con pendientes suaves o moderadas, inferiores al 20 %. Esta tipología de olivar es la más extendida, con un 52 % de la superficie nacional.
- Olivar intensivo: son parcelas con árboles usualmente formados a un pie y con poda en vaso, plantados en zonas de orografía suave, y que registran producciones elevadas (4.000 – 12.000 kg/ha). La densidad de plantación es elevada, de 200 a 600 árboles/ha y existe una calle ancha de al menos 6 m para permitir la circulación de maquinaria. Este tipo de plantación tiene una vida útil probada de 40 años, ocupando un 22 % de la superficie total de olivar en España (Fig. 4).
- Olivar superintensivo: se trata de plantaciones de olivar de muy alta densidad, 1.000 – 2.000 árboles/ha con árboles formados con un eje central y dispuestos en seto. La calle ancha para la circulación de maquinaria no supera los 5 m y la distancia entre árboles es inferior a 2 m. La recolección se realiza mediante una

cosechadora cabalgante. La vida útil probada es de 15 años, aunque actualmente hay algunas parcelas con una edad mayor en experimentación. Esta tipología de olivar supone un 2 % de la superficie española de olivar, aunque se encuentra en pleno crecimiento (Fig. 5).

Fig. 3. Olivar tradicional no mecanizable debido a la pendiente (izquierda), y olivar tradicional mecanizable (derecha).

Fig. 4. Olivar intensivo de mesa, formado a un pie y en vaso.

Fig. 5. Olivar superintensivo.

Algunos autores han introducido algunas variantes en esta clasificación como la regularidad de plantación (Vieri & Sarri, 2010), es decir, si los árboles están plantados según un patrón uniforme, o estás distribuidos en el terreno de forma aleatoria. Otra modificación de la clasificación se ha basado en el sistema de poda empleado para formar los árboles, que condiciona el sistema de recolección a emplear, (Lizar, Biurrun, Perez de Ciriza, & Albós, 2003), como ocurre en olivar tradicional, donde no se puede emplear un sistema cabalgante.

Teniendo en cuenta las diferentes tipologías de olivar, se puede deducir que no existe un único sistema de recolección mecanizada capaz de trabajar en todas ellas. Sin embargo, actualmente, la mayor parte del olivar en nuestro pais, se recoge mediante el empleo de vibradores de troncos (Gil-Ribes, López-Gimenez, Blanco-Roldán & Castro-García, 2008), encargados de llevar a cabo el derribo del fruto. El fruto derribado, posteriormente es recogido sobre mallas previamente extendidas o mediante el empleo de estructuras de recepción en forma de paraguas invertido. El vibrador de troncos se emplea principalmente en el olivar tradicional mecanizable y en el olivar intensivo. El uso del vibrador de troncos está poco extendido en olivar tradicional no mecanizable debido a los problemas de estabilidad del tractor al trabajar con una máquina suspendida que afecta de forma importante al centro de gravedad del conjunto. Por otra parte, en olivar superintensivo, el uso del vibrador de troncos es inviable por criterios económicos, ya que el gran número de troncos que debería vibrar por hectárea reduciría de forma importante la capacidad de trabajo.

Otros sistemas de recolección empleados actualmente, están adaptados a una tipología específica de olivar, como ocurre con las cosechadoras cabalgantes para seto en el caso del olivar superintensivo, o para los paraguas invertidos en el caso del olivar intensivo. Para alcanzar un alto grado de eficiencia, es recomentable adaptar la máquina a la estructura del árbol, y la estructura del árbol a la máquina. Ambas operaciones deben realizarse de forma simultánea para mejorar los sistemas de recolección mecanizada.

A día de hoy, el olivar superintensivo ya cuenta con un sistema de recolección eficiente y con una capacidad de trabajo muy notable, aunque requiere una fuerte adaptación de los árboles. Esta es una de las grandes limitaciones de este tipo de plantaciones, ya que se requiere un reducido vigor de los árboles. Además existen otros factores limitantes como el mayor riesgo de enfermedades foliares debido a la falta de aireación y alta densidad de plantación (Tous, Romero, & Hermoso, 2010), o la deficiente iluminación que puede provocar un crecimiento excesivo del seto (Pastor y Humanes, 2006). Sin embargo, actualmente esta tipología de olivar es minoritaria a nivel mundial con 80.000 ha de las cuales la mitad se encuentran en nuestro país (Tous et al., 2010), aunque en los últimos años se ha incrementado notablemente su superficie. A pesar de que el olivar superintensivo ya cuenta con un sistema de recolección muy conseguido, buena parte de la investigación en olivar se centra en el (Connor, Gómez-del-Campo, Rousseaux, & Searles, 2014). Por lo tanto, es importante suplir la carencia de investigación básica que existe para el olivar tradicional e intensivo, que actualmente suponen la mayor parte de la superficie mundial de este cultivo.

En el extremo opuesto al olivar superintensivo se encuentra el olivar tradicional, que presenta un nivel de competitividad menor que el resto de tipologías de olivar. Esta falta de competitividad puede achacarse a la falta de adaptación para una mecanización eficiente, o a la excesiva atomización y dispersión de las parcelas, y a los altos costes de explotación (Vilar Hernández, Velasco Gámez, Puentes Poyatos, & Martínez Rodriguez, 2011). Otro aspecto a tener en cuenta para mejorar la competitividad y rentabilidad del olivar en relación al empleo de maquinaria es aplicar distintos modelos de gestión de maquinaria que optimizan el coste horario (cooperativas de uso en común de la maquinaria agrícola o empresas de servicios). Estas estrategias reducen la dispersión de las parcelas, aumentando la competitividad del olivar (Vilar Hernández, Velasco Gámez, & Puentes Poyatos, 2010).

Sistemas de recolección comerciales y en desarrollo.

En la actualidad coexisten numerosos sistemas de recolección mecanizada, sistemas de ayuda a la recolección portados por el operario, (vibradores y sacudidores de ramas) e incluso sistemas exclusivamente manuales (vareo y ordeño) ya que no existe una solución única válida para todos los tipos de olivar. Los sistemas de derribo del fruto por vibración son los más extendidos y aplicables, conviviendo, actualmente, con sistemas constituidos por sacudidores de copa y con las cosechadoras de olivar superintensivo. Sin embargo para el olivar tradicional no existe ninguna cosechadora comercial que permita la recolección integral de este cultivo (Gil-Ribes, Blanco-Roldán & Castro-García, 2009), aunque existen algunos prototipos en desarrollo (Sola-Guirado, 2016).

En general, la recolección del olivar está muy condicionada al empleo de mano de obra para la recogida, limpieza, carga y descarga del fruto hasta la industria. En numerosas ocasiones, su coste supone más de la mitad de todos los costes del cultivo por lo que su mejora es clave para la sostenibilidad del cultivo (Gil-Ribes, López-Gimenez, Blanco-Roldán & Castro-García, 2008). Los diferentes sistemas de recolección no integrales que se emplean en la actualidad consiguen efectuar el derribo del fruto aplicando patrones de vibración muy diversos. Sin embargo, a la hora de realizar la recepción y manejo del fruto, la mayor parte de los sistemas suelen realizar el derribo sobre mallas (Fig. 6) y en algunas ocasiones se derrba el fruto al suelo (Fig. 7) y se hilera con sopladores neumáticos para después recoger manualmente o con una barredora. Esta práctica está cada vez más en desuso para evitar la pérdida de calidad que tiene lugar cuando se recogen los frutos del suelo (Porras, 1987).

Fig. 6. Derribo con vibrador autopropulsado y vareo complementario sobre mallas.

Fig. 7. Derribo de fruto al suelo, para ser hilerado y recogido posteriormente.

Las nuevas tendencias en recolección mecanizada inciden en la recolección integral para el manejo del fruto derribado. La recolección integral mecanizada de un cultivo es aquella que puede realizarse mediante una sola máquina que se encarga de realizar el derribo, recepción y manejo del fruto. Las máquinas que realizan la recolección integral se conocen como cosechadoras y han sido desarrolladas y adaptadas a diversos cultivos como el olivar superintensivo e intensivo, los cítricos, la viña, jatropha, frutos rojos y otras bayas. En trabajos realizados por el grupo de investigación AGR-126, se están desarrollando sistemas de recolección integral basados en la sacudida de copa para el olivar tradicional e intensivo, tanto de almazara, como de mesa (Sola-Guirado, 2016).

Las cosechadoras para cultivos leñosos existentes y en desarrollo en la actualidad se pueden clasificar según tres características principales: la estructura de la cosechadora, el sistema de derribo, y el sistema de propulsión (Tabla 1). La estructura de la cosechadora condiciona de forma muy importante la formación de los árboles que van a ser recogidos con la máquina, por ejemplo, las cosechadoras cabalgantes limitan la altura y ancho de copa de los árboles a recoger, limitando el crecimiento del árbol (Farinelli & Tombesi, 2015). Sin embargo los sistemas de cosecha laterales pueden presentar problemas de estabilidad de la máquina mientras que los paraguas invertidos están limitados por los bajos porcentajes de derribo y la dificultad que presenta el empleo de sistemas de apure complementario. El sistema de derribo también condicionará la formación del árbol, la zona de la copa en la que se potencia la fructificación, y por último, el sistema de propulsión determina las dimensiones, peso, coste y maniobrabilidad del sistema. Actualmente se han identificado dos tecnologías de derribo: la sacudida de copa y la vibración de tronco (Ferguson & Castro-Garcia, 2014) Cualquier combinación de estas opciones puede ser válida para la recolección de olivar, aunque es necesario adaptar el árbol y el diseño de plantanción a la máquina que se vaya a emplear.

Tabla 1. Clasificación de las cosechadoras integrales para cultivos leñosos.

Clasificación	Categoría	Descripción
Según la estructura de la máquina	Cosechadora lateral (*side by side*) (Ravetti & Robb, 2010)	Cosecha lateral que trabaja en línea o alrededor del árbol. Cuando se realiza en línea suele ir acompañada de dos máquinas, una por cada lado de la hilera de árboles. Requiere una altura de cruz y de las ramas bajas determinada.
	Cosechadora cabalgante (*Straddle harvester*) (Ravetti & Robb, 2010)	Sólo puede trabajar en línea, pasando una estructura en forma de pórtico por encima del árbol. Limita las dimensiones de la copa.
	Cosechadora con sistema de recepción en forma de paraguas invertido (*reverse umbrella*) (Leone, Romaniello, Tamborrino, Catalano, & Peri, 2015)	Consiste en un sistema de lonas u otro material flexible anclado a una serie de barras que recogen o extienden el sistema de recepción. Este sistema forma una superficie de revolución en forma de tronco de cono. Requiere una cierta separación entre árboles y altura de ramas bajas determinada.
Según el sistema de derribo	Vibrador de troncos	Agarra el tronco mediante una pinza con dos o tres puntos de sujección, y lo vibra generando un movimiento alternativo mediante la revolución de unas masas excéntricas
	Sacudidor de copa	Sistema de vareo mecánico rotativo o alternativo que aplica la vibración directamente a las ramas del árbol.
Según el sistema de propulsión.	Arrastrada por el tractor	Aumenta la longitud del conjunto y disminuye la maniobrabilidad
	Autopropulsada	Aumenta el coste de adquisición y amortización de la máquina.

Las cosechadoras cabalgantes son una opción que hasta el momento ha dado un buen resultado en la recolección de olivar superintensivo, y actualmente está en desarrollo para olivar intensivo (Fig. 8). El mayor inconveniente de esta estructura de cosechadora es que limita el crecimiento de los árboles, reduciendo las variedades de olivo que pueden emplearse, ya que debido al elevado vigor del olivo, la planta se hace demasiado grande para el sistema de recolección en un corto periodo de tiempo. Para solventar estos inconvenientes, se están desarrollando nuevas variedades de olivo con reducido vigor, con algunas variedades patentadas en la actualidad como Olea europaea 'Chiquitita' (Barranco & Rallo, 2008), 'Oliana' u otras variedades comerciales (Cunill & Durán 2014).

Fig. 8. Cosechadora cabalgante basada en la vibración de tronco para olivar intensivo.

En el caso de las cosechadoras laterales, lo más común es que de una pasada se recoja la mitad de la copa en una calle de olivar intensivo, pudiendo emplear una máquina por un lado para dar dos pasadas por línea (Fig. 9) o dos máquinas trabajando de forma simultánea (Fig. 10). Cuando trabajan dos máquinas, una a cada lado de la línea de árboles, se reduce la proyección de fruto, pero se debe coordinar el movimiento de ambas cosechadoras para optimizar el sistema de recolección.

Fig. 9. Sacudidor de copa lateral en olivar intensivo. Este sistema debe realizar dos pasadas por línea de árboles.

Fig. 10. Cosechadora side by side arrastrada y basada en la sacudida de copa desarrollada por la Universidad de Évora y la empresa Vicort (Peça, Pinheiro, Dias, Cardoso 2013).

Las estructuras en forma de paraguas invertido son otra alternativa para la recolección de olivar intensivo. Actualmente son ampliamente usadas junto con un vibrador de troncos, ambos montados sotre un tractor o sobre una máquina autopropulsada. En conjunto, ambas máquinas realizan el derribo, recepción y manejo del fruto, pero presentan varios problemas. Por un lado, estos sistemas limitan el marco de plantación, que no debe ser inferior a 7 x 5 m, y las dimensiones de los árboles, en cuanto a la altura de las bajeras y a la amchura de copa. Todo ello para poder posicionarse correctamente (Fig. 11). Por otro lado, necesitan un tractor y un remolque auxiliares para efectuar la descarga del fruto de forma eficiente (Fig. 12), y por últmo, dificultan el vareo u otros métodos de apoyo para aumentar la eficiencia de derribo del sistema de recolección.

Fig. 11. Paraguas invertido con vibrador de troncos recogiendo en una finca de olivar intensivo.

Fig. 12. Paraguas invertido realizando la descarga en un remolque.

Poda y diseño de plantación en olivar: relación con la recolección

En general, los sistemas de recolección integral, requieren una adaptación del cultivo a la máquina mediante la poda de formación y de producción, que asegure que la estructura del árbol se adecua al trabajo de la cosechadora. El sistema de poda y el diseño de plantación, deben adaptarse al sistema de cosecha que se vaya a emplear en una explotación, incluso para aquellas máquinas que no son integrales como es el caso de los vibradores de troncos (Humanes-Guillén, 1994) o para sacudidores de copa, (Ferguson & Castro-García, 2014). Además, el tamaño de los árboles también es un factor a tener en cuenta para mejorar la eficiencia de derribo con vibradores de troncos, ya que se ha encontrado una relación negativa entre el tamaño de los árboles y la eficiencia de derribo (Porras, 1987).

La estructura del árbol viene condicionada principalmente por la tipología de olivar en la que estamos trabajando. En este sentido, el olivar superintensivo, viene caracterizado por una estructura en eje central, que favorece el trabajo de la cosechadora, aunque se deben limitar las dimensiones en altura y anchura del seto para permitir la cosecha mecanizada (Tombesi & Farinelli, 2014) frecuentemente mediante la poda mecanizada, aunque su efecto e intensidad dependen del vigor de cada variedad (Vivaldi, Strippoli, Pascuzzi, Stellacci, & Camposeo, 2015). En el caso de los olivares intensivos, suelen estar formados en vaso, contando con una estructura entre 2 y 4 ramas principales y con una altura de tronco de al menos 0,8 – 1 m para garantizar el buen trabajo de los vibradores de troncos. Además, en Italia, ha sido frecuente la formación del olivar intensivo en monocono (Fig. 13), aunque este sistema requere mayores tiempos de poda y genera menos crecimiento en los árboles (Preziosi, Proietti, Famiani, & Alfei, 1994).

Fig. 13. Olivar intensivo formado en monocono. Perugia, Italia.

En cuanto al olivar tradicional, existen diversos sistemas de formación, desde la formación con varios troncos típica en el sur de España, hasta la existencia de grandes árboles con alturas entre 10 y 15 m en Italia y el norte de áfrica, con la consiguiente dificultad para recoger estos árboles (Famiani et al., 2014). El olivar tradicional puede recibir podas de renovación más o menos intensas en función de las condiciones climáticas, por ejemplo, en el sur de España es frecuente aplicar podas de renovación (Fig. 14) con el objetivo de mantener la copa rejuvenecida y con una alta eficiencia productiva (Pastor & Humanes, 2006), mientras que en otras zonas del mediterráneo, el olivar tradicional adolece de podas de renovación, mermando su capacidad productiva debido a el envejecimiento de la estructura del árbol (Fig. 15). No obstante, conviene resaltar, que esta falta de podas de renovación, no es casual, sino que responde a las necesidades impuestas por un ciclo de crecimiento más corto.

Fig. 14. Poda de renovación en olivar tradicional. Jaén, España.

Fig. 15. Olivar tradicional sin renovación de ramas principales. Perugia, Italia.

El impacto de la formación de los árboles, el diseño de plantación y el periodo de recolección sobre la velocidad, eficiencia y coste de recolección requiere un estudio cuidadoso para las nuevas cosechadoras de olivar (Ravetti & Robb, 2010). Una forma de estudiar las operaciones mecanizadas en campo es el empleo de equipos de adquisición de datos basados en la tecnología GPS, que combinados con distintos sensores, permiten obtener grandes volúmenes de información en condiciones de trabajo reales empleando recursos limitados (Hejazian, Hosseini, Lotfalian, & Ahmadikoolaei, 2013). Para aumentar la precisión de la localización, los sistemas de navegación actuales recurren a diferentes sistemas de navegación (al menos GPS y GLONASS), que evitan la falta de cobertura especialmente en terrenos con grandes árboles (Valbuena, Mauro, Rodríguez-Solano, & Manzanera, 2012).

Es necesario el estudio de la adaptación del olivo a la mecanización mediante un correcto diseño de plantación (marco, cabeceras y calles de servicio) y el desarrollo del árbol (altura del tronco, número de ramas principales y poda) que favorezcan la realización de la recolección (Dias et al., 2004). Además, se requiere la adecuación de los parámetros de funcionamiento de la máquina al tipo de árbol lo que ha sido estudiado anteriormente en otros cultivos recogidos por vibración (Rosa et al., 2008; Torregrosa, Ortí, Martín., Gil. & Ortiz. 2009). En este sentido, el modelado del sistema fruto-pedúnculo de la aceituna revela que aunque gran parte de los frutos caen durante el periodo transitorio, la rotura del sistema fruto-pedúnculo requiere de un determinado número de ciclos ya que la intervención de los esfuerzos inerciales necesitaría aceleraciones muy elevadas (López-Giménez, 1979).

La estructura de la planta afecta directamente a los frutos derribados por vibración, variando la eficiencia de derribo en función de la inclinación de las ramas (Herruzo, Pastor, & Holgado. 1975), sin embargo, la eliminación de las ramas en las que la vibración actúa con menor eficacia no es aconsejable desde el punto de vista agronómico, pues reduce de forma importante la producción (Pastor & Humanes, 2006). La poda de formación en frutales, afecta a la eficiencia de cosecha mediante sacudidores de copa (Mika et al., 2012), y mediante vibradores de troncos (Tombesi, Boco, Pilli, & Farinelli, 2002), por lo tanto es recomendable desarrollar un método de poda que mejore la eficiencia de derribo empleando estas máquinas, de forma que se consiga un método de recolección integral sin dejar porcentajes elevados de fruto en el árbol.

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CAPITULO 3. HIPÓTESIS Y OBJETIVOS A ALCANZAR

Hipótesis: Es posible optimizar el proceso de recolección, adaptando los árboles mediante la poda y el diseño de plantación a la cosechadora. Este proceso debe generar una mejora de la eficiencia de recolección sin afectar a la producción.

El objetivo general de la presente tesis doctoral es proveer una caracterización de los sistemas de recolección integrales existentes en la actualidad. Además se va a realizar un estudio sobre la infuencia de la estructura de la copa y la distribución de frutos en la recolección mecanizada del olivo. Por último, se aborda cómo se puede modificar la estructura del árbol para aumentar por un lado, la eficiencia productiva, mejorando o manteniendo la producción cosechable y por otro lado, mejorando la eficiencia de la recolección mecanizada integral.

Para simplificar la definición de los objetivos, se dividen en los siguientes objetivos parciales:

Análisis y evaluación de la recolección mecanizada con cosechadoras en olivar de almazara. Artículo / paper 1.

Se ha desarrollado y ensayado un sistema de seguimiento para maquinaria agrícola y un monitor de rendimiento para cosechadoras de cultivos leñosos. Se ha analizado el trabajo de distintas cosechadoras en olivar para determinar la capacidad de trabajo y el rendimiento de campo de las mismas, evaluando cómo varían estos parámetros en función de distintas características de las plantaciones como la longitud de línea, la forma de la parcela, el ancho de calle o el ángulo entre las hileras de árboles y las calles de servicio.

Publicado en: Development of a telemetry and yield mapping system of olive harvester. 2015. F.J. Castillo-Ruiz, M. Pérez-Ruiz, G.L. Blanco-Roldán, J.A. Gil-Ribes, J. Agüera. Sensors, 15, 4001-4018. JCR ® 2015 con índice de impacto de 2,033; posición 12/56 (1º cuartil) en el área temática: Instruments & Instrumentation.

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Determinación de los patrones de distribución de la producción, rendimiento graso y calidad del aceite de oliva en la copa. Artículo / paper 2.

Se ha determinado la distribución de la producción de frutos, rendimiento graso y calidad del aceite de oliva dentro de diferentes zonas de la copa de los árboles. Además se han identificado las zonas de la copa donde es prioritario alcanzar una alta eficiencia de cosecha para adecuar el diseño de futuras cosechadoras, maximizando la eficiencia del proceso de recolección. Las zonas prioritarias de la copa se establecen en función de la cantidad de frutos, o a la calidad del aceite obtenido.

Publicado en: Analysis of fruit and oil quantity and quality distribution in high-density olive trees in order to improve the mechanical harvesting process. 2015. F.J. Castillo-Ruiz, F. Jiménez-Jiménez, G. L. Blanco-Roldán, R. R. Sola-Guirado, J. Agüera-Vega, S. Castro-García. Spanish Journal of Agricultural Research, 13 (2), 0209. JCR ® 2015 con índice de impacto de 0,76; posición 24/57 (2º cuartil) en el área temática Agriculture, Multidisciplinary.

DOI: 10.5424/sjar/2015132-6513

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Caracterización de la estructura de la copa del olivo en función de la poda aplicada. Artículo / paper 3.

Se ha desarrollado una metodología para caracterizar la porosidad de la copa en olivar tradicional en función de la aplicación de diferentes podas que adaptan la estructura del árbol a varios sistemas de recolección. Además, se busca validar el método de medida con diferentes ángulos cenitales del sol y discernir cómo se puede influir en la porosidad de la copa mediante la poda.

Publicado en: Olive crown porosity measurement based on radiation transmittance: an assessment of pruning effect. 2016. F.J. Castillo-Ruiz, S. Castro-Garcia, G.L. Blanco-Roldán, R.R. Sola-Guirado, J.A. Gil-Ribes. Sensors, 16, 723. JCR ® 2015 con índice de impacto de 2,033; posición 12/56 (1º cuartil) en el área temática Instruments & Instrumentation.

DOI: 10.3390/s16050723

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Estudios adicionales / additional studies.

El primer estudio adicional, evalúa el efecto de los sistemas de poda empleados sobre la recolección con sacudidores de copa, evaluando la influencia de la poda sobre la producción total y la producción interior.

En el segundo estudio adicional se ha cuantificado la influencia de los esfuerzos torsores en el desprendimiento del fruto en diferentes variedades y a lo largo de todo el periodo de maduración del fruto.

Estos trabajos se encuentran enviados para su publicación. Actualmente se encuentran en proceso de revisión.

CAPITULO 4. ANÁLISIS Y EVALUACIÓN DE LA RECOLECCIÓN MECANIZADA CON COSECHADORAS EN OLIVAR DE ALMAZARA

Resumen

La introducción de sensores, sistemas de comunicación y georreferenciación en agricultura, es recomendable para alcanzar un óptimo manejo de los insumos desde el punto de vista económico y ambiental. En el presente trabajo, se han seguido tres cosechadoras de olivar basadas en la sacudida de copa durante dos campañas en España y Chile. Para ello se han empleado equipos autónomos con envío remoto de datos para determinar la capacidad real de trabajo y la eficiencia de campo. Durante este tiempo, las cosechadoras han trabajado en olivar intensivo y superintensivo. Para determinar la posición de las cosechadoras se ha empleado el sistema de navegación GNSS (*Global Navigation Satellite System*) y los datos han sido enviados vía GSM (*Global System for Mobile Communications*). El trabajo de la cosechadora no se ha visto interrumpido por el sistema de seguimiento. Se ha desarrollado un sistema de separación de tiempos para analizar los datos y obtener la capacidad de trabajo real y la eficiencia de campo. Además, se ha evaluado la influencia de la forma de parcela, longitud de línea, ángulo entre la línea y la calle de servicio y ancho de calle sobre el trabajo de la cosechadora, para dar pautas sobre el diseño de plantación adaptado a la recolección mecánica integral. Además, se desarrolló e instaló un monitor de rendimiento en una cosechadora para olivar tradicional. La cosechadora de olivar superintensivo, destacó por su elevada capacidad de trabajo, aunque la eficiencia de campo fue mayor en la cosechadora no integral. Los parámetros estudiados del diseño de plantación han influido ya sea en la capacidad de trabajo real o en la eficiencia de campo de las cosechadoras, principalmente en las plantaciones de olivar superintensivo. Por ejemplo, anchos de calle de 3.5 m han generado una reducción del 40 % de la capacidad de trabajo real respecto a anchos de calle de 4 m o superiores. Finalmente, el monitor de rendimiento ha permitido la elaboración de un mapa de cosecha en el que se aprecia el gradiente de producción a lo largo de la parcela, a pesar de la alta variabilidad entre árboles.

Palabras clave: Toma remota de datos, agricultura de precisión, capacidad de trabajo real, eficiencia de campo.

Abstract

Sensors, communication systems and geo-reference units are required to achieve an optimized management of agricultural inputs with respect to the economic and environmental aspects of olive groves. In this study, three commercial olive harvesters were tracked during two harvesting seasons in Spain and Chile using remote and autonomous equipment that was developed to determine their time efficiency and effective field capacity based on canopy shaking for fruit detachment. These harvesters work in intensive/high-density (HD) and super-high-density (SHD) olive orchards. A GNSS (Global Navigation Satellite System) and GSM (Global System for Mobile Communications) device was installed to track these harvesters. The driver's work schedule was not affected by the GNSS receiver. Time elements methodology was adapted to the remote data acquisition system. The effective field capacity and field efficiency were investigated. In addition, the field shape, row length, angle between headland alley and row, and row alley width were measured to determine the optimum orchard design parameters. Moreover, a yield monitor was developed and installed on a traditional olive harvester to obtain a yield map from the harvested area. The hedge straddle harvester stood out for its high effective field capacity; nevertheless, higher field efficiency was provided by a non-integral lateral canopy shaker. All of the measured orchard parameters have influenced machinery yields, whether effective field capacity or field efficiency, chiefly, for SHD olive harvester, for instance, a reduction in alley width from 4 m or higher widths to 3.5 m caused a 40 % of reduction in its effective field capacity. A yield map was plotted using data that were acquired by a yield monitor, reflecting the yield gradient in spite of the larger differences between tree yields.

Keywords: Remote data acquisition, precision agriculture, effective field capacity, field efficiency.

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Introduction

Olive trees are the main woody crop in Spain. Olive orchards cover 2.58 Mha, of which 96% is dedicated to oil olive production [1]. Most of the olive orchard area (~76%) is currently planted according to the traditional model: 2, 3 or 4 trunks per tree and wide spacing between trees. However, 24% of the area presents a major challenge to mechanized operations due to steep slopes. Only 56% of the area is considered to be suitable for mechanization under traditional orchards [2]. Cropping olives for oil has traditionally been performed in the Mediterranean basin. However, in the last decade, this practice has spread to other countries, such as Chile, where the area for this crop increased from 5000 ha in 2003 to 18000 ha in 2013 [3].

Since the introduction of the trunk shaker, no new harvesting systems have been developed for olives [4]. Thus far, canopy shaker systems have been tested in traditional olive oil orchards in Spain. This harvesting method is characterized by a high amplitude and low frequency applied directly to fruit-bearing branches [5]. However, mechanical harvesting is still in the developmental stage. Currently, it is possible to observe more than 50 units of large continuous straddle harvesters operating in modern groves throughout the world: high and super-high-density olive groves with more than 1000 trees per hectare and one trunk per tree (Spain, Argentina, Chile, USA, and Australia) [6]. This solution requires a strong orchard and tree adaptation to the machine [7].

According to the MAX program (Conservation Technology Information Center, West Lafayette, Indiana), machinery operation can be as high as 25% of the total cost of crop production. Agricultural machinery is seldom engaged in productive work 100 percent of the field time. Many delays occur that result in lost time, and any operation will vary greatly from field to field and farm to farm [8,9]. Effective field capacity and field efficiency are two primary parameters that are used to evaluate machinery performance. While the effective field capacity represents the amount of processing that a machine can accomplish per hour of time [10], the field efficiency is defined as the ratio between effective and theoretical machine capacities and relates the estimated and actual time that are required to complete a field operation (with no reference to the area) [11]. In the past, collecting and managing field data have had a significant component of human labor that is time consuming and labor intensive. Modern telecommunication technologies are required to improve the data collection efficiency and precision agriculture [12].

A large body of research has reported the use of a global system for mobile communication (GSM) and short message services (SMS) to conduct field operation data acquisition and has investigated the feasibility of this system [12-14]. The advantages of agricultural field operation data transmission through GSM system are 1) simple power solution, 2) coverage of a wide range of areas [15], 3) maintenance of user data in the GSM service center for 24 h if the host server is out of service, and 4) group broadcast easily enabled to send real-time alerts from any dysfunctional devices for immediate attention. These technologies have been developed for tracking equipment transport vehicles, ambulances, fire, etc. with various data uses that are very different from those required in agriculture. In other cases, the devices require interventions that are far too costly for a fleet that is composed of multiple units [16].

Optimum machinery management is considered to be one of the main factors in making olive orchards more profitable and environmentally sustainable. In mechanized operations, at least two factors play a very important role in the effective field capacity. One factor is machine management, which involves such items as machine speed selection, labor force used, machine hours, machine geographical location, flow of material to and away from the machine, and maintenance information. The second factor involves the physical condition of the field, which includes field size and shape, topography, row length and orchard layout, row-end turning space, and surface condition in the turn area [17]. Overall, precision agriculture, particularly precise vehicle tracking systems, is considered to be essential to reach mechanized operation efficiency. These systems can avoid that technicians travel over long distances to be on-site during operations in olive tree fields; therefore, Global Navigation Satellite Systems (GNSS) can reduce the time and cost for studies [18].

In agriculture, the use of a positioning satellite system to determine the real-time machine position is a reality. The new position location receivers that are available for agricultural operation combine multiple GNSS systems (at least with GPS & GLONASS) to provide better accuracy under canopy coverage. This improvement prevents problems due to GNSS outages under tree canopy and increases the overall performance improvement and robustness of satellite-based navigation, thus making it possible to obtain a better position fix within an orchard with large trees [19].

Furthermore, yield variability in herbaceous crops may arise due to soil characteristics. In olive groves, however, there is great variability among individual trees each year, although mainly in non-irrigated plants [20]. In addition, the occurrence of alternate bearing in olive trees makes it more difficult to interpret yield maps for fruit trees. Few studies have been conducted on yield mapping in woody crops. For hand-harvested citrus, yield maps [21,22] or canopy size maps [23] have been reported. [24] developed a load-cell-based yield monitoring system for the Oxbo citrus mechanical harvesting machines, achieving a correlation of 0.97 between the actual weight and the computed weight with an average error of 7.81%.

According to [25] both farmers and researchers can benefit from advances in real-time data geo-referenced data logging, which often can be reviewed off-site to examine traffic patterns, field practices, and other operational issues. Currently, the monitoring of agricultural field operation is now feasible and may be a useful tool for olive farmers, but as of yet, it is not widely used in commercial olive groves. Bakhtiari [26] reported a savings range from 18% to 40% of the total non-working travelling distance for a combine harvester, making optimal mechanized operation planning.

Previous research on mechanized operation performance and field layout has shown a significant trend between forage harvester effective field capacity and crop yield, lengthwise slope and field area [27]. Some authors suggest that field shape influence on effectvive field capacity [28], and some studies have even determined that the optimal field shape should be rectangular with 4:1 length:width ratio [29].

The objective of this research was to determine the olive harvester field performance (effective field capacity and field efficiency) using a new remote and autonomous device in three olive harvesters and to evaluate a yield-monitoring system for a mechanical olive harvester that was fabricated for this study

Material and methods

All of the design decisions with respect to the developed telemetry tracking system were made with two criteria in mind: low-cost study and scalable capabilities. The structure of the system that is presented in this research can be divided into two major sections: the Machine Remote Monitoring Platform (MRMP) and the Host Control Platform (HCP) for monitoring, statistical analysis and field information reporting for decision-making.

Machine Remote Monitoring Platform

The MRMPs were located aboard on each olive harvester that was used in this study, and each MRMP was equipped with a terminal MTX 65+G (Matrix Electronica, S.L., Madrid, Spain) that was programmed using JAVA language. The terminal MTX 65+G integrated a GSM (Global System for Mobile communications) GPRS radio system and a DGNSS (Differential Global Navigation Satellite System) receiver with 16 channels, including a range of I/Os and USB/SPI/I2C/RS232 ports, was used to track the olive harvesters. The terminal had storage capacity to keep the data when GSM coverage was not available. In addition, it had a preprocess functionality to provide understandable packets to the HCP. The GSM module enables to the MRMP to transmit data packets in real time every 4 s, which will allow further analyses. Each data packet that was used in this study contained the agricultural vehicle identification machine (IM), date, time, latitude and longitude, altitude, speed, heading, coverage, and four digital and two analogical inputs with 12 bit. One digital input signal enabled the monitoring the status of the hydraulic valve to determine when the shaking system of the harvesters was working. One analogical input signal was used for the MRMP mounted on lateral canopy shaker to sense the accumulated fruit weight and to determine each olive yield.

Host Control Platform (HCP)

To exploit the data that were generated by the system, two programs were used. These programs accomplish two functions: data storage and data consultation and downloading. These programs were programmed on Visual Basic and implemented in Excel (Microsoft Corp., Redmond, WA, USA). These data were used as input files directly downloaded, previously converting from coordinated universal time convention (UTC) to local time.

The first computer program was used to create a file Keyhole Markup Language (KML), which permits the rendering of data of the vehicle on Google Earth [30]. Each record is a "placemark", which permits the examining of particular locations, and appearance characteristics may differ according the vehicle status sensors at the time. Clicking on the "placemarks" generates the associated information, that is, the content of all the field that composes the record; latitude (y) and longitude (x) can always be read by another application window. In addition, these data indicate where the vehicle was at a particular time period and the status of the digital inputs. With these specific tools, it may be possible to determine the field works that are performed for the farm vehicle: field plots visited, time worked, surfaces worked and distances travelled. However, this determination would be time consuming and therefore costly whether it was performed manually by in situ technicians examining (Fig. 16).

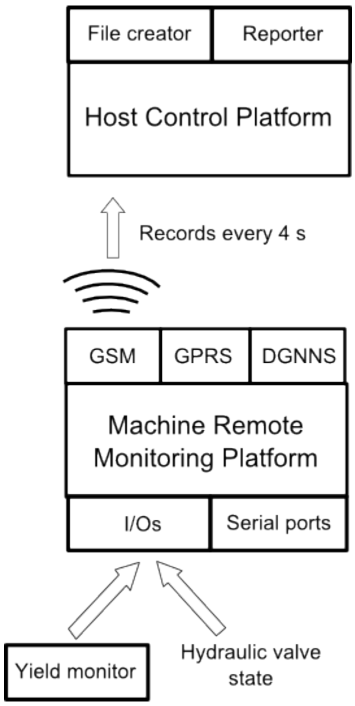

Fig. 16. Hardware scheme of a remote wireless automatic monitoring system. Data transmission and communication between agricultural vehicles and expertise center.

The second computer program that was developed was called "REPORTER", which enables a rapid and easy analysis. Once the file to be processed is selected, the program create a results table in which each row refers to a worked plot, with the name in the first column, while the remaining columns are labeled with the different times used and distances traveled for the vehicle. To implement this program, it is necessary to previously compile a database of plots that are worked by the vehicle, with boundary map polygon information from ESRI's shape files and a series of programming modules that are specialized in handling shp files, topology, projections of geographical coordinates, etc.

Yield Monitor

A prototype automatic system to record yield that was designed and fabricated specifically for this study was installed on a lateral canopy shaker (Oxbo 3210) that included a catch frame to perform an integral harvesting for traditional orchards. This system consisted of a controller box, and the force transducer (MLC807-3000kg, ManyYear Technology Co., Ltd., Hong Kong, China), which was installed in the rear receptacle support to measure its accumulated weight. This force transducer was wired to provide an analogical signal from 0 to 3.3 V and the circuitry was adjusted for an offset of zero volts. The procedure for calibrating the force transducer in the laboratory in accordance with the standards for linear measurements device (USBR 1045-89) was provided. The laboratory test procedures consisted of a first set of 6 loads from 40 to 240 kg (in 40-kg increments). These loads were sequentially loaded into the harvester receptacle and then unloaded. In a second set, a large known load weight of 288 kg was located into the receptacle. Incremental loads of 40 kg were then added to a total of 528 kg, after which the receptacle was unloaded. Load weights of 40 kg were used with the purpose of simulating the average kilograms per tree harvested under the expected conditions. Two repetitions were used for developing the calibration equation that will determine the estimated olive fruit load in the field tests.

In the field tests, the yield monitor system provided the accumulated weight of the harvested fruit in real-time and when the receptacle was unloaded. The weight data were processed after the harvester operation to obtain each tree harvest and were assigned to each harvested tree depending on the provided harvester location for each record. Fruit management delay along the catch frame belts was used to determine how long it takes the fruit to be stored in the receptacle. The data from the load cells together with the DGNSS data for the fruit receptacle locations were transmitted for the terminal unit wirelessly to the host control platform. The setup instructions and data were transmitted. The sequence of data transmission was DGNSS, weight, A/D, and RS-232.

The GNSS sensor that was used for this work was integrated in the MTX 65+G Siemens terminal with output data in the NMEA-0183 GGA string via an RS-232-compatible serial port at 9600 bps.

Spatial distribution maps were created using the GIS software SStoolbox (SST Development Group, Inc., Stillwater, OK, USA) by interpolating the harvest of 33 trees using the inverse distance weighted method.

Time study methodology validation

In the past, machinery field operation research was tedious and time consuming, requiring the travel of large distances and the researcher to be on-site during the operation. In this study, an automatic methodology was used to examine the time elements and to classify them into each field task. This methodology did not consider the harvester actions but instead classified time intervals depending on work parameters, such as speed, covered distance or status of the digital inputs (in this case, the hydraulic valve state). The automatic methodology was programmed on a computer using conditions on time elements to determine in which category the record would be included. The proposed methodology arranged the time elements into four categories:

- Movement time: Time in which the machine was moving
  - Working time: Time in which the machine was performing the work it was designed to carry out.
  - Transport time: Time in which the machine was moving without performing the work it was designed to carry out.
- Stoppage time: Time in which the machine was stopped but its engine was on.
- Parking time: Time in which the machine was stopped and its engine was off.
- Uncertainly time: Time during which the data that were provided by MRMP were inadequate or insufficient to discern what the machine was doing.

To evaluate the automatic methodology, a manual time division and data analysis was provided and compared to an automatic time elements classification. Automatic methodology employed the hydraulic valve state to separate working from transport time; speed was used to discern stoppage and parking time from movement time, and stoppage time was separated from parking time considering that the MRMP did not emit data when the machine engine was off.

The effective field capacity [Eq. 1] and field efficiency [Eq- 2] [31] were calculated using the automatic and manual methodology to test the appropriateness of the automatic methodology for tracking agricultural machinery. The travel times between fields and intervals with insufficient information regarding the harvester were omitted in the calculation process. The potential work parameters were obtained for each type of harvester to determine its appropriateness for each field operation. The displacement and preparation time elements of the machine were removed from the process.

$$Effective\ field\ capacity\ (ha\ h^{-1}) = \frac{Harvested\ area}{In\ field\ total\ working\ time} \text{ [Eq. 1]}$$

$$Field\ efficiency = \frac{Effective\ field\ capacity}{Theoretica\ \ field\ capacity}\ \text{[Eq. 2]}$$

Experimental field

Field tests were conducted in commercial olive orchards in southern Spain and Chile to evaluate ability to record remote information from harvesters yielding the ability to characterize the farming operation. Three commercial olive harvesters were tracked during the 2010-2011 and 2011-2012 olive harvesting seasons in southern Spain and northern Chile (Fig. 17). The harvester models were the following: MaqTec, Colossus (MaqTec, Venado Tuerto, Santa Fe, Argentina); Oxbo, 3210 (Oxbo International corp., Kingsburg, CA, U.S.A.); and New Holland, VX7090 (CNH Global, Burr Ridge, IL, USA). A New Holland VX7090 harvester was used on a super-high-density olive orchard (more than 1000 trees/ha hedgerow trained). The self-propelled MaqTec, Colossus straddle harvester was used on a high-density olive orchard (285-830 trees/ha single trunk trained), located in Córdoba, Spain. The tractor drawn Oxbo, 3210 harvester was used in two configurations: (i) in a high-density olive orchard (400 trees/ha hedgerow trained) without a catch frame and (ii) in a traditional olive orchard (70 trees/ha, quincunx spacing, several trunks trained) with a catch frame that was designed at the University of Córdoba (Table 2).

Table 2. Detailed description of the tracked harvesters, and commercial field harvested.

Harvester	Harvester typology	Olive orchard typology	Location	Harvesting season
MaqTec, Colossus	Straddle harvester	High density (285-830 trees ha^{-1})	Spain	2010-2011
New Holland, VX7090	Hedge straddle harvester	Super high density (> 1000 trees ha^{-1})	Spain and Chile	2010-2011 and 2011-2012
Oxbo, 3210	Lateral canopy shaker	High density (400 trees ha^{-1})	Spain	2010-2011
Oxbo, 3210 + catch frame	Lateral canopy shaker	Traditional (70 trees ha^{-1})	Spain	2011-2012

Fig. 17. Tracked harvesters: (A) Oxbo 3210 with catch frame; (B) Maqtec, Colossus; (C) New Holland VX 7090 and (D) Oxbo 3210 without catch frame.

Field representation and data analysis

A field area is represented as a closed loop, 2D polygon and is stored in shape-files with associated informational attributes that describe the geometrical field representation. The field characteristics, such as feature geometry (regular, standard and irregular), angle between headland and row (perpendicular, perpendicular-acute and acute), row length and alley width, were measured for both the straddle harvester and hedge straddle harvester in the 2011/2012 harvesting season. Regular geometry indicates an approximately rectangular or squared field, which has some irregularities, and irregular geometry indicates a triangular or irregular shaped field. All of the characteristics were compared based on field efficiency except for the row width, which depended on the effective field capacity. A homogeneous work unit was defined for each case as one workday or a day fraction when the considered field characteristic value did not change significantly.

SPSS (IBM, Armonk, NY, USA) and Statistix 8 (Analytical Software, Tallahassee, FL, USA) were used for the statistical analyses.

Results and discussion

Time elements methodology validation

Of the 781 h that were recorded for the hedge straddle harvester, 720 h that corresponded to the season 2011–2012 with a high temporal resolution (4 s) which were used to validate the new methodology. This methodology was compared to the manual calculation of the time elements. Fig. 18 shows the mean and standard deviation values that were obtained for the new and manual methodology for effective field capacity and field efficiency.

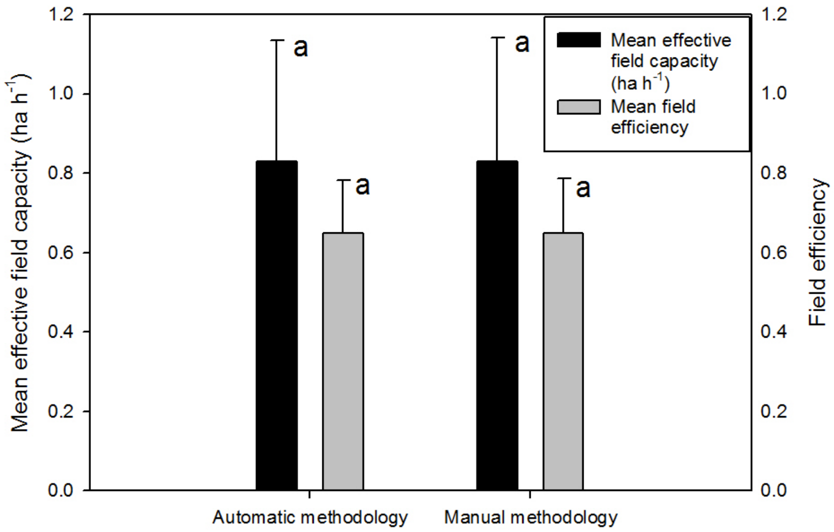

Fig. 18. Effective field capacity and field efficiency calculated using automatic and manual methodologies. Different letters show significant differences between groups according to Student's t-test (ρ < 0.05).

The aim of this study was to validate this new methodology in an experimental setting. No significant differences were found between the methodologies. Therefore, these preliminary results indicate that the methodology may be appropriate for use in agriculture machinery tracking while improving the work efficiency of technicians by reducing their time in the field.

Effective field capacity and field efficiency

In this study, the recorded tracking time was 11 hours for the lateral canopy shaker, 257 hours for the straddle harvester and 781 hours for the hedge straddle harvester. The hedge straddle harvester stands out for its highly effective field capacity, with one season in Spain with 0.70 ha h^{-1} (SD ± 0.1) and two seasons in Chile with 0.74

ha h^{-1} (SD ± 0.2) and 0.83 ha h^{-1} (SD ± 0.3). However, the highest field efficiency was achieved by the lateral canopy shaker (Table 3). This machine was a non-integral harvester and did not suffer from time losses when unloading fruit. Furthermore, this machine is smaller in size and weight. The straddle harvester obtained low values of the effective field capacity and field efficiency, most likely due to the dampness of the 2010-2011 harvesting season in the south of Spain (from October 2010 to March 2011, the average relative humidity was 71.7 %, and the total rain was 865 mm). The straddle harvester was the most voluminous (4.0/6.83 × 8.08 × 4.35/4.68 m, width × length × height) and heaviest (28 tons) indicate that the working and travelling speeds were very slow. The orchard topography, which was not completely flat, may also have influenced the low values that were shown by the straddle harvester. In Australia, this harvester had an effective field capacity of 0.30 ha h^{-1} [32]. Nevertheless an effective field capacity of 0.30 ha h^{-1} is lower that of the other harvesters under our conditions. The low speed directly affects the effective field capacity; however, in an integral harvester, this affect means more time shaking the olive tree, which could lead to the additional falling of fruit (out of the scope of this work).

Table 3. Effective field capacity and field efficiency for tracked olive harvesters.

Harvester	Harvesting season	Tracking time (h)	Effective field capacity (ha h^{-1})	Field efficiency
Lateral canopy shaker with catch frame	2011-2012	1.5	0.36	0.71
Lateral canopy shaker	2010-2011	11	0.36 ± 0.12	0.88 ± 0.12
Straddle harvester	2010-2011	257	0.15 ± 0.05	0.63 ± 0.13
Hedge straddle harvester in Spain	2010-2011	38	0.70 ± 0.1	0.60 ± 0.07
Hedge straddle harvester in Chile	2010-2011	23	0.74 ± 0.2	0.75 ± 0.12
Hedge straddle harvester in Chile	2011-2012	720	0.83 ± 0.3	0.65 ± 0.13

Tracked canopy shakers improve the effective field capacity of conventional harvesting methods, which usually varies from 0.12 to 0.20 ha h^{-1} [33], as reported for tractor-hitched trunk shakers, or from 0.25 to 0.30 ha h^{-1}, as measured for self-propelled trunk shakers [34]. In Australia, a COE L2-E Receiver (3453, Riviera Rd., Live Oak, CA, U.S.A.) side-by-side harvester showed field capacities of approximately 0.39 ha h^{-1} [32], and in Italy, canopy shakers with a catch frame for high-density olive orchards can harvest 0.25 ha h^{-1} [35]. In previous tests, a lateral canopy shaker without the catch frame was used on traditional olive orchards; working around tree canopies, this shaker harvested 0.39 ha h^{-1}. This machine can also make crossed rounds to harvest a square spaced olive orchard, and its effective field capacity is 0.23 ha h^{-1} [36]. Traditional olive orchard competitiveness could be improved using a canopy shaker to perform integral harvesting to similar levels of intensive olive orchards.

Field characteristics influence the harvesting operation

The integral harvester field efficiency was influenced by both the row length and down-the-row speed. These factors reduce the turning time and unloading elements when the harvester used the receptacle to store harvested fruit. When this storage occurs, the row length is limited by the receptacle storage capacity as related to the row production per length unit. At this point, the optimal orchard design may permit the harvesting of two rows before unloading to perform this operation only at one end of the row.

The row length was significantly related to the field efficiency for the hedge straddle harvester but not to the straddle harvester for high density olive orchards. This result was due to the straddle harvester performing less homogeneous work units than the hedge straddle harvester. The data scatter was very similar in both cases (Fig. 19). Our results agree with the results that were reported by other authors regarding the influence of geometry on the effective field capacity [37,27]

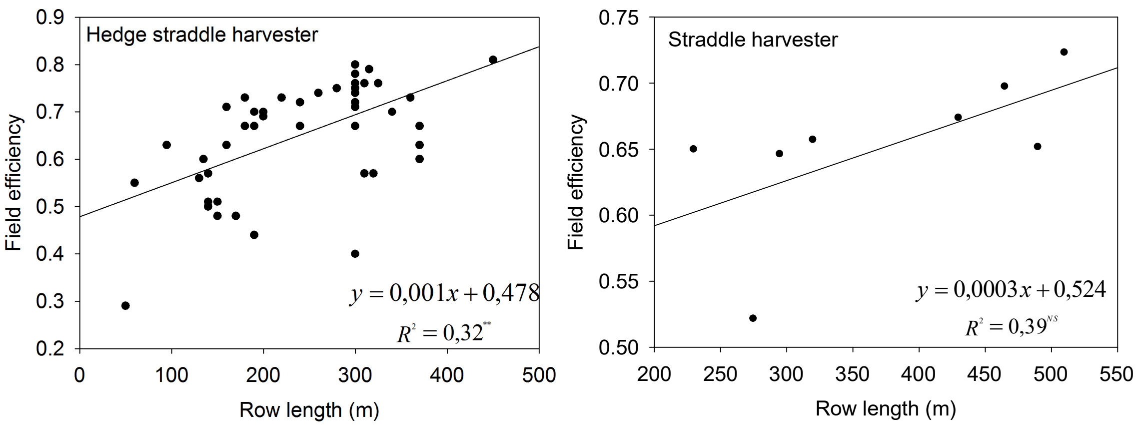

Fig. 19. Trend between the effective field capacity and row length for both the hedge straddle *harvester* (left) and the straddle harvester (right).

Data in Table 4 show the mean and standard deviation for field efficiency according to the field shape. For the hedge straddle harvester, the geometry have significantly influenced the field efficiency, while for the straddle harvester, significant differences were not found. Field size and geometry also affect labor organization because if the row length varies, the driver must change the number of harvested rows to unload the receptacles, or the driving pattern must be changed.

Table 4. Field efficiency based on the field shape and angle between the headland and row.

Hedge straddle harvester		**Field efficiency**	
Factor	**Category**	**Mean**	**SD**
Field shape	Regular	0.69b	0.11
	Standard	0.61b	0.15
	Irregular	0.56a	0.15
Angle between the headland and row	Perpendicular/both ends	0.69b	0.11
	Perpendicular/acute	0.61b	0.10
	Acute/both ends	0.43a	0.20
Straddle harvester		**Field efficiency**	
Factor	**Category**	**Mean**	**SD**
Field shape	Regular	0.66a	0.08
	Standard	0.60a	0.10

**Mean values with the same grouping letter are not significantly different (ρ<0,05) according to Wilcoxon test.*

Table 4 shows no significant differences between the regular and standard geometry for both of the harvesters. These data show that the angle between the headland and perpendicular row increased the field efficiency, thereby influencing the turning time elements and work organization when the angle was acute; more frequently, the workers used loop driving patterns to increase the turning radius. The hedge straddle harvester had significant differences between orchards that had a perpendicular angle between the headland and row at both ends and the others orchards that had an acute angle between the headland and row at both ends. These results agree with those of Shamshiri [38], who noted that the turning time was greatly influenced by the field size, shape and driving pattern. Irregular field shapes with rows not intersecting the field boundary at a right angle presented additional turning problems.

The effective field capacity and field efficiency were affected by the row alley width. The hedge straddle harvester worked at different row alley widths, while the straddle harvester for high densities worked at similar alley widths. Therefore, the hedge straddle harvester was the only machine that provided data to analyze the alley width influence on the effective field capacity.

The hedge straddle harvester provided significant differences between 3.5 m and 4 m or greater row alley widths. When the row alley was wide enough, this harvester easily made machinery paths, reducing turning time elements. With a high row alley width, the harvester would provide a high effective field capacity. Nevertheless, these differences were not significant when the row alley width was greater than 4 m, most likely because in super-high-density olive orchards, the vegetative row width and production increased when row alley width increased, thus reducing the harvester work speed and affecting the effective field capacity (Fig. 20).

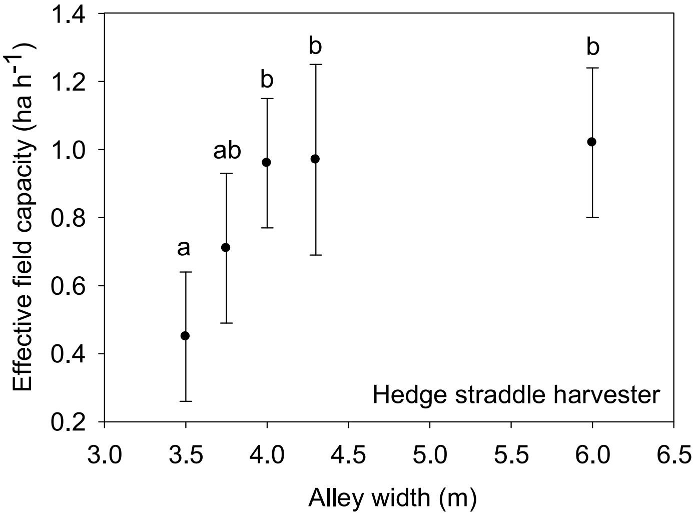

Fig. 20. Effective field capacity and row alley width relationship. Different letters indicate significant differences (ρ<0,05) according to Scheffé's test.

Yield Mapping

The yield monitoring system performed very well in laboratory tests. Fig. 21 shows a linear relationship between the output voltage and the known loads (R^2=0.9991, p<2.210^{-16}). The straight-line least-trimmed squares exhibited the following relationship [Eq. 3]:

$$\boldsymbol{y = 0.9046 \cdot x - 284.94} \text{ [Eq. 3]}$$

Where y is the known loads (kg) and x is the output voltage of the load cell (mV).

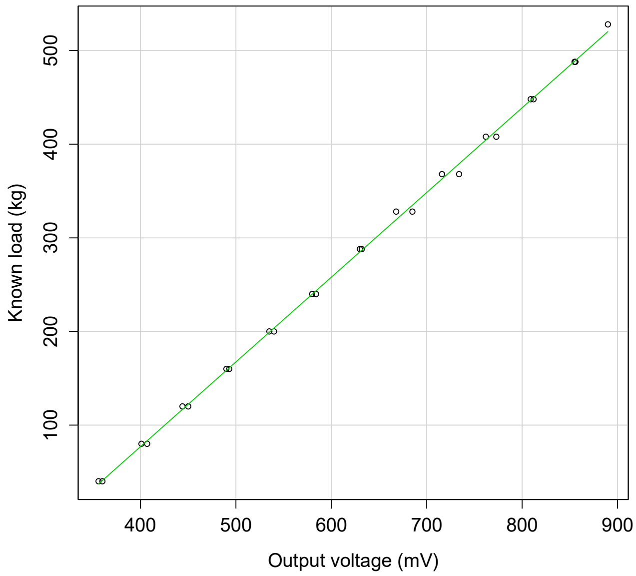

Fig. 21. Relationship between the output voltage in the load cell and the known load weight.

This equation was used to obtain the estimated olive fruit weight per tree in the field tests. The x-intercept is (315) due to the support of the harvester receptacle on the load cell. The value 315 mV is the load cell output for the empty receptacle, and the offset adjustment load cell output voltage corresponded to 284.94 kg. Due to the constraint in the harvester receptacle as limited by the transport capacity, the maximum weight that can be loaded per test run cannot exceed 600 kg.

In the field, for preliminary results, thirty-three olive trees were harvested from the orchard. The yield monitor provided a realistic estimate of the yield differences between olive trees, with average values of 41.24 kg per tree and standard deviation of 20.13 kg per tree. This high standard deviation was due to the irregularity of the trees in the traditional orchards. In the same area of study, variations over 50 % in fruit load per tree were found in an olive orchard [39]. The yield assignment to each tree and the structural variations in vegetation are crucial pieces of information for constructing prescription maps for olive orchards. Using these precision farming techniques assists decision-making systems, allowing for variable-rate input application.

A potential application of a telemetry system combinated with yield monitoring is olive fruit yield mapping in real time as shown in Fig. 22. The performance of the olive fruit yield monitor ranged between 8.4 kg per tree and 85.83 kg per tree. High variability orchard plot was chosen to test the yield monitor in order to demonstrate its performance in high changeable conditions. This map presents a gradient of decreasing production from northwest to southeast. The altitude decreased from the northwest corner to the southeast corner, which was the lower point in the map on the south stream end. Based on the author´s assumptions and farm technician consultation, this decrease was due to fungal disease attacks, mainly by olive tree peacock leaf spot (*Fusicladium* *oleagineum*) and anthracnose infections (*Colletotrichum gloeosporioides*). The map information could be used to develop models that describe the relationship between disease severity and yield (kg/tree). In addition, these models could be used to optimize the control of fungal diseases.

A yield contour map was generated using a kriging for a conventional orchard system. This study demonstrates the possibility of identifying localized zones for site-specific application. Results such as these indicate that such technologies could be implemented on real harvesters and, in the near future, could be used on commercial farms. However, further studies are required to determine whether these techniques would be profitable for use in olive groves, even on small farms, where economic efficiency must be achieved [20].

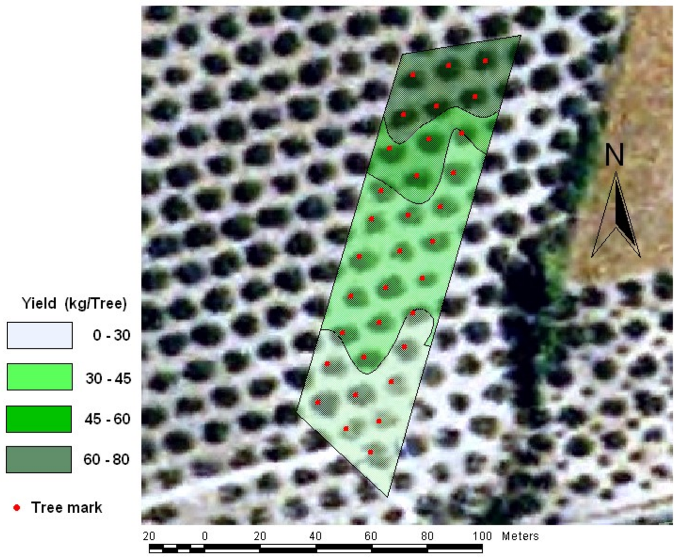

Fig. 22. Olive fruit yield map estimated for a traditional olive orchard.

Conclusions

A low cost telemetry tracking system for agricultural vehicles were developed. Time study methodology was also validated using telemetry system data. This methodology was adapted for an automatic time elements classification process that help to improve agricultural machinery studies efficiency, processing the large amount of data provided by the tracking system. The telemetry system can incorporate a yield monitor which was developed and operated. Both systems were successfully implemented on an olive fruit harvester and tested in commercial olive orchards in southern Spain. One of the great advantages of this system is the low cost and the ability to connect field system with expertise centers located at distant geographical sites.

Three commercial olive harvesters were tracked using the telemetry system to determine their effective field capacity and field efficiency. Each harvester was designed to harvest one orchard category (traditional orchards, high density orchards or super high density ones) although lateral canopy shaker can work in both, high density and traditional orchard). Hedge straddle harvester achieved the highest effective field capacity (0.70 – 0.83 ha h^{-1}), but only can harvest super high density orchards, while lateral canopy shaker achieved the highest field efficiency (0.88). Also collected data were used to discern the orchard characteristics influence on the harvester performance. Row length, field shape, angle between headland and row, and alley width significantly influenced hedge straddle harvester performance, while significant differences were not found for straddle harvester. Further research is needed to determine the optimal orchard layout to maximize harvester efficiency in order to improve olive orchard competitiveness. Also, it has to be proved whether these techniques would be profitable for use in olive orchards, even on small farms, where economic efficiency must be achieved.

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CAPITULO 5. DETERMINACIÓN DE LOS PATRONES DE DISTRIBUCIÓN DE LA PRODUCCIÓN, RENDIMIENTO GRASO Y CALIDAD DEL ACEITE DE OLIVA EN LA COPA.

Resumen

La distribución de la producción de fruto y aceite dentro de la copa en olivar debe ser un criterio a tener en cuenta para la selección y mejora de métodos de recolección mecánica. Se han llevado a cabo ensayos en una parcela de olivar intensivo *Olea europea* L., 'Arbequina' en el sur de España. La producción, características de los frutos, rendimiento graso y parámetros químicos del aceite se midieron en diferentes zonas de la copa en 12 árboles. Los resultados mostraron que un alto porcentaje de frutos estaba localizado en la zona exterior de la copa a una altura media y en la parte superior, englobando esta región de la copa más del 60 % de la producción total. La posición accesible de estos frutos junto a su mayor tamaño, índice de madurez, y contenido en polifenoles, hace que estas zonas de la copa sean un objetivo prioritario para cualquier sistema de recolección. La cosecha localizada en la parte baja de la copa supone cerca de un 30 % de la producción tanto de aceite como de fruto, sin embargo, la recolección mecánica de esta zona de la copa no suele ser muy eficiente, salvo para los métodos manuales. Para mejorar la eficiencia de los sistemas de recolección, se recomienda mejorar la formación del árbol, elevando las ramas bajas. Los frutos localizados en el interior de la copa suponen menos del 10 % de la produccion, por lo que no son prioritarios para los sistemas de recolección mecánica. Se encontraron diferencias significativas en el contenido en polifenoles del aceite, en función de la altura de copa de donde se ha recogido el fruto. Por otro lado, no se apreciaron diferencias en cuanto a la acidez entre las distintas zonas de la copa. Además, el índice de madurez no influyó en el contenido de polifenoles ni en la acidez del aceite. La producción, el rendimiento graso, las características del fruto y los parámetros de calidad del aceite proporcionaron diferencias signficativas en función de la zona de la copa. Por lo tanto, los sistemas de recolección deberían focalizar su actuación en función de la zona de la copa, acompañados de un correcto sistema de formación del árbol para maximizar la eficiencia de cosecha.

Palabras clave: *Olea europaea* L., sacudidor de copa, cosechadora cabalgante, vibrador de troncos, poda de formación.

Abstract

Olive fruit production and oil quality distribution with respect to olive canopy are important criteria for selection and improvement of mechanical harvesting methods. Tests were performed in a high-density olive orchard (*Olea europea* L., 'Arbequina' in southern Spain. Fruit distribution, fruit properties and oil parameters were measured by taken separate samples for each canopy location and tree. Results showed a high percentage of fruit and oil located in the middle-outer and upper canopy, representing more than 60% of total production. The position of these fruit along with their higher weight per fruit, maturity index and polyphenol content make them the target for all mechanical harvesting systems. Fruit from the lower canopy represented close to 30% of fruit and oil production, however, the mechanical harvesting of these fruit is inefficient apart from manual systems. Whether these fruit cannot be properly harvested, enhance tree training to raise their position is recommended. Fruit located inside the canopy are not a target location for mechanical harvesting systems as they were a small percentage of the total fruit (<10%). Significant differences were found for polyphenol content with respect to canopy height, although this was not the case with acidity. In addition, the ripening index did not influence polyphenol content and acidity values within the canopy. Fruit production, properties and oil quality varied depending on fruit canopy position. Thus harvesting systems may be targeted at maximize harvesting efficiency including an adequate tree training system adapted to the harvesting system.

Keywords: *Olea europaea* L., canopy shaker, straddle harvester, trunk shaker, tree training.

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Introduction

There is currently a wide range of available production systems for olive oil with significant variation according to irrigation resources and investment level. These systems range from traditional systems with 30-173 trees/ha and yields between 1.1-4.5 t/ha to super high-density production systems with 1700-3000 trees/ha and yields between 2.7-17.5 t/ha (Vossen, 2007). In Spain, 73.5% of the olive growing surface has a plantation density <200 trees/ha, 18.4% are planted with between 200 and 1,000 trees/ha, and only 1.4% are planted using a plantation density >1,000 trees/ha (ESYRCE, 2013). Worldwide, only 80,000 ha, about 1% of the total crop surface, are planted following the super high-density model (Tous *et al.*, 2010). Fruit harvesting is the most expensive process in olive production, often representing more than 40% of the total costs (AEMO, 2010). The mechanical harvesting of olive trees is transforming the crop and producing more modern and competitive orchard models (Vieri & Sarri, 2010; Ferguson & Castro-Garcia, 2014).

High-density production systems are characterized by rectangular tree layouts and orchard densities between 150 and 800 trees/ha, which facilitates the use of machinery and harvesting operations (Rallo *et al*., 2013). Nowadays, such production systems are among the most widely used, due to their greater profitability and ease of mechanization. High-density olive trees are harvested manually (Cicek *et al*., 2010), as well as using trunk shakers (Castro-Garcia *et al*., 2007), canopy shakers (Ferguson, 2006) or other integral mechanical harvesting systems (Ravetti & Robb, 2010) [see Supplementary material Fig. 24].

However, there is a trend towards intensifying olive orchards and the integral mechanization of harvesting (Metzidakis *et al*., 2008). Field tests have shown that espalier training in high-density hedgerows does not reduce yield. Moreover, these orchards can be harvested using canopy contact or trunk shaker systems (Ferguson *et al*., 2010). At the same time, varieties better adapted to high-density orchards and which have reduced vigour, such as ‘Arbequina’, ‘Arbosana’ or ‘Koroneiki’, are replacing more traditional and higher vigor cultivars (De la Rosa *et al*., 2007; Tous *et al*., 2007).

Orchard design together with formative pruning and tree production are key factors in the efficiency of harvesting systems (Tombesi *et al*., 2002; Dias *et al*., 2012). Current systems must be improved and new harvesting methods must be developed to increase the percentage of fruit harvested and reduce possible damage caused to the fruit and tree, as well as to reduce harvesting costs (Vieri & Sarri, 2010). In fact, table olive groves in California are undergoing a transformation driven by the available mechanical harvesting technologies, in order to achieve harvester efficiency of around 80% and to improve the economic sustainability of the sector (Ferguson & Castro-Garcia, 2014). Although no harvest system is capable of collecting 100% of the fruit from the tree, machine design should always take into account the need to maximize harvest efficiency and obtain the best quality olive oils.

Traditionally, olive trees have been trained based on the requirements of manual harvesting. In traditional olive orchards, pruning for manual harvesting has shown that the poorest quality fruit are produced at the lower and inner areas of the canopy, which are close to the ground, thick and receive little sunlight (Ortega Nieto, 1969). However, fruit obtained from better-lit areas are of better quality, larger and have a higher oil yield (Acebedo *et al*., 2000). Similar results have been reported in citrus orchards (Whitney & Wheaton, 1984). Orchard intensification would give rise to shading problems that affect oil quantity and quality (Connor, 2006). By increasing the canopy volume of the orchard (from 8,000 to 12,000 m^3/ha), the most productive area of the canopy is at the top of the trees, which receives the most sunlight (Pastor Muñoz-Cobo & Humanes Guillén, 2010). However, canopy volume regulation by manual or mechanized pruning is necessary in order to allow mechanical harvesting and to produce marketable harvests (Ferguson & Castro-Garcia, 2014)

The location of the fruit in the canopy directly affects olive oil composition and quality (Gómez-del-Campo *et al*., 2009), although its effect is less evident with respect to the sensory attributes of the oil (Gómez-del-Campo & García, 2012). Olive oil acidity and total phenol content is affected by the ripening stage, although acidity does not show statistical differences (Gutierrez *et al.*, 1999). However, fruit canopy position strongly affects the efficiency of the harvesting system used, although the row or direction in which the tree faces is less significant for mechanical harvesting. Canopy shape becomes important in facilitating access to the most numerous fruit with the best quality of oil.

This study aims to enhance the mechanical harvesting process for high-density olive orchards. Fresh weight, oil content, fruit retention force (FRF), ripening index and detachment force of fruit were selected as important parameters in terms of enhancing the harvest efficiency of mechanical harvesting technologies and were analysed at different canopy positions. Oil acidity and polyphenol content were also studied. It is within the scope of this study to establish criteria for olive training and adaption to commercial harvesting technologies. In this process, crop mechanization usually tends to be a two-stage process: first crops are adapted to the harvester and then the harvester is adapted to the crop (Gil-Ribes *et al.*, 2014).

Materials and methods

The tests were performed in a commercial high density orchard of *Olea europaea* L. cv. Arbequina in Cordoba, southern Spain (37.648890 N, -4.731579 W) during the third week of December 2011 and the last week of November 2013. The orchard was in good phytosanitary condition and had irrigation. Fruit were harvested within the appropriate harvest period (Wiesman, 2009), which occurs when the fruit is yellowish but less than half of the fruit epicarp has become purple. Both test years produced yields of 10,000-12,000 kg/ha. Trees were 10-12 years old, vase-shaped, with two or three main branches and a 0.8 m-high trunk, and planted at 7 × 5 m spacing (285 trees/ha). The mean tree height remained constant at 3.2 m although mean canopy volume increased from 11.7 m^3 in 2011 to 12.6 m^3 in 2013. The same 12 trees were selected in both harvesting seasons to perform the tests. The chosen sample size was intended to restrict data scatter and to avoid bias by obtaining a representative sampling plot.

Each tree canopy was divided into four areas according to the height from the ground: fruit on the ground; lower canopy, < 1.0 m; middle canopy, 1.0-2.2 m; upper canopy, 2.2-3.2 m. Fruit position in terms of depth inside the tree canopy was also considered and divided into two groups: outer canopy, which was the first 0.5 m measured inwards from the external canopy surface, and inner canopy, including the rest of the canopy. The outer area of the canopy encompasses the lower, middle and upper locations. Fig. 23 shows the canopy locations studied. Any fruit that had fallen to the ground prior to harvesting due to natural causes was also included in the study. Fruit was harvested separately from each canopy volume studied.

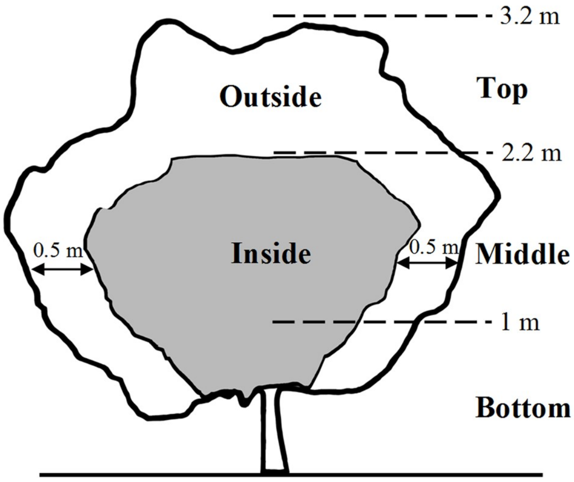

Fig. 23. Olive tree canopy locations according to height and canopy depth.

The FRF was determined for 30 randomly selected fruit from each location, using a dynamometer (Correx, Haag-Streit, Switzerland) adapted for this purpose, with a range of 1-10 N and 0.2 N accuracy. The fruit from each location were then harvested and weighed. For each location and tree, three fruit samples were taken in order to determine the study parameters, two of which related to chemical properties (oil, acidity and polyphenol content) and the other to weight and maturity measurements. The unit weight of the fruit and level of olive maturation were obtained from a randomly-taken sample of 100 healthy fruit. The level of olive maturation was calculated according to the ripening index using the Jaen method (García *et al*., 1996; Uceda & Hermoso, 1998), according to equation [Eq. 4].

$$Ripening\ index = \frac{\sum(RS \cdot n)}{100} \quad [Eq. 4]$$

Where, *RS* is the value of each ripening stage for each fruit evaluated, according to Jaen ripening index (Uceda & Frías, 1975) [Supplementary material Table 9] and *n* is the number of fruit classified in each *RS* from each canopy location and tree.

The analysis of the properties of the fruit and oil was performed at the Laboratorio Agroalimentario de Córdoba, Spain. There, the olive samples were pressed, cold-centrifuged and filtered. Fat acidity was determined using acid-base titration according to the official method described in OJ (1991). Oil content (%) was measured in wet samples by nuclear magnetic resonance contrasted with the Shoxlet method. Afterwards, the samples were oven-dried to determine percentage humidity (%). Total polyphenol content was determined with a spectrophotometer using caffeic acid as the reference (Ayton *et al*., 2007).

Results and discussion

Tree growth between harvest seasons (2011 and 2013) was mainly reflected in an increase in trunk diameter. Canopy volume and tree height also increased but did not show significant differences due to the biennial pruning carried out in an off year (Table 5). Harvesting dates produced differences in the characteristic parameters of olive fruit and oil, as shown in Table 6, Table 7 and Table 8.

Table 5. Tree harvesting parameters (values are mean ± standard deviation.

Harvesting season	Trunk diameter ± cm	Canopy volume ± m^3	Tree height ± m	Yield § ± kg $tree^{-1}$	Ripening index
2011-12	12.97 ± 0.76 b	11.69 ± 2.35 a	3.18 ± 0.23 a	38.38 ± 4.32 a	2.85 ± 0.54 a
2013-14	13.61 ± 0.62 a	12.56 ± 2.06 a	3.26 ± 0.20 a	39.78 ± 5.20 a	1.63 ± 0.26 b

§ *Yield calculated including fallen fruit. Between the two tested harvesting seasons, values in the same row followed by the same letter are not significantly different at p≤0.05 based on paired Student's T test.*

Table 6. Production of olive fruit and oil in each tree canopy location for the two considered harvesting seasons. Values are means ± standard deviations.

	Fruit position	Samples per season (No.)	Fruit (%)			Oil (%)		
			2011-12	2013-14	Mean	2011-12	2013-14	Mean
	Ground	12	3.3 ± 0.8	1.9 ± 0.5	2.6 ± 1.0	3.5 ± 1.0	2.1 ± 0.5	2.8 ± 1.0
Canopy height [1]	Top	12	14.9 ± 4.9 c	19.5 ± 4.5 c	17.2 ± 5.1 c	16.5 ± 5.2 c	20.8 ± 4.9 c	18.7 ± 5.4 c
	Middle	12	44.3 ± 4.4 a	45.6 ± 5.8 a	44.9 ± 5.1 a	44.4 ± 4.2 a	45.3 ± 5.6 a	44.8 ± 4.9 a
	Lower	12	28.2 ± 5.2 b	24.1 ± 5.9 b	26.1 ± 5.8 b	26.9 ± 4.8 b	23.3 ± 5.9 b	25.1 ± 5.5 b
Canopy depth [2]	Outside	36	87.4 ± 3.6 a	89.2 ± 2.7 a	88.3 ± 3.2 a	87.8 ± 3.5 a	89.5 ± 2.8 a	88.6 ± 3.2 a
	Inside	12	9.3 ± 3.6 b	8.9 ± 2.6 b	9.1 ± 3.1 b	8.7 ± 3.5 b	8.4 ± 2.7 b	8.5 ± 3.1 b

[1] *In these fruit positions, values in the same column followed by the same letter are not significantly different at p≤0.05 based on Duncan's multiple range test.*

[2] *In these fruit positions, values in the same column followed by the same letter are not significantly different at p≤0.05 based on Student's T-test.*

Table 7. Distribution and characteristics of olive oil parameters according to tree canopy position for both harvesting seasons. Values are means ± standard deviation.

	Fruit position	Oil content (% fresh weight)		Acidity (%)		Polyphenol content (mg/L)	
		2011-12	**2013-14**	**2011-12**	**2013-14**	**2011-12**	**2013-14**
	Ground	26.7 ± 1.8	23.1 ± 0.1	4.1 ± 0.93	4.4 ± 2.30	100.0 ± 12.9	95.9 ± 2.2
Canopy height [1]	**Top**	27.9 ± 1.1 a	22.2 ± 1.3 a	0.23 ± 0.06 a	0.42 ± 0.19 a	348.5 ± 25.3 a	356.5 ± 62.4 a
	Middle	25.2 ± 0.7 b	20.7 ± 1.0 ab	0.27 ± 0.07 a	0.51 ± 0.31 a	364.5 ± 29.7 a	344.7 ± 107.0 ab
	Lower	24.0 ± 1.0 c	20.1 ± 0.8 b	0.26 ± 0.05 a	0.48 ± 0.19 a	292.3 ± 46.3 b	282.8 ± 108.9 b
Canopy depth [2]	**Outside**	25.7 ± 1.2 a	21.0 ± 1.4 a	0.25 ± 0.06 a	0.47 ± 0.24 a	332.4 ± 47.5 a	328.0 ± 98.1 a
	Inside	23.3 ± 1.1 b	19.5 ± 1.6 b	0.18 ± 0.06 b	0.35 ± 0.15 a	314.1 ± 67.0 a	305.6 ± 86.7 a

[1] *In these fruit positions, values in the same column followed by the same letter are not significantly different at p ≤0.05 based on Duncan's multiple range test.*

[2] *In these fruit positions, values in the same column followed by the same letter are not significantly different at p ≤0.05 based on Student's T-test.*

Table 8. Distribution and characteristics of olive fruit parameters according to tree canopy position. Values are means ± standard deviation.

	Fruit location	FRF (cN) [1]		Ratio FRF / Fruit fresh weight (cN/g) [1]		Fruit weight (g per 100 fruit)		Ripening index [2]	
		2011-12	2013-14	2011-12	2013-14	2011-12	2013-14	2011-12	2013-14
	Ground	-	-	-	-	130.2 ± 12.7	128.5 ± 6.8	5.1 ± 0.3	2.5 ± 0.2
Canopy height [3]	**Top**	363 ± 45 a	333 ± 31 ab	186.6 ± 23.3 b	222.6 ± 19.9 b	168.6 ± 12.2 a	150.8 ± 16.4 a	4.3 ± 0.6 a	2.1 ± 0.4 a
	Middle	292 ± 37 b	317 ± 36 b	194.8 ± 30.1 b	236.1 ± 23.9 b	151.8 ± 11.4 b	135.2 ± 16.2 b	2.9 ± 0.7 b	1.7 ± 0.3 b
	Lower	320 ± 41 b	340 ± 18 a	224.1 ± 29.5 a	263.5 ± 35.1 a	142.5 ± 8.7 b	130.6 ± 15.9 b	2.3 ± 0.6 c	1.4 ± 0.4 b
Canopy depth [4]	**Outside**	315 ± 26 a	309 ± 21 a	201.8 ± 31.6 b	240.7 ± 31.4 a	154.3 ± 15.2 a	138.9 ± 18.0 a	2.6 ± 0.5 a	1.5 ± 0.2 a
	Inside	279 ± 33 b	291 ± 16 b	274.9 ± 61.2 a	230.5 ± 26.4 a	134.1 ± 15.0 b	135.7 ± 17.3 a	2.4 ± 0.5 a	1.5 ± 0.2 a

[1] *Each value for these parameters is the mean value of 20 determinations.*

[2] *Each value for this parameter is the mean value of 100 determinations.*

[3] *In these fruit positions, values in the same column followed by the same letter are not significant different at p ≤0.05 based on Duncan's multiple range test.*

[4] *In these fruit positions, values in the same column followed by the same letter are not significant different at p ≤0.05 based on Student's T-test*

Detached fruit before harvesting

The fruit which had fallen to the ground before harvesting represented a mean value of only 2.6 % of tree production, showing similar values to those reported by Tous *et al*. (1995) for this cultivar just before harvesting. Differences between harvesting seasons are due to the percentage of fruit which had a FRF of less than 3 N. In the 2011/12 harvesting season, this figure was 41.8 ± 14.4 % and 34.4 ± 13.6 % for the 2013/14 harvesting season (mean ± SD). Fruit fallen to the ground was explained by the percentage of fruit that exhibited FRF levels under 3 N, as well as by the ratio between FRF and fruit weight, which was around 2 N/g in both harvesting seasons predicting an adequate fruit removal percentage (Farinelli *et al*., 2012a). This fruit quantity varied between harvesting seasons, depending on the harvest dates, phytosanitary state of the tree and meteorological conditions (Barranco *et al*., 2010). Normally, farmers harvest the tree before an excessive amount of fruit falls to the ground. The cost of harvesting fruit from the ground is higher than fruit harvested from the tree canopy and in some cases these fruit are not worth collecting. The fruit on the ground presented acidity values from 9 to 21 times higher and polyphenol content values about 3 times lower than the fruit from the canopy (Table 7). Although harvesting fruit from the ground increases the quantity of fruit harvested, there is a decrease in quality, which is why ground fruit are usually harvested and processed separately.

Fruit from inner canopy position

The fruit from inner canopy position (>0.5 m from the canopy exterior) represented 9.1 % of tree production and 8.5 % of olive oil production (Table 6). These fruit are relatively difficult to reach with manual harvesting systems and canopy contact systems. This is a particular problem when the canopy volume is high and reduces the efficiency of these harvesting methods (Ferguson *et al*., 2010).

The growth of new shoots on the olive tree provides a potential reproductive site and photosynthetic surface, but flowering, and therefore production, is also influenced by previous bearing (Castillo-Llanque & Rapoport, 2011). In particular, the production of fruit of 'Arbequina' is highly influenced by the most sunlit areas. Accordingly, the interior and lower areas of the tree showed fewer inflorescences per twig than the other locations of the tree (Acebedo *et al*., 2000). Therefore, vase-shaped trees with open centres favour fructification on the inner canopy areas, unlike more intensive hedgerow systems, with low canopy porosity (Connor *et al*., 2009). The lower intercepted radiation inside the canopy played a key role in producing smaller fruit on the inner and lower canopy (134.9 and 136.6 g per 100 fruit, respectively), which also have a lower fat content (21.4 % and 22.1 %, respectively) than other fruit in the tree canopy (Connor *et al*., 2009). However, these differences between canopy locations and tree orientations can be mitigated as the fruit can attract assimilates from other better-lit areas during development (Proietti *et al*., 2006). Similar differences were reported by Acebedo *et al*. (2000) with respect to the oil content of dry matter according to fruit location. Previous research performed by Pastor Muñoz-Cobo & Humanes Guillén (2010) points out the differences with inner fruit with regard to their size and fat content when located at heights of less than 2 m off the ground. Although reduced fruit weight is one of the factors limiting shaker efficiency (Kouraba *et al*., 2004), the inner fruit presented the lowest mean FRF values in each harvesting season (279 and 291 cN, respectively), a parameter that facilitates their removal by vibration. However, harvesting efficiency is also dependent on the ratio between FRF fruit and fresh fruit weight (Farinelli *et al*., 2012b). Measured values were higher in the 2013/14 harvesting season, and within the canopy, values were significantly higher on lower branches; that, along with vibration transmission, could explain why it is more difficult to detach fruit from lower branches. Inner and outer canopy fruit showed opposite trends in the two years under study. In other fruit crops, such as vase-shaped sweet cherry trees with open centers, the inner fruit are located on high and elongated branches, where the vibration energy is amplified, thus improving the harvest efficiency of the fruit with trunk shaker systems (Du *et al*., 2012). Pastor Muñoz-Cobo & Humanes Guillén (2010) showed that trunk shaker efficiency in fruit removal increased by up to 16% when moving from branches with an incline of 48 degrees to vertical branches. Tree pruning can improve harvest efficiency with trunk shakers; severe pruning is useful in reducing canopy density, increasing the unit weight of the fruit and providing a regular distribution of fruiting shoots (Tombesi *et al*., 2002).

The results showed that fewer fruit were harvested from inside the canopy in high-density orchards and these fruit have reduced fat content. Consequently, the harvesting of these fruit is not a priority in the design and use of harvesting systems based on canopy shakers or manual equipment. However, fructification inside the canopy is not a limiting factor for trunk shaker efficiency.

Fruit from outer canopy positions

The acidity values of the fruit from outer canopy positions presented no significant differences compared to inner positions. The mean acidity value was 0.23% for the 2011-13 harvesting season, and it was 0.44% for the 2013-14 harvesting season, almost double than the mean value in the previous harvesting season. These are typical values for fruit with no mechanical damage and which are free from disease or plagues that would otherwise affect their quality (Yousfi *et al.,* 2006). No significant differences in acidity were found between the different canopy areas except in the 2011/12 harvesting season, when acidity values were higher for fruit from outer canopy positions. The ripening index, however, did register significant differences in both years and so we can state that ripening process was not a determinant factor for oil acidity.

There were no significant differences in terms of polyphenol content between fruit from inner and outer canopy positions. However, the two harvesting seasons under study did not produce the same polyphenol pattern and the content varied. As reported by Tovar *et al*., (2002), polyphenol content shows a positive linear correlation with the L-phenylalanine ammonia-lyase activity, which decreases over the course of the ripening process. Polyphenol oxidase activity also increases in riper fruit (Ortega-García *et al.*, 2008). For this reason, the polyphenol content in the 2013/14 harvesting season could be slightly lower than in the 2011/12 harvesting season. However, in the interior of the tree canopy the opposite relationship between polyphenol content and fruit ripening stage was observed for the same harvesting date (Table 7 and Table 8).

The fruit from lower canopy positions represented approximately a quarter of tree fruit production (26.1 %) and oil content (25.2 %). Unlike the fruit inside the canopy, the lower fruit presented a higher FRF (330 cN). In addition, the position of these fruit on outer pendulous branches, where the vibration must travel a longer distance from the trunk and there is an increase in damping, make fruit removal with trunk shakers difficult (Castro-Garcia *et al*., 2008) and also presents a problem when using catching frames. The harvest efficiency of these fruit is reduced if the branches make contact with the catching frame and they may even restrict its movement. Shaking technology, whether it is hand-held, tractor-mounted, or self-propelled requires skirt pruning for trunk or branch access (Ferguson, 2006). The reduction of canopy skirts is recommended when using trunk shakers, in order to increase harvesting efficiency. This area, however, contains a large quantity of fruit. Similarly, skirt pruning is important when using straddle harvesters [see Supplementary material Fig. 24]. With canopy shaker systems, most of the fruit remaining on the tree after harvest (1.4%) are concentrated on the canopy skirts because they are not accessible to the machine (Ravetti & Robb, 2010).

The outer fruit located at heights of between 1 and 2.2 m from the ground represent almost half of the fruit and oil produced by the tree (44.9 % and 44.8 %, respectively). The fruit in the middle of the canopy presented a low FRF (from 292 to 317 cN), exhibiting less fruit retention than the fruit at the top of the tree. The ripening index of the fruit located in the middle was greater than the fruit from the lower canopy but less than fruit from the upper canopy. In super high-density olive orchards (tree distance 3.5 × 1.5 m), the majority of the fruit (>95 %) are located between 1.5 and 2.25 m from the ground (Pastor Muñoz-Cobo & Humanes Guillén, 2010); showing intense bud initiation at the higher levels (Gómez-del-Campo *et al*., 2009). These differences are less marked in high-density olive orchards, where 62% of the fruit are concentrated above a height of 1.5 m, exhibiting an increase in fat content and fruit unit weight as their height on the tree increases (Pastor Muñoz-Cobo & Humanes Guillén, 2010).

The fruit from the upper canopy presented a higher value for fat content as a percentage of total wet matter and higher polyphenol content compared to the lower and middle canopy. However, fruit accessibility and detachment from the middle of the canopy, as well as fruit quantity and quality, make these fruit a priority for any efficient mechanical harvesting system. In fact, the straddle harvester easily removes the fruit from this position, with only 0.7 % of the production left on the tree (Ravetti & Robb, 2010).

The fruit from the upper canopy position were characterized by the highest weight and ripening index values, as well as oil and polyphenol content. These fruit represented 17.2 % of the fruit on the tree and 18.7 % of the oil (close to double the oil from inner canopy fruit). Furthermore, this difference can quadruple in the case of super high-density olive orchards (Acebedo *et al*., 2000). The fruit from the upper canopy presented a higher fat content as a percentage of total wet content than at other canopy heights, and medium polyphenol content. Even though the harvesting of upper fruit may not be a priority in terms of increasing harvest efficiency, it should be targeted as a way of increasing harvested oil quality, considering that these fruit increase the polyphenol content of the harvest. In studies performed on 'Arbequina' hedgerows, fruit maturity and size were greater in the upper layers while oil content increased by nearly 50 % from the lower to upper layers (Gómez del Campo *et al*., 2009).

The position of the upper fruit (between 2.2 and 3.2 m from the ground) makes these fruit difficult to harvest with manual systems. It is also difficult for canopy shakers to reach these fruit due to their upper canopy position and the lack of foliar mass necessary for the shaking to detach the fruit. Canopy shakers are more effective on farms with orchards that have a good level of vegetative development and a high level of production (Ravetti & Robb, 2010). A high fruit retention force makes fruit detachment even more difficult. However, trunk shakers could remove the fruit borne on the upper canopy, as they are located on high and elongated branches, exhibiting a principal vibratory transmission path from the trunk to the fruit-bearing branch (Du *et al*., 2012). Finally, annual pruning of the upper canopy is recommended to increase and facilitate the mechanical harvesting efficiency, whether trunk- or canopy-contact technology are used (Ferguson & Castro-Garcia, 2014).

Conclusions

In summary, fruit and oil quality distribution varied according to the position of the fruit in the olive tree canopy, although further research is needed in order to extend the results to other varieties and locations. Fruit quality properties varied to a lesser extent with respect to the tree canopy height, because only polyphenol content showing significant differences. The outer middle and upper tree canopy held more than 60 % of the production, which makes these areas a priority for any mechanical harvesting system. Although the fruit from the lower canopy represented close to a quarter of the fruit and oil production, pruning of this area could be recommended due to its low harvest efficiency with all harvesting technologies except hand held. This could be improved with different tree training, lengthened trunk height or, for trees that have already been planted, the lower canopy may be pruned to the extent that it affects the harvester performance. The fruit from an interior canopy position are not an important objective due to their small quantity (>10 %) and difficult access. At any case, all oil obtained from different canopy positions achieved the extra virgin olive oil requirements based on acidity. The adaptation of each mechanical harvesting system and tree training are necessary to achieve an efficient and quality harvest.

Supplementary material

Table 9. Classification of olive fruit ripeness according to epicarp and pulp color. (Uceda & Frias, 1975).

Stage of ripeness	Description
0	Bright green epicarp
1	Green-yellowish epicarp
2	Green with reddish spots epicarp
3	Reddish-brown epicarp
4	Black epicarp with white flesh
5	Black epicarp with < 50 % purple flesh
6	Black epicarp with > 50 % purple flesh
7	Black epicarp and purple flesh

Fig. 24. Hand-held branch shakers removing fruit on nets (A); tractor-hitched trunk shaker on a high-density olive tree (B); side-by-side harvester detaching fruit using a trunk shaker and collecting them on a catch frame (C); and straddle harvester based on a canopy shaker collecting fruit on a catch frame (D)

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CAPITULO 6. CARACTERIZACIÓN DE LA ESTRUCTURA DE LA COPA DEL OLIVO EN FUNCIÓN DE LA PODA APLICADA.

Resumen

La porosidad de copa condiciona la intercepción de radiación, la circulación de aire a través de la plantación o la evolución de la operación de recolección en cultivos leñosos. El objetivo del presente estudio ha sido desarrollar una metodología precisa para medir la porosidad de la copa en diferentes tratamientos de poda basándose en la radiación transmitida. La radiación transmitida actuó como una medida indirecta para medir la porosidad de copa en dos parcelas de olivar tradicional de las variedades 'Picual' y 'Hojiblanca'. En estas parcelas se establecieron tres tratamientos de poda para determinar si la poda afecta a la porosidad de copa. Este estudio ha evaluado la precisión y repetibilidad de cuatro algoritmos para procesar los datos obtenidos bajo diferentes condiciones determinadas por el ángulo cenital del sol. Se realizaron medidas con un ángulo cenital del sol entre 14 y 30º, obteniendo un error absoluto por debajo del 5% y una repetibilidad por encima de 0,9. El método y algoritmo desarrollados ha permitido obtener datos de forma satisfactoria en campo, haciendo posible la medida de la porosidad de copa bajo distintos ángulos cenitales del sol. Sin embargo, el peso fresco de material vegetal podado no ha mostrado ninguna relación con la porosidad de copa, debido principalmente a las grandes diferencias de peso entre las ramas podadas, fundamentalmente por la estructura de madera de la rama. En este trabajo se ha desarrollado un sistema y un algoritmo para la medida de la porosidad de copa en olivar tradicional, que ha permitido encontrar diferencias entre distintos tratamientos de poda.

Palabras clave: *Olea europaea* L., densidad de área foliar, índice de área foliar, fracción porosa, balance de radiación, vibrador de troncos, sacudidor de copa, poda mecánica, recolección.

Abstract

Crown porosity influences radiation interception, air movement through the fruit orchard, spray penetration or harvesting performance in fruit crops. The aim of the present study was to develop an accurate and reliable methodology based on transmitted radiation measurements to assess the porosity of traditional olive trees under different pruning treatments. Transmitted radiation was employed as an indirect method to measure crown porosity in two olive orchards of the Picual and Hojiblanca cultivars. Also, three different pruning treatments were considered, to determine if the pruning system influences crown porosity. This study evaluated the accuracy and repeatability of four algorithms in measuring crown porosity under different solar zenith angles. From 14 to 30º of solar zenith angle, the selected algorithm showed an absolute error of less than 5 % and a repeatability higher than 0.9. The described method and selected algorithm showed satisfactory in field results, making it possible to measure crown porosity at different solar zenith angles. However, pruning fresh weight did not show any relationship with crown porosity because of the great differences between removed branches. A robust and accurate algorithm was selected for crown porosity measurements in traditional olive trees, making it possible to discern between different pruning treatments.

Keywords: *Olea europaea* L., leaf area density, leaf area index, gap fraction, radiation balance, trunk shaker, canopy shaker, mechanical pruning, harvesting.

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Introduction

The European Union is the world's foremost olive oil (2/3) and table olive (1/3) producer with an average production of 2,034,300 metric tonnes of olive oil and 776,800 metric tonnes of table olives in the last 6 years. Spain is the largest grower of olives; its production reached 1,274,900 metric tonnes of olive oil and 538,800 metric tonnes of table olives in the same period [1]. In this country, the olive sector has a notable social and economic importance generating an average €1,886 million per year (from 2007 to 2012) and an estimated 46 million working days each year [2].

Because of this sector's importance, a public pre-commercial procurement project, Mecaolivar, was set up to stimulate competitiveness and modernization in the olive sector through the introduction of innovations in olive machinery accompanied by adaptation of trees through pruning [3].

Taking measurements of crown parameters in woody crops and forests is a difficult task that requires a high level of accuracy and represents a major effort in data post-processing. Tree canopies follow irregular geometries, although some features may be explained by mathematical models or coefficients. Canopy structure, leaf distribution and intercepted radiation are important factors that determine crop yield or biomass production.

Several technologies are available to characterize tree crowns and forest architecture: radiation measurements [4], hemispherical photography [5], terrestrial laser [6], Unmanned Aerial System (UAS) imagery [7] and lateral imagery analysis [8]. Furthermore, flowering assessment can be performed by using a smartphone application based on imagery analysis [9]. Imagery analysis is a high-accuracy, cost-effective method to take canopy measurements, but it presents serious difficulties when attempting to generate crown to soil pixel segmentation, above all in crown shaded areas. Therefore, imagery analysis is a highly accurate and reliable method when pixel segmentation is feasible, otherwise alternative methods should be used. Radiation measurement is employed as an indirect method for canopy porosity measurement along the sunbeam direction.

Canopy gap size distribution, or crown porosity, can be used to describe radiation penetration through tree structure as a function of zenith angle [10]. In olive orchards, very few studies have investigated canopy structure and crown porosity. Radiation interception and its relation with olive productivity have been well-assessed, [11]. Daily intercepted photosynthetically active radiation (PAR) in high-density and super-high-density olive orchards varied from 6 to 25 mol/m^2, representing between 15 to 60 % of horizontally incident radiation [12]. However, other effects such as air movement through an olive orchard or spray penetration effectiveness have not yet been studied [13]. Also, porosity may influence canopy shaker efficiency during the harvesting process. Woody parts in the tree canopy also affect PAR interception, air movement or spray penetration. Moreover, some authors have recorded that wood area density affects PAR transmittance through the tree canopy, reducing PAR transmittance by 29 % [14], although this effect has more importance in deciduous trees than in evergreens.

Pruning is a key factor in crown porosity adjustment, mainly for traditional olive orchards. Traditionally, pruning has been used as a cultural practice to regulate production levels and help to avoid pests and disease in rainfed olive groves [15]. [16] found no significant differences in incident irradiance for wild olives in similar topographic conditions either by direct measurement or by estimation from hemispherical photographs. In some windy areas, pruning can also act as a preventive practice to protect trees against being blown down, considering that it has been demonstrated that pruning affects tree performance against hurricane force winds [17].

The way to regulate olive crown porosity by means of pruning has not been studied. Therefore, evaluation of the influence of pruning on olive canopy structure is an important issue that could affect crown porosity, radiation transmittance, clumping coefficient and other geometrical features or coefficients [15]. Assessment of how pruning regulates crown structure should be used to modify radiation balance in order to maximize crop production and machinery performance.

The objective of the present study is to develop an accurate and reliable methodology, based on transmitted radiation measurements, to assess the porosity of traditional olive trees under different pruning treatments. The influence of direct and diffuse PAR on crown porosity and data processing is also evaluated.

Materials and methods

Pruning treatments

Pruning was performed on two traditional multi-trunk olive (Olea europaea L.) orchards in Cordoba (37.717 º N, 4.806º W) and Jaen (37.738º N, 4.145º W) with Hojiblanca and Picual cultivars respectively. Trees were over 100 years old, in good health and phytosanitary condition, and tree density varied from 70 to 80 trees ha^{-1}.

Two pruning treatments were applied to adapt tree architecture for two different harvesting methods: trunk shakers [18] and canopy shakers [19]. Finally, a mechanical pruning treatment was performed that focused on cost saving. The influence of these pruning systems on tree crown architecture and porosity was recorded.

A pruning schedule was performed according to Table 10 in spring from 2013 to 2015. Fresh weight was obtained separately for each tree and each pruning year. Pruning frequency was established in accordance with the pruning system's purpose. Therefore, trunk shaker targeted pruning was applied every two years, while canopy shaker targeted pruning, which required more intense adaption, was performed annually. Mechanical pruning was applied only once because a large canopy volume was previously needed to get adequate results. Pruning was carried out two or three months before PAR measures to include budding effect. Both orchards started the pruning program in 2013 and it continues to date.

Table 10. Pruning Schedule in both olive groves. X means the year in which pruning was applied for each treatment.

Pruning treatment	2013	2014	2015
Trunk shaker targeted pruning	X		X
Canopy shaker targeted manual pruning	X	X	X
Mechanical manual pruning		X	

Pruning treatment features were:

Trunk shaker targeted pruning: This pruning system is widely used in southern Spain as the standard pruning method in many olive orchards. For this study hand-held chainsaw was used to perform the cuts. Lower branches that hindered trunk shaker driver vision were removed, together with the inner branches which were more difficult to reach with pole manual harvesting or hand-held devices. Pole manual harvesting or hand-held devices were used to aid the trunk shaker in order to reach a harvesting efficiency over 85 %. Renewal pruning was also used for scaffolds with the aim of maintaining an adequate yield and tree vigour while keeping a high leaf/wood ratio. This tree architecture made it possible to achieve high harvesting efficiency, high olive yield and adequate effective field capacity during the harvesting operation with trunk shakers.

Canopy shaker targeted pruning: This pruning system was developed with the aim of adapting tree structure in order to obtain higher efficiency and canopy shaker performance in traditional olive trees with several trunks [19]. A hand- held chainsaw was used to perform the cuts. Inner branches were removed because canopy shaker sticks could not reach the canopy central volume. Outer branches that hindered continuous canopy shaker work around the tree canopy were also removed to procure a round canopy perimeter. Renewal pruning was only used for secondary limbs when it enhanced a round path around the tree canopy.

Mechanical pruning: Pruning was performed by a tractor-mounted disc saw pruner, which was hitched to a frontal loader. Light inner shoot clearing was performed with a hand-held chainsaw, which was used to clean up inappropriate mechanical cuts or wood without leaves. This pruning system aimed to increase effective field capacity in the pruning operation and to reduce pruning costs.

Method for ceptometer calibration

An SS1, Sunscan ceptometer (Delta-T devices, Cambridge, UK) was used to measure PAR under olive canopies. This device has a measurement range between 0 µmol m^{-2} s^{-1} and 2,500 µmol m^{-2} s^{-1}, and was connected to a PC through a serial port to gather data. The radiometer probe has 64 individual photodiode readers which provided 64 individual readings. The mean value was obtained from every probe position to determine the radiation that passed through the porous sheet or the tree canopy.

The ceptometer was calibrated under sun radiation. A wood structure was used to avoid diffuse radiation reaching the probe and affecting the final value. Firstly, PAR transmittance to porosity was modelled by using drilled sheets placed over the radiometer (Fig. 25). There were different sheets with a different number of holes, but always a constant distance between holes was kept, taking the centre of the sheet as a reference point. The dimension of the drilled sheets was 150 x 1000 mm (width x length) and the holes had a 24 mm diameter.

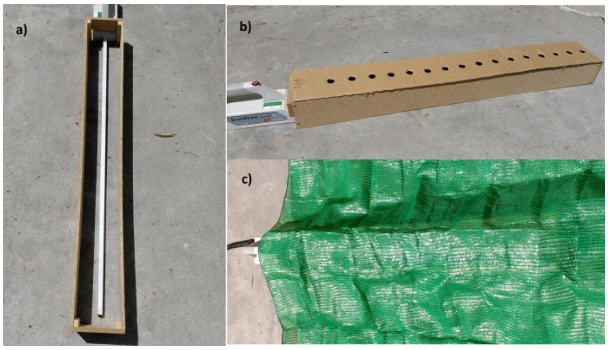

Fig. 25. Ceptometer during calibration process. a) ceptometer with wood structure to avoid diffuse radiation at sun exposed conditions, b) ceptometer with wood structure under drilled sheets and c) ceptometer with wood structure under porous nets.

Secondly, another method was used to assess how solar zenith angle affected PAR transmittance under porous media. Moreover, porous nets were used to evaluate accuracy and repeatability of transmitted PAR measurements (Fig. 25). The same wood structure was used to avoid diffuse radiation, but nets with known porosity were placed over the probe and measurements were taken over a large range of solar zenith angles from 14 to 56º.

In-field measurements of transmitted radiation.

In-field measurements were taken under pruned traditional olive trees, placing the probe on the sides of a 1 m sided grid, spread out under canopy shade. Only those sides which were completely shaded by the olive crown were considered. Afterwards, PAR was calculated as a mean value of the measurements to obtain a mean value of olive crown porosity. Sun-exposed PAR and shaded PAR were also measured for each tree. Ten trees of each pruning treatment were measured per year and per cultivar to assess how crown porosity changed depending on pruning treatment.

Algorithms for data processing

Crown porosity was calculated using under-crown PAR ($PAR_{Under\ crown}$), sun-exposed PAR as direct radiation (PAR_{Sun}) and completely shaded PAR under a solid object as diffuse radiation (PAR_{Shaded}).

Algorithm 1 used the drilled sheet experimental calibration method. The calibration method was performed taking measurements under sun-exposed conditions, keeping the same solar zenith angle and varying drilled sheet porosity [Eq. 5].

$$\phi_1 = 0.059 \cdot PAR_{Under\ crown} + 5.715 \quad [Eq. 5]$$

Algorithm 2 supposed that PAR and porosity are related by a linear regression that intercepted the Y axis at 0 value because shaded PAR was not considered as diffuse radiation [Eq. 6].

$$\phi_2 = \frac{PAR_{Under\ crown}}{PAR_{Sun}} \cdot 100 \quad [Eq. 6]$$

Algorithm 3 considered diffuse radiation as shaded PAR which influenced the calibration model and the under-crown measurements. Shaded PAR was considered as an unwanted steady offset which was removed to zero the measure [Eq. 7].

$$\phi_3 = \frac{PAR_{Under\ crown} - PAR_{Shaded}}{PAR_{Sun} - PAR_{Shaded}} \cdot 100 \quad [Eq. 7]$$

Algorithm 4 introduced diffuse radiation as shaded PAR, but only in the calibration model. This algorithm considered that the canopy was a complex solid net where diffuse radiation represented an important fraction which cannot be subtracted to under-crown PAR. However, diffuse radiation was taken into account to determine calibration interval [Eq. 8].

$$\phi_4 = \frac{PAR_{Under\ crown}}{PAR_{Sun} - PAR_{Shaded}} \cdot 100 \quad [Eq. 8]$$

Algorithms 2 to 4 are based on an equation proposed by [20] that relates leaf area index (LAI) to PAR; these authors describe the importance of both the direct and the diffuse radiation fraction in determining crown porosity.

To evaluate the performance of in-field algorithms, 18 trees (6 per pruning treatment) were measured twice in the same cloudless day. They were first measured in the morning when the solar zenith angle was high, between 28 and 43º. Measurements were later taken under the tree crown around the noon, when the solar declination angle was low, between 14 – 18º. Porosity was calculated using the different suggested algorithms and it was compared to determine how robust the method was against solar zenith angle variations.

Evaluation of algorithm accuracy and repeatability

The accuracy and repeatability of measurements were also evaluated using porous nets as a known porous media at different solar zenith angles. The porosity of measured and known nets was compared to obtain absolute error values. Repeatability (r) was also calculated using the variance between porosity measurements under all porous media at different solar zenith angles (σ_θ^2) and the variance between porosity measurements under one porous medium for different solar zenith angles (σ_ϕ^2) [Eq. 9].

$$r = \frac{\sigma_\theta^2}{\sigma_\theta^2 + \sigma_\phi^2} \quad \text{[Eq. 9]}$$

Results and discussion

Ceptometer calibration and evaluation with known porous media

The calibration model using drilled sheets demonstrated that there was a porosity interval where porosity and PAR under a porous medium were related linearly (Fig. 26). Porosities over 60 % could not be tested because of geometrical constraints in the drilled sheet layout.

Both calibration line ends were less accurate due to the higher or lower porosities of the drilled sheets that supposed substantial or limited lighted or shaded areas (Fig. 26). This calibration method generated a noticeable regular sunfleck pattern with shaded and sunlit areas while real olive trees often show a highly variable spatial distribution [15]. This variability might be represented by a clumping coefficient, although it is more a fitting than a bio-physically meaningful parameter to adjust theoretical to real canopy volume [21]. In the canopy, leaf inclination is represented by G function, leaf reflectance and transmittance also influence radiation interception by olives [22] therefore the shown calibration only demonstrated that there was a porosity interval at which transmitted PAR and porosity were linearly related within a porosity range from 7.5 to 60 %.

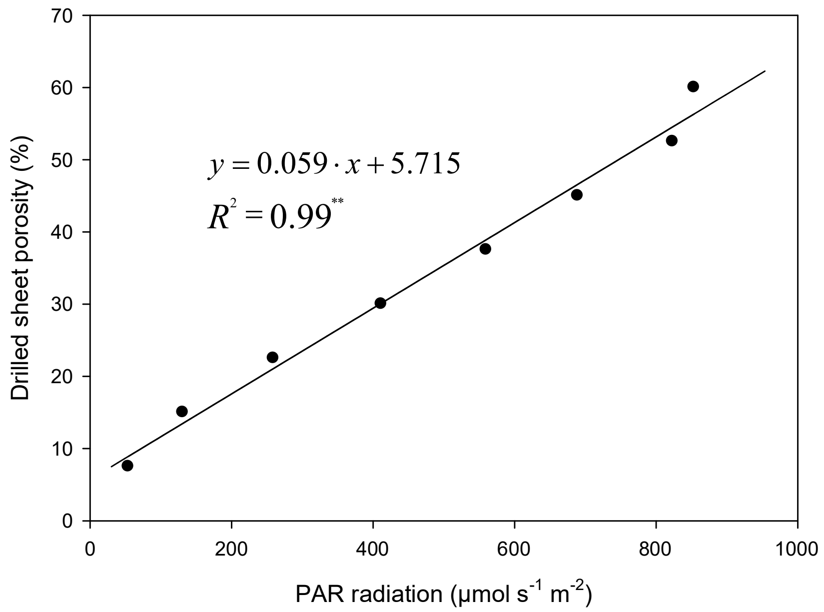

Fig. 26. SSI, Sunscan calibration and regression between PAR radiation and porosity using drilled sheets to shade the probe.

PAR radiation under porous media was affected by solar zenith angle, and therefore, there was a range of time in which PAR could be measured with an adequate repeatability. Measurements taken only below 31º solar zenith angle were considered to keep an adequate repeatability of over 0.9 within a porosity range from 15 to 55 %. Repeatability was severely affected by solar zenith angle, and it also varied depending on medium porosity (Fig. 27). For the tested range of porosities, differences in measured PAR, showed reduced differences when solar zenith angle was below 31º (Fig. 28). [23] state that direct PAR within the crowns of wild olives does not vary during the day in summer conditions but it varies in winter conditions, while diffuse PAR does not differ during the day.

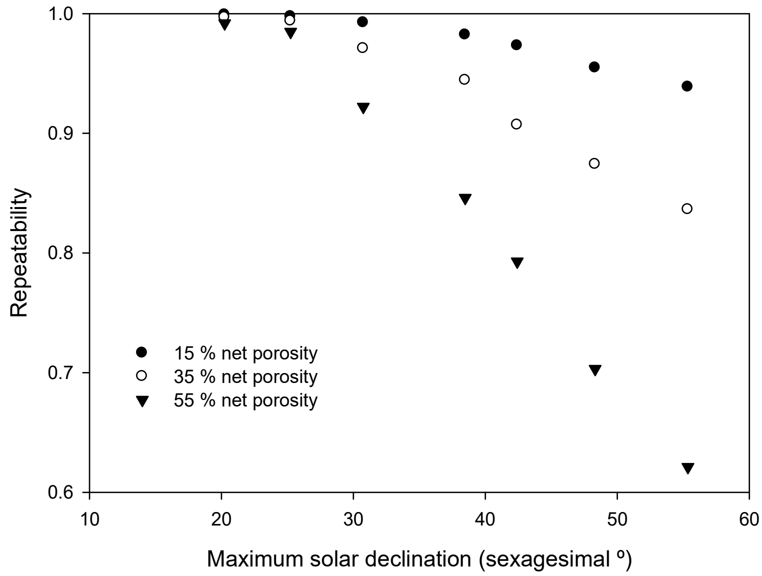

Fig. 27. Repeatability depending on solar zenith angle and net porosity.

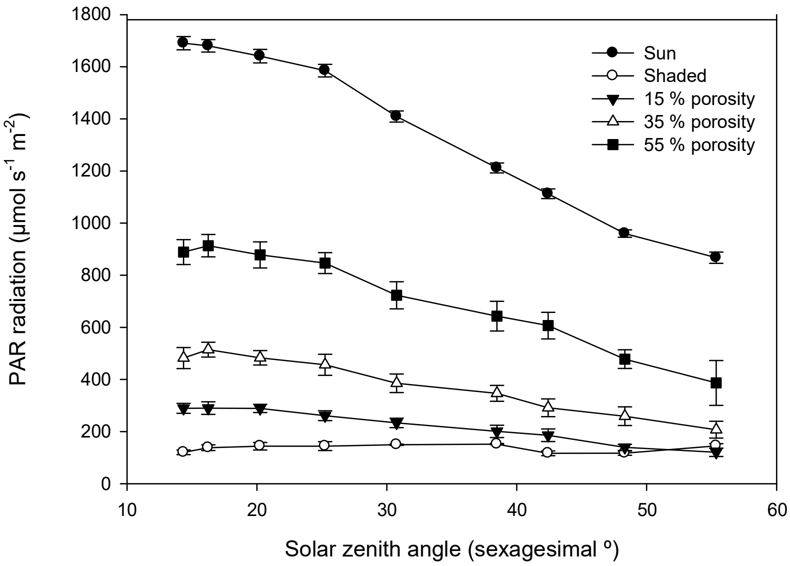

Fig. 28. PAR measurements evolution depending on solar zenith angle and radiation exposure under porous nets.

Ceptometer evaluation for in-field conditions

The worthiness of algorithms was evaluated by measuring tree crown porosity in the same trees at high and low solar zenith angles (Table 11). Algorithms 1 and 3 showed significant differences in crown porosity at different solar zenith angles according to the Wilcoxon test ($\rho < 0.05$). However, Algorithms 2 and 4 were suitable for measuring tree crown porosity at different solar zenith angles. The most robust algorithm against radiation incident direction was Algorithm 4, which uses shaded PAR as diffuse radiation only to calibrate PAR radiation in the measurement time range. With Algorithm 4 it was demonstrated that olive crown porosity did not vary within a zenith direction from 14 to 43º thus, vertical crown porosity was equal at different zenith angles in this range. However, previous research has stated that olive canopy porosity or gap fraction varies depending on the point of view [13]. Thus, assessing the solar zenith angle interval at which crown porosity could be measured and the most robust algorithm to analyze data is an important issue to determine olive crown porosity accurately.

Table 11. Olive crown porosity (Φ[1]) measurements depending on solar zenith angle. Values are mean ± standard deviation. Significance (ρ) was calculated according to Wilcoxon signed rank test. P > 0.05 indicated that both measurements were not significantly different and then the method was not robust against solar zenith angle.

Algorithm	Φ at high solar zenith angle (28 – 43 º)	Φ at low solar zenith angle (14 – 18 º)	ρ
1	21.6 ± 4.1	24.2 ± 3.6	0.000
2	17.6 ± 4.1	17.8 ± 3.7	0.679
3	16.4 ± 4.3	17.1 ± 3.9	0.043
4	17.9 ± 4.3	18.0 ± 3.7	0.983

Assessment of method and algorithms accuracy

The accuracy of porosity measurement varied depending on the calculation algorithm and solar zenith angle (Fig. 29). On the one hand, higher accuracy was provided by Algorithm 4 (absolute error < 5 % crown porosity) without perceptible variations depending on solar zenith angle between 14 and 31º, while Algorithm 2 provided absolute errors up to 10 % of crown porosity depending on solar zenith angle. On the other hand, Algorithms 1 and 3 showed high variability depending on solar zenith angle according to the results shown in Table 11. Regarding zenith angle, it was demonstrated that porous nets and olive canopy showed the same behaviour, although canopy represented a 3D porous solid medium while nets could be represented by a 2D solid porous medium. Instruments for indirect canopy measurements generally provide 20 % accuracy, being mainly limited by the assumption of randomness [20], thus Algorithm 4 showed an appropriate accuracy always over 5 %. According the tested accuracy (Fig. 29), the solar zenith angle range in which crown porosity can be measured, keeping accuracy over 5 %, was 30º. Moreover, within this solar zenith angle range, solar radiation showed parallel behaviour between different porosities (Fig. 28).

The accuracy of algorithms was evaluated by measuring PAR radiation under porous nets and comparing the obtained results with known porosity. Algorithm 1 provided high accuracy when the solar zenith angle was low. However, this algorithm

[1]*Φ: Porosidad de la copa / Crown porosity*

was highly affected by solar zenith angle. Higher porosities also provided better results than lower and medium porosities. Algorithm 3 provided inaccurate and slanted information, thus it indicated that diffuse radiation represented an important fraction in under porous net PAR even at low solar zenith angles. Diversity within the canopy geometry also generates scattering radiation due to reflectance and transmittance, although leaf reflectance is much higher than leaf transmittance [24]. Therefore, it is advisable to measure the canopy gap fraction at low solar zenith angles.

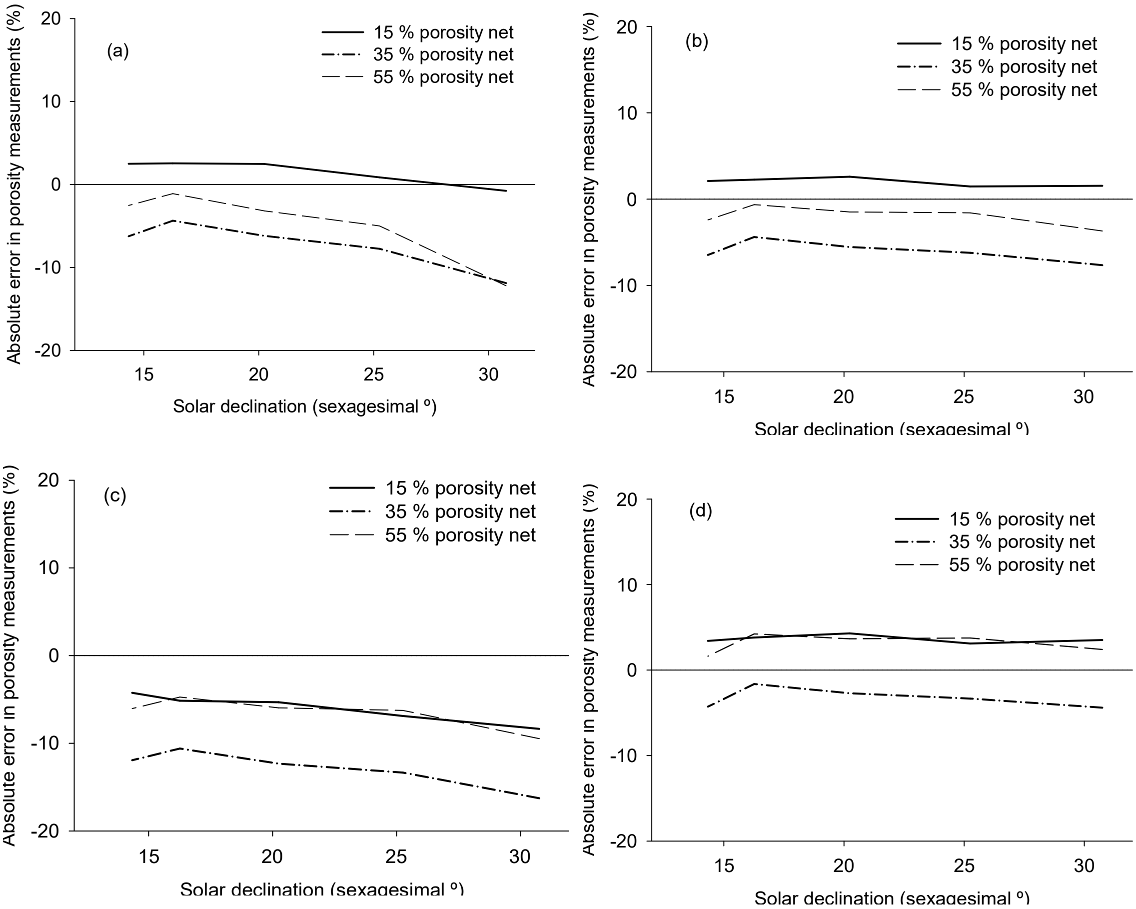

Fig. 29. The accuracy of porosity measurement and absolute error of different porous nets depending on solar zenith angle. (a) Absolute error for algorithm 1; (b) Absolute error for algorithm 2; (c) Absolute error for algorithm 3; (d) Absolute error for algorithm 4.

Finally, Algorithms 2 and 4 were selected as suitable in terms of accuracy for calculating olive crown porosity by means of PAR transmittance across the olive canopy due to measuring stability against solar declination angle. Nevertheless, Table 11 showed a better behaviour of Algorithm 4 for in-field performance and it was demonstrated as the best algorithm to process PAR measurements for olive crown porosity calculation.

Pruning influence on crown porosity

PAR measurements were useful to determine crown porosity, which changed depending on the pruning system (Table 12). Also, tree crown porosity changed depending on previous pruning, pests or diseases which affected the plant leaf area index. Mechanical pruning showed significantly lower porosity values for all sampling dates, orchards and varieties than other pruning treatments. However, when mechanical pruning was carried out (2014) crown porosity was higher for this treatment. Only in 2014, trunk shaker targeted pruning provided lower crown porosity than mechanical pruning. This was due to the fact that pruning was not applied to this treatment in this year. It is possible to state that olive pruning modifies crown porosity, which decreases in every year that pruning was applied to every treatment, although crown porosity fitted, neither with pruning fresh weight in the same season, nor with pruning cumulated fresh weight [Supplementary material Fig. 30]. This could be due to great differences in removed branches and the influence of wood weight, considering that branch fresh weight range went from 0.1 to more than 50 kilograms. In addition, pruning treatments did not shown clear significant differences for tree dimensions [Supplementary material Table 14] Results demonstrate that the pruning system influences crown porosity, according to previous research done in vines, which shows that orchard layout and training system are more important than cultivar or year for crown porosity [25]. In contrast, years showed a great influence on olive trees, mainly due to the fact that olive pruning is usually applied every two years, while vine pruning is applied every year. On the one hand, plant area density ranged from 1.16 to 2.72 m^2 m^{-3}, of which 91 % was leaf in adult olive trees [26]. On the other hand, leaf area density shows values below 2 m^2 m^{-3} [11] while [27] reported values from 2.5 to 2.7 m^{-2} m^{-3}.

Table 12. Crown porosity measured in different olive varieties and dates for each pruning treatment. Different letters indicate significant differences (ρ < 0.05) between pruning treatments for the same cultivar and sampling date according to Duncan's test.

Variety	Sampling date	Pruning treatment	Φ (Algorithm 4) (%)
Hojiblanca	17/07/2013	Trunk shaker targeted	21.3 ± 0.9 a
		Canopy shaker targeted	23.8 ± 2.5 a
		Mechanical	13.8 ± 2 b
	05/06/2014	Trunk shaker targeted	13.9 ± 1.4 c
		Canopy shaker targeted	24.6 ± 3.8 a
		Mechanical	18.8 ± 3.9 b
Picual	15/07/2015	Trunk shaker targeted	18.9 ± 4.2 a
		Canopy shaker targeted	17.7 ± 3.4 a
		Mechanical	13.3 ± 1.5 b

Table 13. Pruning residues removed from the trees for each variety, treatment and year. Different letters indicate significant differences (ρ < 0.05) between pruning treatments for the same cultivar, according to Duncan's test.

Variety	Pruning treatment	Pruning fresh weight 2013 (kg tree^{-1})	Pruning fresh weight 2014 (kg tree^{-1})	Pruning fresh weight 2015 (kg tree^{-1})	Pruning cumulated fresh weight 2013 – 2014 (kg tree^{-1})	Pruning cumulated fresh weight 2013 – 2015 (kg tree^{-1})
Hojiblanca	Trunk shaker targeted	39.5 ± 25.0 a	-	30.6 ± 18.9 a	39.5 ± 25.0 b	70.1 ± 35.4 b
	Canopy shaker targeted	20.5 ± 14.3 b	50.3 ± 32.2 a	32.8 ± 26.7 a	76.5 ± 31.1 a	108.7 ± 53.1 a
	Mechanical	-	55.5 ± 33.4 a	-	31.9 ± 14.8 b	55.5 ± 33.4 b
Picual	Trunk shaker targeted	47.9 ± 18.5 a	-	87.7 ± 38.1 a	47.9 ± 18.5 b	135.5 ± 47.5 a
	Canopy shaker targeted	34.1 ± 12.2 b	58.2 ± 24.6 a	31.9 ± 25.7 b	92.3 ± 25.6 a	124.2 ± 26.6 a
	Mechanical	-	36.8 ± 15.7 b	-	36.8 ± 15.6 b	36.8 ± 15.7 b

The shown measurements were based on radiation transmittance to ground level through the tree canopy. The reported values (Table 12) were for 30 to 14º zenith angle transect, but coincided with horizontal porosity which was measured for a super-high-density olive hedge at a medium height (1 – 1.5 m) obtaining 15 %, while in the upper hedge section porosity increases to 37 % [27]. In high latitude locations it has been described that crown porosity does not affect light measurements under tundra forests [28]. However, in lower latitudes other authors state that 50 % of the total irradiance was lost in the first 0.5 – 0.8 m within the olive tree canopy [23].

Conclusions

Olive crown porosity measurements using PAR transmittance through traditional olive trees crowns is a difficult task because of solar zenith angle variations. Direct and diffuse radiation was used to develop an accurate method to measure olive crown porosity by means of under-crown PAR measurements. Moreover, one of the tested algorithms provided an accurate and robust method against different solar zenith angles, enabling a wide range of working conditions. Porosity and transmitted PAR regression did not provide suitable methods to determine olive crown porosity, but direct, diffuse and transmitted PAR weighting allows processing of PAR data into crown porosity. Algorithm 4 used diffuse and direct PAR to determine crown porosity. This would be the most appropriate method to process PAR radiation under the crown into porosity. The influence of diffuse radiation should not be dismissed when calculating under-crown PAR, but shaded PAR should be deducted from sun-exposed PAR to obtain a reliable algorithm for data processing.

PAR measurements also made it possible to discern between different pruning treatments in traditional olive trees, making it an accurate and reliable method to evaluate crown porosity and canopy structure. Crown porosity in traditional olive orchards was related with the pruning system. Further research is needed to describe how pruning can affect crown porosity and intercepted radiation in the olive canopy; research that would also consider different training systems such as super-high-density, and high-density olive orchards.

Supplementary material.

Table 14. Tree dimensions for tested years in different olive cultivars for each pruning treatment. Values are mean ± standard deviation. Different letters showed significant differences (ρ < 0.05) according to Duncan's test between different pruning treatments for the same cultivar and in the same year.

Variety	Year	Pruning treatment	Skirt height (m)	Tree height (m)	Canopy volume (m^3)
Hojiblanca	2013[1]	Trunk shaker targeted	0.7 ± 0.1 a	4.1 ± 0.3 a	92.2 ± 3.7 a
		Canopy shaker targeted	0.6 ± 0.1 a	4.1 ± 0.4 a	97.4 ± 20.3 a
		Mechanical	0.6 ± 0.1 a	3.6 ± 0.4 a	82.3 ± 2.3 a
	2014	Trunk shaker targeted	0.6 ± 0.2 a	3.9 ± 0.2 a	40.3 ± 9.2 a
		Canopy shaker targeted	0.5 ± 0.2 a	3.9 ± 0.3 a	42.7 ± 9.6 a
		Mechanical	0.4 ± 0.1 a	4 ± 0.5 a	67.5 ± 7.7 b
Picual	2015	Trunk shaker targeted	0.5 ± 0.1 b	3.9 ± 0.1 a	59.5 ± 11.8 a
		Canopy shaker targeted	0.4 ± 0.1 b	3.8 ± 0.3 a	63.7 ± 9 a
		Mechanical	0.3 ± 0.1 a	4.1 ± 0.1 b	72.5 ± 19.2 a

[1] *In 2013, tree crown measurements were taken before to carry out pruning.*

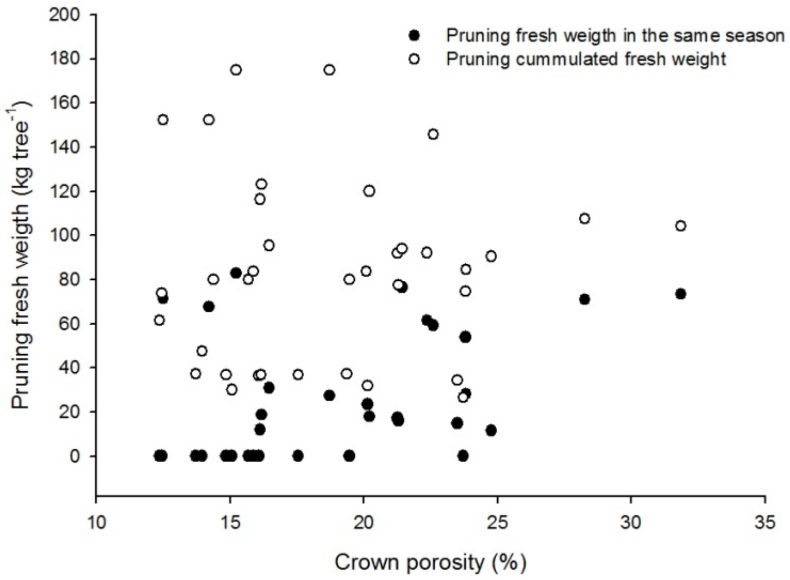

Fig. 30. Pruning fresh weight relation with crown porosity.

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CAPÍTULO 7.1. ESTUDIOS ADICIONALES: COMPORTAMIENTO DE SACUDIDORES DE COPA EN DIFERENTES SISTEMAS DE PODA.

Resumen

La recolección y poda son dos labores que influyen de forma importante sobre los costes de cultivo en olivar, y por tanto sobre su competitividad. Ambas operaciones deben realizarse en consonancia para optimizar el manejo de cualquier explotación de olivar. La estructura del árbol y el diseño de plantación deben adaptarse al método de cosecha seleccionado. En el presente estudio se ha intentado evaluar cómo el olivar tradicional podría adaptarse a la recolección con sacudidores de copa, midiendo diferentes parámetros de poda y recolección. Para éste propósito, se han establecido dos ensayos de poda en dos parcelas de olivar tradicional de las variedades 'Picual' y 'Hojiblanca' durante cuatro años. En estas parcelas se han aplicado tres tratamientos de poda para adaptar la copa del árbol a diferentes sistemas de recolección. La recolección se ha realizado con dos sacudidores de copa diferentes en dos campañas, midiendo la eficiencia de cosecha y los daños generados por cada máquina cómo variables descriptivas de su funcionamiento. Los resultados han determinado que, por un lado, el peso fresco de la poda ha mostrado grandes variaciones entre años, sin embargo, la poda adaptada a la recolección con vibradores de troncos ha proporcionado mayor cantidad de peso fresco de la poda a nivel anual, mientras que la poda adaptada a los sacudidores de copa ha producido mayor cantidad de peso fresco acumulado. Por otro lado, atendiendo a la operación de recolección, el sacudidor de copa precomercial ha obtenidodo un mayor porcentaje de derribo en la poda adaptada a los sacudidores de copa. En cuanto al daño generado, los resultados han sido muy variables, pero han aportado diferencias significativas entre variedades. Por último, la poda y la recolección en olivar, deben estar en consonancia para elegir una cosechadora eficiente adaptando los árboles a la cosechadora y viceversa. En este sentido, es recomendable seguir el proceso de adaptación para realizar una mecanización eficiente en una explotación de olivar.

Palabras clave: Biomasa, restos de poda, eficiencia de cosecha, poda mecánica, vibrador de troncos, daños durante la recolección.

Abstract

Olive harvesting and pruning are two operations than highly influenced olive growing costs and competitiveness. Both operations should be related to reach an efficient orchard management. Tree structure should be adapted to selected harvesting method, but also it has to be in accordance with tree and orchard features. This research attempts to assess how traditional olives could be adapted to harvesting with canopy shakers, measuring different parameters for pruning and harvester performance. For this purpose, two pruning tests were performed during four years in 'Picual' and 'Hojiblanca' traditional olive orchards. Three pruning treatments were applied to adapt tree canopy to different harvesting systems. Harvesting was performed using two different canopy shakers. Harvesting efficiency and debris production were considered as descriptive variables to analyze harvester performance. On the one hand, pruning fresh weight was highly variable between years, however trunk shaker pruning provided higher amount of yearly pruning biomass while canopy shaker pruning generated higher accumulated biomass wastes. On the other hand, canopy shaker pruning provided higher harvesting efficiency than other pruning systems for pre-commercial harvester. With regard to debris production was highly variable, although it provided significant differences between both cultivars. Finally, pruning and harvesting operations should be related to choose an efficient harvesting system and to adapt the trees to the harvester and vice versa. This rule should be taken into account to carry out an adequate mechanization of an olive orchard.

Keywords: Pruning biomass, pruning wastes, harvesting efficiency, mechanical pruning, trunk shaker, Debris production.

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Introduction

The European Union (EU) is the top world olive oil and table olives producer, being the main producer areas located in the Mediterranean basin (EUROSTAT, 2012). Spain is the larger producer within the EU both for olive oil and table olives (IOOC, 2015) having 2,605,000 ha cultivated (ESYRCE, 2015) although this crop is extending to other areas all over the world. Therefore, it is an important issue to keep a competitive and profitable olive sector, considering that the olive growing has an outstanding importance for economy and job-creating (MAPAMA, 2016) in large rural areas.

Because of the sector importance, a public pre-commercial procurement Mecaolivar has been carried out to stimulate olive sector competitiveness and modernization through introducing innovations in olive machinery accompanied by tree adaptation by means of pruning (Gil-Ribes et al, 2014). Harvesters developed within this process require an adaption of tree structure to get adequate harvesting efficiency.

Many olive orchards are mainly managed in traditional low-intensity manner (Duarte, Jones, & Fleskens, 2008), consequently, exploitation profitability and competitiveness is often reduced, mainly in traditional orchards or in those non suitable for mechanization. In this country, olive growing area is mainly occupied by four main cultivars; Picual, Cornicabra, Hojiblanca and Lechin de Sevilla, which represents more than 63 % of total olive growing area (Barranco & Rallo, 2000). Picual and Hojiblanca have an outstanding importance in olives for oil and table olives (Hojiblanca only). Picual cultivar was characterized by high tree vigour, regular crop, early ripening and low resistance to fruit retention force (FRF), in contrast, Hojiblanca often provides biennial crop, late ripening and high FRF (Rallo & Barranco, 1983).

Olive cultivar affects several factors such as harvesting efficiency (Farinelli et al. 2012), tree vigour, shape and pruning (Vivaldi, Strippoli, Pascuzzi, Stellacci, & Camposeo, 2015) or oil quality, which depends also on fruit ripeness (Jiménez-Herrera et al., 2012). However, other factors may be taken into account to get an adequate olive management. In this way, olive harvesting has a high weight on olive total growing costs being around 40 %, while pruning could oscillate between 15 and 20 % (AEMO, 2012). It is due to pruning operation usually requires well-trained operators that often supposes a high cost or are scarce in the main producing areas, otherwise mechanical pruning should be implemented to increase effective field capacity and reduce costs (Tombesi, Farinelli, Ruffolo, & Sforna, 2012). Furthermore, those operations are related, because the main objective of pruning is to keep actual yield as close as possible to potential yield according to the environment. In addition, olive pruning influences harvesting performance, for instance in super high density olive orchards the hedgerow should be kept within 250 cm height and 150 cm width (S. Tombesi & Farinelli, 2014).

In other olive categories such as high density or traditional orchards, the tree canopy size and architecture should be also adapted to the harvesting system requirements.

Another purpose of pruning is to increase fruit production maintaining fruit bearing branches within the tree canopy. Vegetative and reproductive growth could also affect olive yield especially in medium-high vigour cultivars (Tombesi and Farinelli, 2011). Usually, trees response to mechanical pruning reduces yield in high vigour cultivars which increase sylleptic bud breaking and sprout growth reducing fruit set. When irrigation amount is not a limiting factor, some exploitations choose a postponed pruning strategy, but often yield decrease due to reciprocal shading (Gómez-del-Campo, Centeno, & Connor, 2009). In addition, growth and fruiting are not the same for all cultivars, therefore tree training should be adapted to each cultivar, mainly in early years after plantation (Moutier, Garcia, & Lauri, 2004).

Finally, olive pruning should be studied in relation to harvesting process, considering that tree pruning could not be the same for manual harvested trees than for mechanical harvested ones. Moreover, there are some different mechanical systems available for olive harvesting such as hand held branch shakers or shaker combs, trunk shakers or canopy shakers. These systems generate different vibration patterns, although all of them carry out a successful harvesting process (Sola-Guirado et al., 2014). Each harvesting system is adapted to different canopy architecture, thus the harvesting system have to be adapted to tree structure and viceversa. It is due to tree architecture has a substantial influence on removal efficiency, fruit catching rate and fruit bruising when a mechanical assist shaker and catch system are used for other fruit crops (Zhou, He, Karkee, & Zhang, 2016). Integral canopy shakers that can harvest all tree canopy in one sweep are being developed for olive orchards, mainly for traditional ones. There are no pruning systems adapted to this harvesting technology. Therefore it is highly recommended to develop a new pruning system that make possible to adapt trees to integral canopy shakers in order to enlarge harvesting efficiency reducing neither harvester effective field capacity, nor olive yield.

The aim of this research is to assess how multi-trunk traditional olive orchards could be adapted to new integral harvesting systems based on canopy shaking. Furthermore, pruning fresh weight was evaluated to determine pruning fresh weight for current traditional olive orchards. Finally, yield, harvesting efficiency and debris production were also measured using canopy shaking systems.

Material and methods

Pruning was performed in two traditional multi-trunk olive (*Olea europaea* L.) orchards in Cordoba (37.717° N, 4.806° W) and Jaen (37.738° N, 4.145° W) planted with Hojiblanca and Picual cultivars, respectively. Trees have been planted more than one century ago at 70-80 trees ha^{-1}. Selected trees were in good health and phytosanitary condition.

Three pruning treatments were applied to both orchards. Pruning treatments features are described below and showed in Fig. 31:

- Trunk shaker targeted pruning: This pruning system is widely used in Southern Spain as the standard tree training in many multi-trunk traditional olive orchards. For this study, a hand-held chainsaw was used to perform the cuts. Lower branches that hindered trunk shaker driver vision were removed, together with the inner branches, which were more difficult to reach with pole manual harvesting or hand-held devices. These harvesting systems were used along trunk shaker to achieve high harvesting efficiency. Renewal pruning was also used to remove scaffolds when they showed low vigor to maintain an adequate yield and tree vigour while a high leaf/wood ratio was also kept. This tree architecture made it possible to achieve high harvesting efficiency by keeping limited tree height that made possible to reach all canopy volume using poles or hand held devices harvesting. In addition this training system made possible to obtain high olive yield and adequate effective field capacity during the harvesting operation using trunk shaker along with hand held harvesting systems or operators with long poles.
- Canopy shaker targeted pruning: This pruning system was developed with the aim of adapting the tree structure in order to obtain high harvesting efficiency and adequate effective field capacity in traditional olive trees with several trunks (Sola-Guirado et al., 2014) or in large-sized canopies (Famiani et al., 2014). A hand-held chainsaw was used to perform the cuts. Inner branches were removed because canopy shaker rods could not reach the canopy central volume while outer bearing branches were kept. Outer branches that hindered continuous canopy shaker work around the tree canopy were also removed to procure a round canopy perimeter. Renewal pruning was only used for secondary limbs when it enhanced a round path around the tree canopy. Lower branches that hindered catch frame performance were also removed to facilitate fruit detaching, catching and management. The scope of this training system was to adapt trees to an integral harvester.
- Mechanical pruning: This pruning system aimed to increase effective field capacity in the pruning operation and to reduce pruning costs (A. Tombesi et al., 2012). Topping and hedging was performed by a tractor-mounted saw pruner, which was hitched to a frontal loader. Light inner shoot clearing was performed manually, using a hand-held chainsaw, which was also used to clean up inappropriate mechanical cuts or wood without leaves. Cut sides were applied to parallel canopy sides in the same pruning year. North and south sides were pruned in 2014, while east and west sides were cut in 2016 applying both topping and hedging cuts. Tree height was limited to 3.5 m and hedging cut depth was between 0.75 and 1 m from the canopy outer surface.

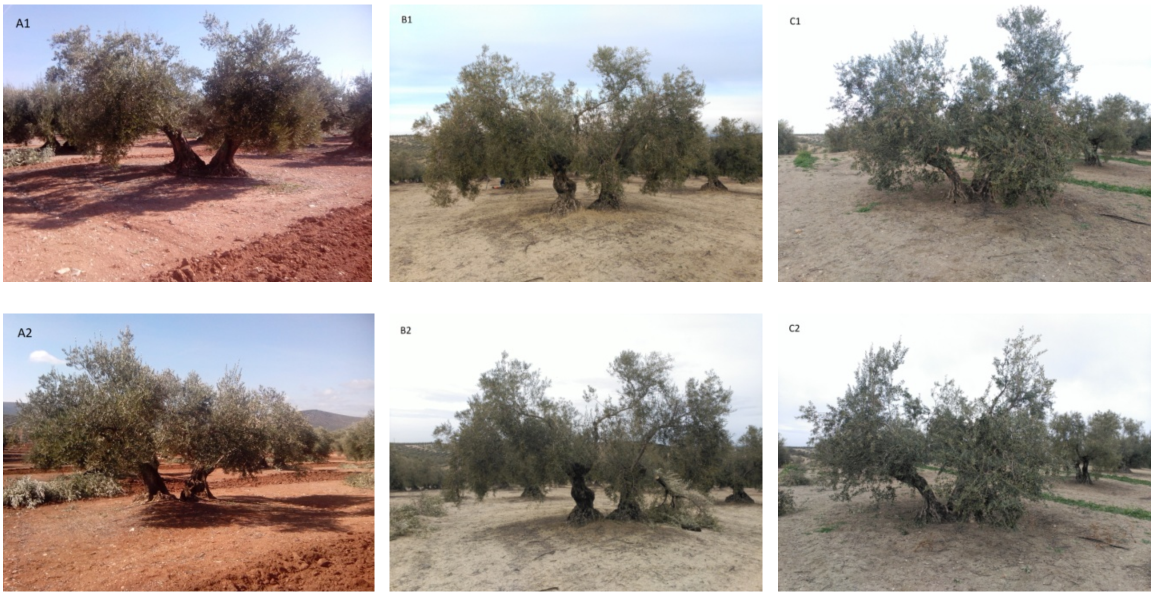

Fig. 31. Tree canopies before and after pruning in 2016 pruning season. A1/A2 trunk shaker targeted pruning in Picual cultivar before/after pruning; B1/B2 canopy shaker targeted pruning in Hojiblanca before/after pruning and C1/C2 mechanical pruning in Hojiblanca before/after pruning.

In each orchard, 96 trees were arranged in a completely randomized block design. The different treatments were applied following biennial pruning schedule for trunk shaker targeted pruning and mechanical pruning while canopy shaker targeted pruning was performed annually (Table 15). It was due to canopy shaker targeted pruning needed more intense tree adaption, considering that canopy shaking was a new harvesting method and subsequently it required intense and specific tree training.

Table 15. Pruning and harvesting schedule followed in tested olive groves. X means the year in which pruning was applied for each treatment.

Pruning treatment	Pruning season				Harvesting season		
	2013	2014	2015	2016	2013/14	2014/15	2015/16
Trunk-shaker-targeted pruning	X		X				
Canopy-shaker-targeted pruning	X	X	X	X	Canopy shaker prototype	*	Pre—commercial harvester
Mechanical pruning		X		X			

** Mechanical harvesting was not performed this year due to low yield.*

Pruning fresh weight was measured for each tree separately including wood shoots and leaves. To perform this task, cut branches were counted separated into five groups depending on their weight: scaffolds, secondary branches, big sized branches, medium sized branches and bearing branches. Every group of branches is represented by a mean fresh weight obtained from several samples of trees.

Yield was also measured including harvested and unharvested fruit using two canopy shakers without any harvesting system to exhaust remained fruit. Yield was measured separating fruit in reachable or harvestable canopy volume from the inner fruit, located in unreachable or unharvestable canopy volume. Reachable canopy volume was defined as a ring elliptical cylinder 1.5 m depth from the outer canopy surface (Fig. 32), which was the volume in contact with shaker rods. In the reachable canopy volume were located the harvestable fruit, which were those fruit suitable for mechanical harvesting with canopy shakers. Unharvested fruit were also collected using hand held shaker comb to calculate harvesting efficiency.

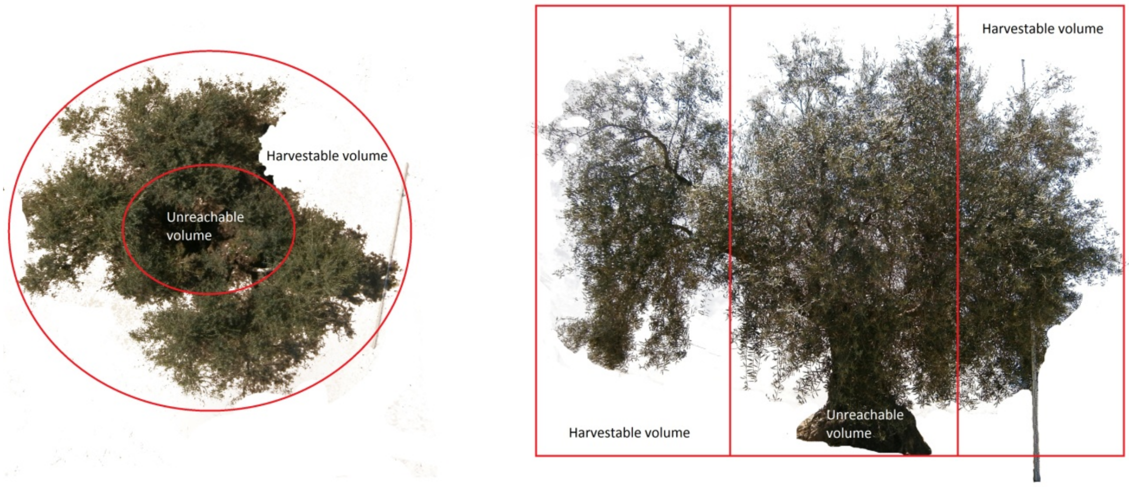

Fig. 32. Ring elliptical cylinder that determines the reachable canopy volume for canopy shakers.

Two harvesters were built and tested in the pruned plots. The Canopy shaker prototype was designed by University of Córdoba along with the Spanish Olive Oil Interprofessional Organisation. This harvester was tested in 2013/14 harvesting season. The pre-commercial harvester was built by Colossus Maqtec S.L. in collaboration with University of Córdoba based on the previous prototype within Pre commercial procurement Mecaolivar. This harvester was tested in 2015/16 harvesting season (Fig. 33).

Fig. 33. Two tested canopy shaker harvesters: a) Canopy shaker prototype tested in 2013/14 harvesting season; b) Pre-commercial harvester tested in 2015/16 harvesting season.

Both tested harvesters were pulled by the same tractor to avoid influence of the harvester-tractor manoeuvrability. Trees were harvested separately working around the tree to make a one wipe harvesting reaching adequate harvesting efficiency. Both harvesters included catch frames to collect and manage fallen fruit.

Two parameters were measured to characterize pruning operation for the three pruning treatments:

- Pruning fresh weight: It weighted the cut branches to characterize every pruning treatment for each year.
- Accumulated pruning fresh weight: It added pruning fresh weight from the beginning of the test for each treatment.

In addition, yield was measured to assess the effect of pruning system on tree production, considering two parameters:

- Yield: It measured the total yield per year.
- Yield within unreachable canopy volume: It measured only those fruit located in the inner elliptical cylinder within canopy volume (Fig. 32).

Finally, regarding the harvesters performance, harvesting efficiency and debris production were evaluated:

- Harvesting efficiency: This parameter included only those fruit that were successfully detached and transported to the storage big bag by the catch frame system. It was considered only within reachable canopy volume (Fig. 32).
- Debris production: Debris production during canopy shaking process was recorded. Fresh weight of broken branches, primarily stems and leaves was measured.

Results and discussion

Pruning fresh weight

Pruning fresh weight showed great variability between years, similar pruning fresh weight were provided for the two tested cultivars, excluding trunk shaker targeted pruning in 2015 for Picual. It was due to, in previous years, trees have grown a lot due to high rain rates and warm wheather. Significant differences (ρ<0.05) were found between pruning treatments both for Hojiblanca and Picual cultivars in some years, being Trunk shaker pruning usually higher than canopy shaker pruning (Fig. 34). However, mechanical pruning provided higher waste production than canopy shaker pruning for Hojiblanca, while Picual cultivar generated less pruning waste than canopy shaker pruning. It was due to Picual and Hojiblanca differences in crown architecture because of, Hojiblanca used to produce less branching than Picual, thus it has more compact canopy volume. For this reason, Mechanical pruning provided higher quantity of pruning fresh weight than canopy shaker pruning for Hojiblanca. Likewise, due to canopy architecture differences, canopy dimensions are affected in a different way, for instance, in 2016, Hojiblanca crown height was reduced in 8.7 % while Picual cut only 6.2 % using mechanical pruning.

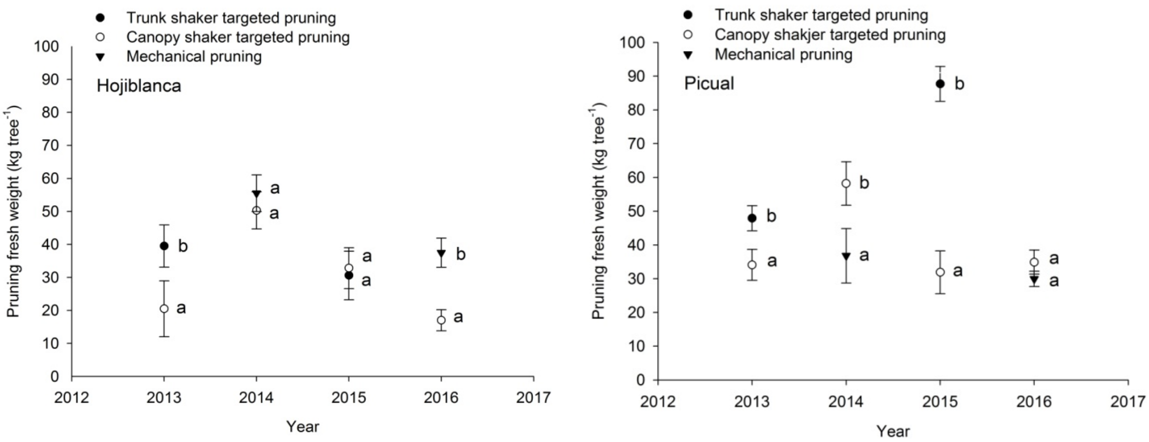

Fig. 34. Mean pruning fresh weight for different years and pruning treatments. Data showed mean ± standard error. Different letters indicate significant differences (ρ<0.05) between pruning treatments for the same cultivar and year according to Student's T test.

Trunk shaker targeted pruning produced more or similar pruning wastes than canopy shaker targeted pruning, mainly because trunk shaker pruning was applied every two years while canopy shaker pruning was carried out every year. Accumulated pruning fresh weight was significantly (ρ<0.05; Duncan's test) higher for canopy shaker pruning than for trunk shaker pruning (Table 16). Mechanical pruning eliminated less accumulated pruning fresh weight for Picual cultivar although for Hojiblanca cultivar, mechanical pruning produced more pruning wastes without showing significant differences with trunk shaker targeted pruning.

Table 16. Accumulated pruning fresh weight in Picual and Hojiblanca cultivars for tested pruning treatments. Data showed mean ± standard error. Different letters indicate significant differences (ρ<0.05) between pruning treatments for the same cultivar according to Duncan's test.

Pruning treatment	Accumulated pruning fresh weight (kg tree^{-1})	
	Picual	Hojiblanca
Trunk shaker targeted pruning	111.2 ± 8.3 b	70.1 ± 6.3 a
Canopy shaker targeted pruning	139.9 ± 7.9 c	125.7 ± 10.6 b
Mechanical pruning	62.8 ± 4 a	93 ± 8.6 a

Pruning fresh weight depends on tree canopy volume considering that higher trees usually provided higher pruning fresh weight. This parameter determining is an important issue for biomass supply chain, in order to use these wastes to produce energy. Currently, it is possible to predict pruning fresh weight using aerial imagery and terrestrial LIDAR (Light Detection and Ranging) data (Estornell et al., 2015), but this and other forecasting systems should be calibrated with in-field measurements. Previous research provided lower pruning fresh weigh, between 10 and 30 kg tree^{-1} for a high density olive orchard applying manual and mechanical pruning complemented with sucker cutting (Farinelli, Onorati, Ruffolo, & Tombesi, 2011). However, other authors state that manual pruning complementing mechanical pruning increase neither yield nor enlarge harvesting efficiency using trunk shakers (Dias, Peça, & Pinheiro, 2012). Furthermore, different mechanical pruning treatments generate canopy volume reductions from 10 to 50 % (Tombesi et al., 2012) which could be highly useful to control reciprocal shading in intensive orchards.

Pruning fresh weight during pruning operation could influence yield for next years, mainly when severe pruning was applied (Connor, Gómez-del-Campo, Rousseaux, & Searles, 2014) However when cultivars are well adapted to training system, as occurs for Arbequina, Arbosana or Koroneiki in hedgerow orchards, yield is not correlated with pruning fresh weight (Vivaldi et al., 2015). Hedgerow training supposes a more intense adaption of olive trees than trunk shaker targeted pruning, although it depends on cultivar vigour, growing habit and bearing earliness (Farinelli & Tombesi, 2015). Mechanical pruning is widely used in olive industry, mainly for topping, although traditional orchards are less bent to use this technique. Vegetative response to mechanical pruning depends on several factors such as irrigation, fertilization or crop load. For instance in warm climates mechanical pruning should be limited to on-yield years in order to limit vegetative growth and improving light distribution (Cherbiy-Hoffmann, Searles, Hall, & Rousseaux, 2012).

Yield

Yield did not provide significant differences (ρ<0.05; Duncan's test) among pruning treatments for the same cultivar and harvesting season except for Hojiblanca in 2013/14 harvesting season. In that case, mechanical pruning was more productive than trunk or canopy shaker targeted pruning due to there were more bearing branches considering that in this year, mechanical pruning was not already applied. Picual cultivar showed higher yield than Hojiblanca, especially in 2013/14 harvesting season which was extremely high yield (Fig. 35). Yield in 2014/2015 was too low in both orchards to carry out mechanical harvest considering that Picual mean yield was 1.2 kg $tree^{-1}$ while Hojiblanca produced 2.4 kg $tree^{-1}$.

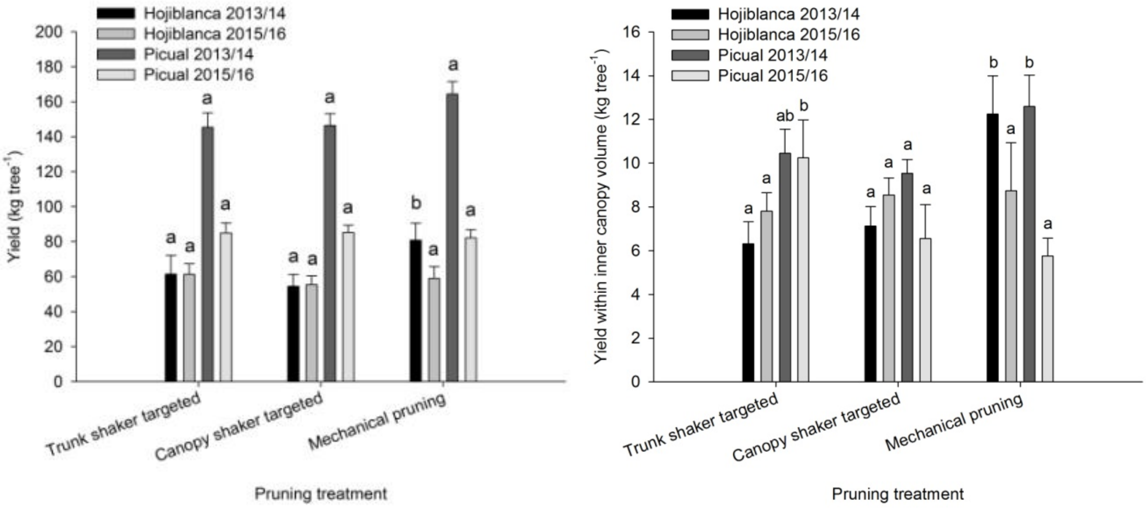

Fig. 35. Mean yield in the two tested cultivars and for both harvesting seasons considering the whole canopy volume (left) and the inner canopy volume (right). Data showed mean ± standard error. Different letters indicate significant differences (ρ<0.05) between pruning treatments for the same cultivar and harvesting season according to Duncan's test.

Regarding yield within inner canopy volume, canopy shaker pruning provided no significant differences or significant lower (ρ<0.05; Duncan's test) inner yield than the other treatments, considering that inner branches cut was more intense when trees were adapted to canopy shakers. Trunk shaker or mechanical pruning did not show a clear trend, although trunk shaker pruning showed different behaviour between olive cultivars. In this sense, Picual provided higher inner yield values than Hojiblanca, which could make it more suitable for canopy shaker harvester due to canopy architecture and budding pattern. Furthermore, mechanical pruning had less inner yield when it was recently pruned for both cultivars. However mechanical pruning produced significantly higher inner fruit when pruning of inner branches was not carried out. This fact could lead to apply less frequent mechanical cuts while, light inner branches cut should be applied yearly in order to get good results using canopy shakers.

Fruit yield depended not only on pruning treatment, but it was also influenced by cultivar and year (Tombesi and Farinelli 2014; Vivaldi et al. 2015), planting pattern (León, Rosa, Rallo, Guerrero, & Barranco, 2007) and location. Despite, mechanical pruning or even no pruning can kept high yield in olive orchards (Pastor and Humanes-Guillen, 2006). Yield is independent from pruning frequency, although previous research showed that less frequent pruned trees has provided lower oil content than those which are pruned more frequently (Mohedano, 2005). However, inadequate illumination or poor ventilation could lead to reduce olive yield (Tous, Romero, & Hermoso, 2010) although over certain values of incident photosyntetically active radiation (PAR), fruit weight and oil content reach an upper threshold (Cherbiy-Hoffmann, Hall, & Rousseaux, 2013). It has been demonstrated that pruning treatment in traditional olive orchards affect to transmitted PAR, and it also be used to calculate crown porosity (Castillo-Ruiz, Castro-Garcia, Blanco-Roldan, Sola-Guirado, & Gil-Ribes, 2016), affecting intercepted PAR and then olive yield, although in the present research it was not found a relationship between pruning fresh weight and yield. Pruning influence on yield, harvesting process and orchard management make highly recommendable to develop new pruning systems, especially for those traditional orchards which were planted long time ago when olive growing and harvesting technology were totally different.

Harvesting efficiency

On the one hand, canopy shaker prototype provided low harvesting efficiency values around 80 % for Picual and around 60 % for Hojiblanca considering only the harvestable fruit. On the other hand, pre-commercial harvester provided higher harvesting efficiencies than canopy shaker prototype for harvestable fruit, keeping similar differences between Picual and Hojiblanca cultivars (Table 17). Canopy shaker pruning system provided higher harvesting efficiency than other pruning systems for both cultivars in 2015/16 harvesting season while trunk shaker and mechanical pruning showed similar results. Comparing both harvesters, lower harvesting efficiency is also explained because canopy shaker prototype had low manoeuvrability, no shaking head approaching system and four self turning wheels compared with pre-commercial harvester which had shaking head approaching system, and only two wheels steered by turning pull bar.

Table 17. Mean harvesting efficiency ± standard error for harvesting efficiency within reachable canopy volume. Different letters indicate significant differences (ρ<0.05) between pruning treatments for the same harvester, cultivar and harvesting season according to Duncan's test.

Harvester	Pruning treatment	Trunk shaker targeted pruning	Canopy shaker targeted pruning	Mechanical pruning
Canopy shaker prototype	Cultivar	Harvesting efficiency in 2013/14 (%)		
	Hojiblanca	65.1 ± 3.2 a	58.9 ± 4.3 a	58.6 ± 3.8 a
	Picual	75.1 ± 4.6 A	81.9 ± 2.1 A	83.3 ± 2.2 A
Pre-commercial harvester	Cultivar	Harvesting efficiency in 2015/16 (%)		
	Hojiblanca	77.1 ± 2.2 a	87.9 ± 3.1 b	79.3 ± 2.5 a
	Picual	86.2 ± 4.8 A	96.6 ± 3.5 B	90.9 ± 3.8 A

Harvesting efficiency was increased between 2013/14 and 2015/16 due to harvester manoeuvrability and shaking heads approach. Harvester capabilities to adapt itself to the crop along with crop adaption to the harvester, were key factors to reach an adequate harvesting efficiency. It would be desirable to achieve harvesting efficiency values higher than 85 % over a wide range of conditions in order to provide a feasible integral harvesting for commercial purposes.

Trunk shakers can reach high harvesting efficiencies (93 – 96 %) for medium sized (29 – 39 m^3) trees (Visco, Molfese, Cipolletti, Corradetti, & Tombesi, 2008), Harvesting efficiency using trunk shakers is reduced mainly when fruit are difficult to detach. Tree structure also affect vibration transmission when tree structure is not adapted to trunk shakers harvesting, as occurred in multi-trunk traditional trees, or when shaking power was not enough to achieve adequate harvesting efficiency (Castro-Garcia, Castillo-Ruiz, Jimenez-Jimenez, Gil-Ribes, & Blanco-Roldan, 2015). Furthermore, fruit properties such as fruit detachment force or fruit weight also influences harvesting efficiency (Farinelli et al. 2012), thus, when harvesting systems have to face some adverse conditions, it is important to optimize machine operation and tree pruning. In addition pole manual harvesting or shaker combs could be used to aid the trunk shaker in order to reach a harvesting efficiency of over 85%. Harvesting efficiency using trunk shakers has also been influenced by pruning intensity, providing efficiency values from 82 to 94 % when annual pruning fresh weight represents from 7 to 21 kg $tree^{-1}$ (Tombesi, Boco, Pilli, & Farinelli, 2002).

Trunk shaker show several problems when it is used in adverse conditions, mainly in traditional trees that are poorly adapted to mechanical harvesting. One example of this limitation could be big sized trees, in which trunk shaker provided low harvesting efficiency between 73 and 40 %, although it could be improved to 87 – 97 % by using a canopy shaker harvester (Famiani et al., 2014). Continuous contact between the harvester and the canopy is proved to be a decisive factor for a correct harvesting process using canopy shakers (Sola-guirado et al., 2016). In this sense, harvester manoeuvrability and shaking heads approach were key factors, increasing harvesting efficiency from 2013/14 to 2015/16 harvesting season due to the improvements included in the new harvesters such as steering wheels or turning pull bar that make possible a more efficient harvester approach to olive canopy. Further research should test approaching systems for each shaking head separately, making possible to keep close contact between shaking rods and olive canopy even when trees would be not properly trained.

Debris production

Debris production showed highly variable values between trees considering that broken branches depended on tree structure and how much canopy shaker head was brought closer to tree canopy. During 2013/14 harvesting season lower debris production was generated due to canopy shaker harvester could only moved away and approach to the canopy by means of tractor steering system and turning pull bar while in 2015/16 pre-commercial harvester included approaching system for shaking head and only two wheels, improving harvester approach to canopy. Harvesting tests showed that mean values were higher in 2015/16 respect to 2013/14 harvesting season. Significant differences were only found for trunk shaker pruning for Hojiblanca in 2015/16 harvesting season (Table 18).

Table 18. Mean debris production ± standard error for debris production. Different letters indicate significant differences (ρ<0.05) between pruning treatments for the same harvester, cultivar and harvesting season according to Duncan's test.

Harvesting season	Cultivar	Trunk shaker targeted pruning (kg tree^{-1})	Canopy shaker targeted pruning (kg tree^{-1})	Mechanical pruning (kg tree^{-1})
2013/14	All	1.4 ± 0.4 a	2.8 ± 0.9 a	3.8 ± 1.1 a
2015/16	All	9.1 ± 1.0 a	6.7 ± 0.7 a	9 ± 0.9 a
2013/14	Picual	3.8 ± 1.5 a	4 ± 1.8 a	4.8 ± 2.1 a
	Hojiblanca	1.9 ± 0.6 a	1.7 ± 0.5 a	3.1 ± 0.9 a
2015/16	Picual	9.4 ± 1.3 a	8.8 ± 1.3 a	9.5 ± 1.0 a
	Hojiblanca	8.7 ± 1.5 b	5.2 ± 0.6 a	8.3 ± 1.8 ab

In 2013/2014 harvesting season, different cultivars did not differ significantly for debris production, while in 2015/2016 significant differences (ρ<0.05) were found between picual and Hojiblanca cultivars [See Supplementary material Fig. 36]. It could be due to Picual architecture is characterized by upright growing with no preference in lateral shooting (Hammami, de la Rosa, Sghaier-Hammami, León, & Rapoport, 2012), considering that cultivar strongly influences shooting, budding and fruiting in fruit bearing branches for olive trees (Moutier et al., 2004). Thus, for Picual cultivar, high number of lateral shoots grew in any direction, and this fact increased the probability that shaking heads impacted against more shoots, generating higher amount of debris. Finally, canopy shaker showed less debris than trunk shaker pruning for Hojiblanca, while Picual did not provide any significant differences.

Previous research determined that canopy shakers debris production is lower than trunk shaker and hand held devices. Surprisingly, the highest value is generated by manual harvesting using long poles which produces 8.5 % of debris of total detached fresh weight (Sola-Guirado et al., 2014). Debris production is an important fact for olive harvesting process, considering that it increases transported weight hindering fruit management process. Furthermore, debris make necessary to include a fruit cleaning process within the harvester or the harvesting procedure. In summary, debris production facilitates the transmission of diseases and it can also affect transport efficiency and fruit processing cost (Spann & Danyluk, 2010).

Conclusions

In summary, pruning fresh weight resulted highly variable between years. In general terms, trunk shaker pruning provide higher yearly pruning wastes, while canopy shaker pruning produced more accumulated pruning fresh weight due to the yearly intense inner branch cut. However, mechanical pruning provided opposite behaviour depending on the cultivar, considering that canopy architecture might influence pruning fresh weight for mechanical pruning. Pruning treatment did not significantly affect yield during four years, thus each orchard should adapt trees by pruning to selected harvesting system without affect orchard profitability in terms of incomes.

Traditional olive harvesting by canopy shakers required tree architecture and machine improvements and adaptations to reach high harvesting efficiency. Tree training through pruning requires long-term tests, considering that until three years after first pruning adaption, significant differences were not found. Canopy shaker pruning provided higher harvesting efficiency, thus it was more suitable for integral harvesting using canopy shakers. Furthermore, debris production increased when harvesting efficiency became higher, this parameter should be taken into account considering that it is highly important for tree health, fruit management process and fruit logistics. Finally, pruning and harvesting operations should be related to choose an efficient harvesting system and to adapt the trees to the harvester and vice versa. This rule should be taken into account to carry out an adequate mechanization of an olive orchard.

Supplemantary material

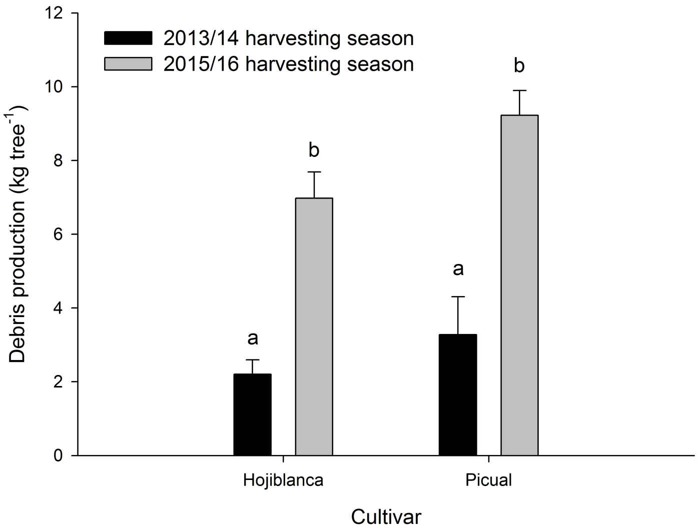

Fig. 36. Mean debris production ± SE for both olive cultivars in two harvesting seasons. Different letters indicate significant differences (ρ<0.05) between cultivars for the same harvesting season according to Duncan's test.

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CAPÍTULO 7.2. ESTUDIOS ADICIONALES: MECANISMO DE DESPRENDIMIENTO DEL FRUTO, EVALUACIÓN DE LA TORSIÓN EN EL PEDÚNCULO.

Resumen

A menudo, la recolección en olivar requiere grandes cantidades de mano de obra debido a la baja eficiencia de recolección. Es frecuente que la recolección mecanizada esté apoyada por operarios con varas o equipos manuales como los sacudidores de ramas para incrementar el porcentaje de frutos cosechados. En la actualidad, la fuerza de retención del fruto (FRF) y el peso fresco se emplean para prever la eficiencia de cosecha y para decidir el momento de la recolección, aunque durante el proceso de derribo el pedúnculo del fruto sufre fuerzas flectoras y de torsión, además de tracción y fuerzas de naturaleza inercial simuladas por las medidas de FRF. Sin embargo, hasta el momento, no queda claro cómo intervienen la aceleración generada, la arquitectura del árbol o la FRF en el proceso de derribo del fruto. Para evaluar el comportamiento mecánico del pedúnculo de la aceituna, se han llevado a cabo unos ensayos a lo largo del proceso de maduración de cuatro variedades de olivo *Olea europaea* L.:'Frantoio', 'Arbequina', 'Leccino' and 'Maurino'. La FRF a tracción se ha medido después de aplicar un esfuerzo torsor con diferentes ángulos de giro del pedúnculo del fruto (0, 90, 180, 270, 360, 540, 720º). La FRF ha sido considerada 0 cuando el fruto ha caído durante la aplicación del esfuerzo torsor. El peso, firmeza, índice de maduración y contenido graso del fruto se han medido para determinar el momento óptimo de recolección. La FRF se ha visto reducida de forma significativa por encima de 180º de giro del pedúnculo previo a la aplicación de la fuerza de tracción. Estas diferencias se han mantenido durante el proceso de maduración del fruto, lo que hace este efecto especialmente interesante en condiciones de recolección temprana. Los esfuerzos torsores son un parámetro importante para el derribo del fruto, teniendo en cuenta que el porcentaje de frutos derribados sólo mediante esfuerzo torsor ha variado entre el 10,7 % y el 58,8 % en función del índice de madurez del fruto. Finalmente, también se han observado diferencias entre variedades, que pueden estar relacionadas con la longitud del pedúnculo u otras características varietales.

Palabras clave: Fuerza de retención del fruto, recolección de olivar, torsión del pedúnculo, rotación del pedúnculo, rotación del fruto, vibrador de troncos.

Abstract

Olive harvesting often requires a high hand labour due to low harvesting efficiency. Frequently, mechanical harvesting is aided by operators with long poles or hand held devices to increase the percentage of harvested fruit. Currently, Fruit retention force (FRF) and fruit fresh weight (FW) were used to predict harvesting efficiency, although during harvesting process, fruit stalk is subjected to bending and twisting movement further pulling and inertial forces simulated by FRF measurements. However, up to date, it is unclear how FRF, acceleration or tree architecture are involved in fruit detaching process. In order to assess mechanic behavior of olive stalk, a trial was carried out during ripening process on four olive (*Olea europaea* L.) cultivars: 'Frantoio', 'Arbequina', 'Leccino' and 'Maurino'. FRF under traction force was measured after applying different stalk twisting angles (0, 90, 180, 270, 360, 540, 720º). FRF was considered to be 0 when fruit was detached from the bearing branch during the twisting process. Fruit weight, firmness, ripeness index and oil content were measured to determine the optimal period for olive harvesting. FRF was significantly reduced, usually over 180º, when stalk was rotated before applying the pull force to measure FRF. Differences were kept along fruit ripeness process. Stalk twisting was an important parameter for olive detachment, considering that fruit detached without pulling forces varied between 10.7 and 58.8 % of the total fruit according with the different sampling dates. In addition different behavior between olive cultivars was described, which could be related to stalk length or specific cultivar features.

Keywords: Fruit retention force, olive harvesting, stalk twisting, stalk spinning, fruit rotation, trunk shaker.

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Introduction

The European Union (EU) is the top world olive oil and table olives producer, being the main producer areas located in the Mediterranean basin. Spain, Italy and Greece hold more than 95 % of the total EU olive oil production during 2015/16 harvesting season (IOOC, 2015). In those countries, olive growing has an outstanding economic and social importance (MAGRAMA, 2016), playing an important role as economic activity in a large number of rural areas. Currently, the decrease of competitiveness in olive sector threatens the survival of olive farms and mills (Pomarici & Vecchio, 2013), that needs to improve farm efficiency through modernisation, shared machinery management or outsourcing labours (Vilar Hernández et al., 2011). In the last decades, olive orchards management evolved towards more intense planting densities and use of high level of mechanization (Novello, Bueno, Andrieu, & Miranda, 2014), however there is still margin for improvement in the farming techniques (Carmona-Torres, Parra-López, Hinojosa-Rodríguez, & Sayadi, 2014).

Manual fruit harvesting is unavoidable for many fresh fruit and vegetables, but it has a low working capacity and uncertain labour availability, although orchard layout, dwarf trees and picking aids can improve manual harvesting performance (Sanders, 2005). Furthermore, manual fruit harvesting may contribute to the development of ailments in the worker musculoskeletal system (Młotek, Kuta, Stopa, & Komarnicki, 2015) as well as hand held shaker combs (Çakmak, Saraçoğlu, Alayunt, & Özarslan, 2011) and branch shakers (Çakmak et al., 2011). Nevertheless, in a large number of olive orchards, harvesting is currently performed using different mechanical devices such as trunk shakers, hand held devices or integral harvesters. In large olive growing areas there are high labor requirements during harvesting operation, mainly for traditional olive orchards in which effective field capacities for harvesting operation are often poor (Castillo-Ruiz, Pérez-Ruiz, Blanco-Roldán, Gil-Ribes, & Agüera, 2015). Current olive harvesting systems achieve harvest efficiencies ranging from 90 %, achieved by trunk shakers in favourable conditions, to 80 %, achieved by lateral canopy shakers, while manual harvesting can reach 98 % of total harvest efficiency (Sola-Guirado et al., 2014). However, trunk shaker performance depends on several external conditions such as fruit ripeness (Blanco-Roldán et al., 2009), tree structure (Castro-García, Blanco-Roldán, Gil-Ribes, & Agüera-Vega, 2008) or machine features (Castro-Garcia et al., 2015). Furthermore it would be desirable that commercial mass harvesting systems for olives will achieve harvesting efficiencies above 90% (D'Agostino, Giametta, Giametta, Mauro, & Zimbalatti, 2008), without using manual or hand held systems to remove left fruit. In fact, the breakeven point for olive harvesting efficiency is considered 85 % (Farinelli, Ruffolo, Boco, & Tombesi, 2012) due to commercial available harvesters limitations in standard harvesting conditions. Nonetheless, straddle canopy shakers usually achieve harvesting efficiency values over 95% (Farinelli & Tombesi, 2015), although these systems have different harvesting efficiency depending on the cultivar (Vivaldi et al., 2015), canopy volume and training system (Tombesi & Farinelli, 2014).

Although harvesting at early ripening stages is becoming a current technique to enhance phenol content in fruit for premium olive oil, at early harvesting season, it is more difficult to achieve high harvesting efficiency (Blanco-Roldán et al., 2009). Therefore, a better understanding of the detachment process is fundamental to improve mechanical harvest efficiency. Up to date, fruit detachment force (FDF) is used as the main index to describe the resistance of fruit to detachment from the tree, but it measures only traction force. It was divided by fruit fresh weight (FDF/FW) to obtain a more representative index able to predict the harvesting efficiency of trunk shaker (Farinelli, Tombesi, Famiani, & Tombesi, 2012). Furthermore, FDF/FW decreases when fruit ripeness moves forward or when abscission chemicals were applied (Sessiz & Özcan, 2006). However, up to date it is unclear how FDF, acceleration or tree architecture are involved in fruit detaching process.

Current harvesting systems provoke limited stalk twisting. In trees subject to forced vibrations produced by trunk shakers, fruit experienced stalk twisting angles under 70 °, with peak angles around 150 º (Castillo-Ruiz et al., 2016). Moreover during cherry harvesting using limb shaker, twisting has limited influence on the number of motion patterns in comparison with tilting or beam column motion patterns (Zhou et al., 2016). Furthermore, some test and simulations performed in oranges harvested by a canopy shaker determine that only 18 % of FDF was applied to fruit stalk which invites to think that the fruit undergo twisting and bending processes during mechanical harvesting (Savary, Ehsani, Salyani, Hebel, & Bora, 2011).

Fruit detachment is affected by stalk geometrical properties and its behavior during tree shaking (López-Giménez, 1979). Motion of fruit-stem subsystem can be described with three translational and three rotational degrees of freedom, which corresponds to precession, mutation and spin of the fruit (Upadhyaya, Cooke, & Rand, 1981). Concerning stalk structure, it can be divided into three different areas from bearing branch to fruit it can be distinguished the peduncle, rachis and pedicel. These sections may be considered as different abscission areas for olive, and fruit abscission is affected by harvesting date and cultivar, while fruit weight doesn't show a significant effect (Castillo-Llanque & Rapoport, 2009).

The aim of the present work was to determine olive stalk behavior against torsion and pulling forces determining these values along the ripening process in different international and Italian cultivars.

Materials and methods

Fruit sampling was carried out in 2015 in a young intensive olive orchard (10 years old) placed at Deruta, Perugia, Central Italy (42°57'39.2"N, 12°25'02.5"E). In the orchard there were four different olive cultivars (*Olea europaea* L.): Frantoio, Arbequina, Leccino, and Maurino planted in different rows, three per each cultivar. The orchard was divided in three blocks laid out perpendicular to the maximum slope and to the cultivar row. Each sampling included three trees, one per block.

Two cultivars, Frantoio and Arbequina, were sampled every week from September 17 to November 12, while Leccino and Maurino were sampled only every two weeks in order to determine optimal sampling rate for olive fruit. Different stalk twisting angles were applied to fruit (0, 90, 180, 270, 360, 540, 720º) before applying a traction force to measure FDF. Traction force was measured using a hand held Push - Pull Dynamometer FD 101 (TR Turoni, Forlì, Italy) that had 0 to 1000 g range and 10 g resolution. The dynamometer hook was custom-modified in order to make possible fruit turning along the attaching rod (Fig. 37). FDF was considered to be 0 when fruit was detached from the bearing branch during the stalk twisting process. If fruit suffered the same stalk twisting during harvesting process, fruit detachment would occur without additional forces.

Fig. 37. Dynamometer with modified hook for apply stalk twisting before FDF measurement.

During each sampling date, one sample of approximately 0.5 kg of fruit was taken from each tree. Stalk length was measured in the first sampling, considering the whole length from the attachment point with fruit bearing branch to the attachment point with fruit (Fig. 38). This length included peduncle, rachis and pedicel (Castillo-Llanque & Rapoport, 2009).

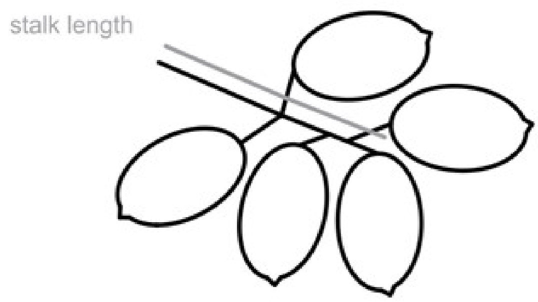

Fig. 38. Measuring process to determinate stalk length for fruit cluster.

Fruit fresh weight was measured by weighting 100 fruit the same day that the samples were taken. These fruit were also evaluating to determine ripening index following the Jaen method [Eq. 10] separating fruit into 8 classes according to the fruit external and internal pigmentation (Uceda and Hermoso, 1998). The same fruit sampling was also used for fruit firmness measurements with a hand held dynamometer FD 101 (TR Turoni, Forli, Italy) that had 0 to 1000 g range and 10 g resolution. To perform the measure, a steel cylindrical tip with 1 mm diameter was pulled to the fruit to prick it and keep the highest resistance. Furthermore, FDF/FW was calculated for each fruit sampling, as a different forecasting value for harvesting efficiency.

$$Ripening\ index = \frac{\sum(RS \cdot n)}{100} \quad \text{[Eq. 10]}$$

Oil and water content was determined as well using near infrared spectrometry (NIRS) previously calibrated for the same olive cultivars. For this purpose, one sample of about 0.2 kg was taken for each tree being milled. The resultant olive paste was stirred and homogenized before measure being located in the measuring dish of a InFralyzer apparatus (SpectraAlyzer Zeutec BRAN+LUEBBE, Rendsburg, Germany), that measured the oil and water content, expressed on fresh weight basis. In addition, oil content related to dry matter was also calculated to track the oil accumulation process.

Statistical analyses have been applied to the studied parameters Data were also analyzed statistically by ANOVA and using the Duncan's-test to compare the means of the two different cultivars.

Results and discussion

FDF was significantly reduced when stalk twisting was applied before pulling the fruit out. FDF reduction was greater when stalk twisting was higher. Differences were kept along fruit ripeness process, although stalk sensitivity to torsion strains varied, depending on the sampling date. Generally, FDF reduction along with stalk twisting was lower at advanced stages of ripening, as a consequence, percentage of detached fruit without traction increased. Moreover, significant differences ($\rho<0.05$)

were commonly found over 180 º of stalk twisting, and when ripening process was advanced, fruit were often detached only by applying a stalk twisting over 360 º (Fig. 39 and Fig. 40).

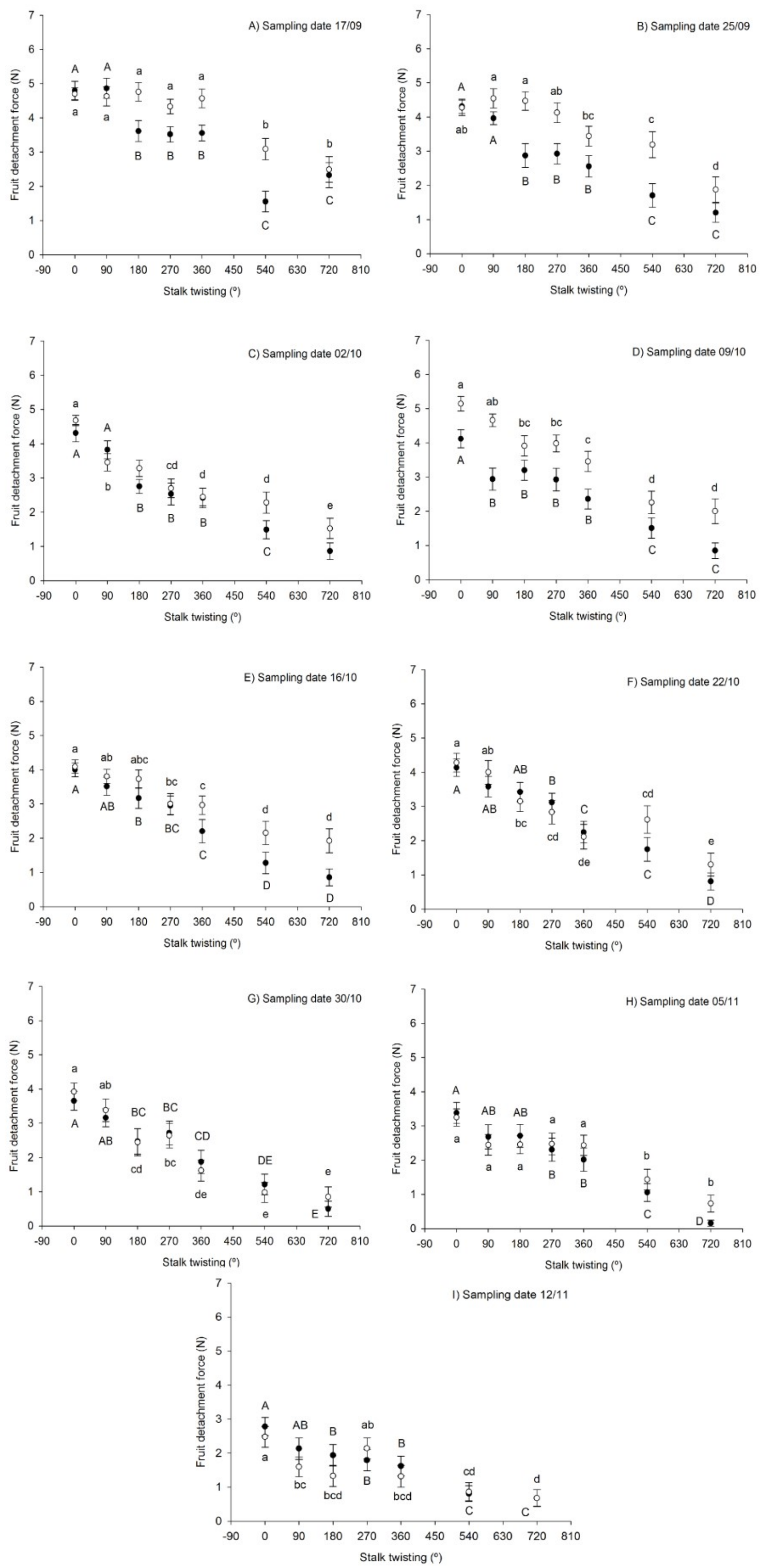

Fig. 39. Mean ± SE for fruit detachment force at different stalk twisting angles for different sampling dates. Different uppercase letters indicate significant differences (ρ < 0.05) for Arbequina cultivar while different lowercase letters indicate significant differences (ρ < 0.05) for Frantoio cultivar. Both of them show differences in detachment force at different spinning angles according to Duncan's test. ○ Frantoio ● Arbequina.

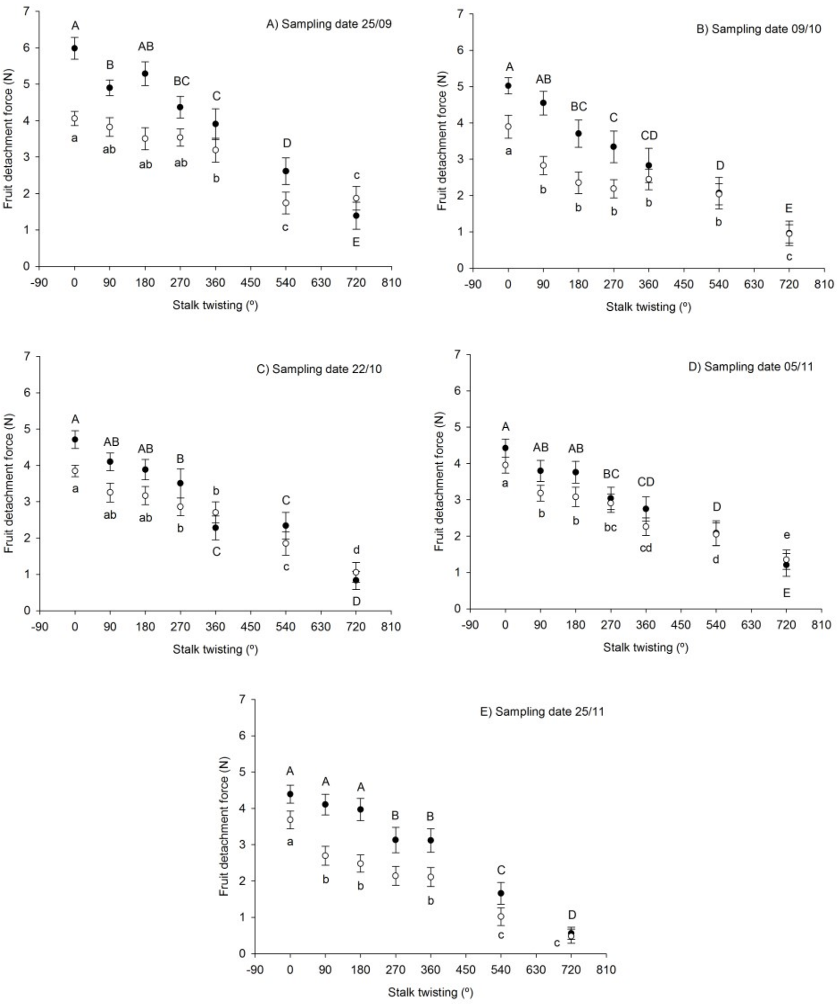

Fig. 40. Mean ± SE for fruit detachment force at different stalk twisting angles for different sampling dates. Different uppercase letters indicate significant differences (ρ < 0.05) for Leccino cultivar while different lowercase letters indicate significant differences (ρ < 0.05) for Maurino cultivar. Both of them show differences in detachment force at different spinning angles according to Duncan's test. ○ Maurino ● Leccino.

Olive stalk susceptibility to fruit spinning, led to hypothesize that stalk torsion strain could play an important role for late harvesting, when it caused an important percentage of fruit detachments by itself, particularly at the end of the ripening process (Table 19). Although in other fruit, twisting movement pattern has limited importance (Zhou et al., 2016), in olive inertial and bending forces could be key factors in fruit detachment process (Tsatsarelis, 1987). Therefore, current harvesters could take advantage of torsion strain at stalk level, due to the effect on FDF decrease. This could be particularly important for increasing harvesting efficiency in early harvesting, when trunk shaker causes a lower percentage of detached fruit than in late harvesting (Blanco-Roldán et al., 2009).

Table 19. Percentage of detached fruit only by applying twisting forces for different cultivars in all sampling dates.

Sampling date	Arbequina	Frantoio	Leccino	Maurino
17/09	14.3	10.7	-	-
25/09	26.5	16.0	21.4	21.1
02/10	27.2	19.4	-	-
09/10	33.0	18.0	36.4	31.0
16/10	35.3	21.8	-	-
22/10	32.0	33.7	30.0	27.2
30/10	45.2	45.6	-	-
05/11	47.6	39.1	28.9	24.5
12/11	53.1	58.8	-	-
25/11	-	-	27.6	37.1
Mean	34.9	29.2	28.9	28.2
SE	4	5.3	3.1	2.1

In oranges, FDF decreases when the pulling direction forms a greater angle with the pistil-calyx axe (Torregrosa, Albert, Aleixos, Ortiz, & Blasco, 2014). Our data support the hypothesis that bending forces collaborate along with traction and inertial forces in fruit detachment process. Furthermore, in manual apple picking bend and pull forces are combined to reduce detachment energy as compared to the application of sole pulling force (Li, Karkee, Zhang, Xiao, & Feng, 2016). Several fruit twisting can also facilitate fruit picking (Chiu, Yang, & Chen, 2013), mainly for fruit which are highly susceptible to bruising as occur for table olives.

Harvesting efficiency depends on several factors such as shaking frequency (Castro García, Gil Ribes, Blanco Roldán, & Agüera Vega, 2007; Leone, Romaniello, Tamborrino, Catalano, & Peri, 2015), abscission agent application (Sessiz & Özcan, 2006), tree features (Farinelli, Ruffolo et al., 2012), time, and harvesting date (Castro-Garcia et al. ,2015). Different shaking technologies and vibration patterns could be applied to olive harvesting with similar final results (Sola-Guirado et al., 2014). Different harvesting systems have variable harvesting efficiency within the canopy with possible effect on the oil quality considering that fruit with the highest oil yield and oil quality are located in the outermost part of the canopy (Castillo-Ruiz, Jimenez-Jimenez, et al., 2015). Finally, future machines should match bending, torsion and traction forces with inertial ones to accomplish a quick and effective fruit detachment that reduces required hand labor, which is currently used to assist trunk shaker harvesting with long poles or hand held devices.

Stalk length showed significant differences (P<0.05) for the four tested cultivars. These cultivars could be grouped in two categories: short stalk cultivars, such as Arbequina and Leccino, and long stalk cultivars, such as Frantoio and Maurino, although no significant differences were found between Leccino and Maurino (Fig. 41). Stalk twisting had different effect on FDF depending on cultivar: Leccino usually had higher FDF for all twisting angles than Maurino, while Arbequina and Frantoio had a more erratic behaviour. In early harvesting, Frantoio was roughly more difficult to detach as long as Arbequina was more difficult to detach during the final part of the ripening process. Those differences can be related to stalk length, physiological aspects or water stress. Furthermore, FDF depends strongly on stalk diameter (Lavee, Avidan, & Ben-Tal, 1982) varying between different olive cultivars (Farinelli, Ruffolo et al., 2012). Stalk length may affect harvesting performance due to vibration transmission from fruit bearing branches to stalk-to-attachment point or to stalk-to-fruit attachment point.

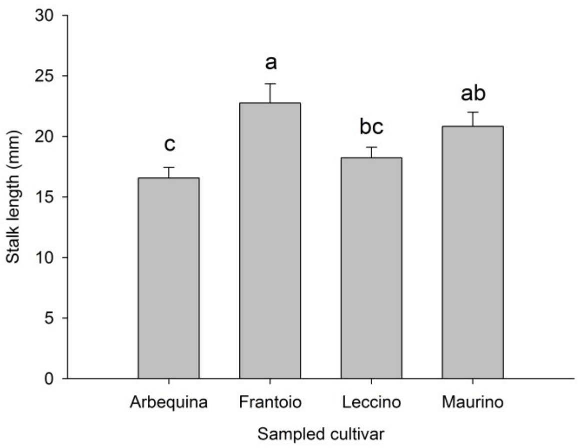

Fig. 41. Mean ± standard error for stalk length measured from attached branch to fruit for considered cultivars. Different letters show significant differences (ρ<0.05) between cultivars according to Duncan's test.

Fresh fruit weight increased along the maturation process due to tissue growing and oil accumulation (Farinelli, Boco, & Tombesi, 2002). These two parameters reached a maximum value at the end of the ripening process, as particularly evident in Leccino and Maurino cultivars. Trees were harvested in mid (Arbequina and Frantoio) and end November when optimal maturity, established on the base of oil content and FDF, was reached (Fig. 42). Fruit weight played an important role during olive harvesting process, FDF/fresh fruit weight affects harvesting efficiency (Farinelli, Tombesi et al., 2012) mainly due to stalk bending forces, inertial phenomena and fatigue (Tsatsarelis, 1987). During early harvesting, high FDF reduces harvesting efficiency, thus, it is necessary to increase shaking time to achieve high removal efficiency (Blanco-Roldán et al., 2009). But prolonged tree shaking can cause bark damages in particular when the tree is still vegetative (Gurusinghe & Shackel, 1995).

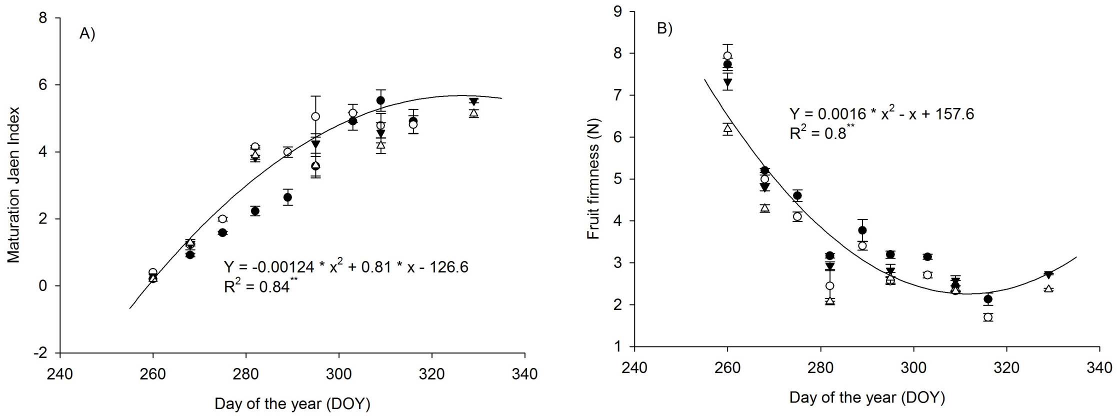

Fig. 42. Maturation Jaen index (A) and fruit firmness (B) along the sampling process for different olive cultivars. R square values with ** superscript indicated that regression provided high significant values (ρ<0.01). ○ Frantoio ● Arbequina ▼Leccino △ Maurino.

All tested cultivars provided an FDF value under 3 N when the stalk twisting was over 180 º except Leccino, which reached the same values when stalk twisting was over 360 º. Therefore, FDF measurement combining pulling and twisting forces could also be a useful index to predict both, harvesting efficiency and maximum oil content on a dry mass basis, determining the optimal harvesting time (Farinelli et al., 2002; Portarena et al., 2015).

Sampling process was carried out during the main part of the maturation process, comprising maturation indexes from 0 to 6 within the Jaen maturation index. All cultivars provided a significant quadratic trend along maturation (R^2=0.84; P<0.01) [Eq. 11] for the sampled period, and fruit firmness also provided significant quadratic trend (R^2=0.8; P<0.01) [Eq. 12] (Fig. 42). However previous research, based on non-destructive methods, reports that olive skin color followed a quadratic trend for Arbequina and Picual cultivars while firmness follows a linear trend (Garcia & Yousfi, 2005). Other non destructive methods to measure olive ripeness could be based on near infrared spectroscopy (Gracia & León, 2011) considering that fruit firmness is an important parameter which influence fruit damages during mechanical harvesting (Tombesi, Tombesi, Molfese, Cipolletti, & Visco, 2011). Furthermore, harvesting efficiency could be predicted using firmness, colorimetric and pigmentation indexes (Camposeo, Vivaldi, & Gattullo, 2013).

$$\boldsymbol{Maturation\ Jaen\ index} = -\mathbf{0.00124} \cdot \boldsymbol{DOY}^{\mathbf{2}} + \mathbf{0.81} \cdot \boldsymbol{DOY} - \mathbf{126.6} \quad \text{[Eq. 11]}$$

$$\boldsymbol{Fruit\ firmness}\ (\boldsymbol{N}) = \mathbf{0.0016} \cdot \boldsymbol{DOY}^{\mathbf{2}} - \boldsymbol{DOY} + \mathbf{157.6} \quad \text{[Eq. 12]}$$

Tests were carried out along the whole oil accumulation process, comprising an important part of the fruit growing season (Fig. 43). Oil content on a dry weight basis was an indicator for optimal harvesting date regarding economic yield, while fruit weight could be used as a predictor of fruit harvesting ease.

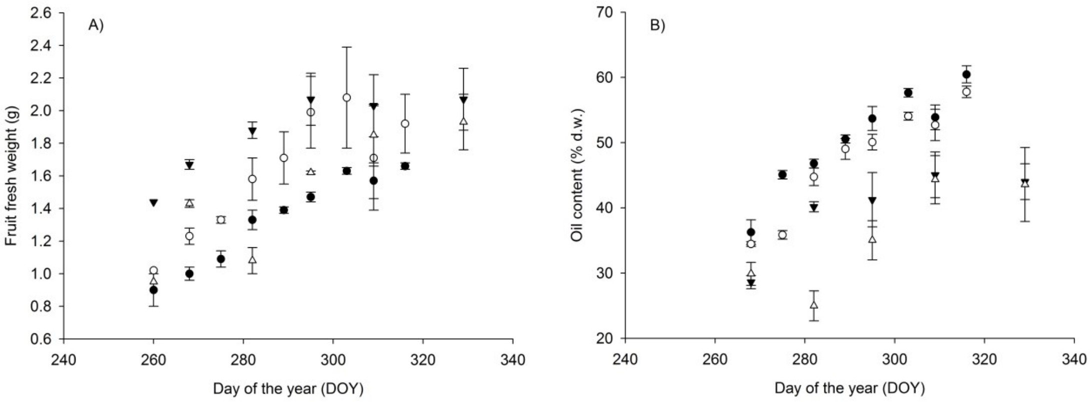

Fig. 43. Mean ± standard error for fruit fresh weight (A) and oil content on dry basis (B) for all cultivars in every sampling date. ○ Frantoio ● Arbequina ▼Leccino △ Maurino.

All studied cultivars showed high susceptibility of FDF and FDF/FW ratio to stalk twisting, while some cultivars such as Arbequina, Leccino and Maurino varied FDF at a lesser extent along ripening process than along stalk twisting. Fruit detachment became easier along ripening process because of FDF reduction although this reduction was usually greater only by applying a stalk twisting angle over 360º. However, all cultivars did not show the same pattern: Arbequina, Leccino and Maurino decreased more regularly along ripening, while Frantoio was more irregular. Furthermore, FDF was consistently reduced at wider stalk twisting angles in all cultivars suggesting a possible facilitation of harvesting process mainly for early harvesting. Fruit weight played also a role along the maturation process, softening FDF changes in frequently sampled cultivars as Arbequina and Frantoio, while in less frequently sampled cultivars, FDF/FW ratio provided higher differences between different stalk twisting angles than along ripeness process (Fig. 39, Fig. 40 and Fig. 44).

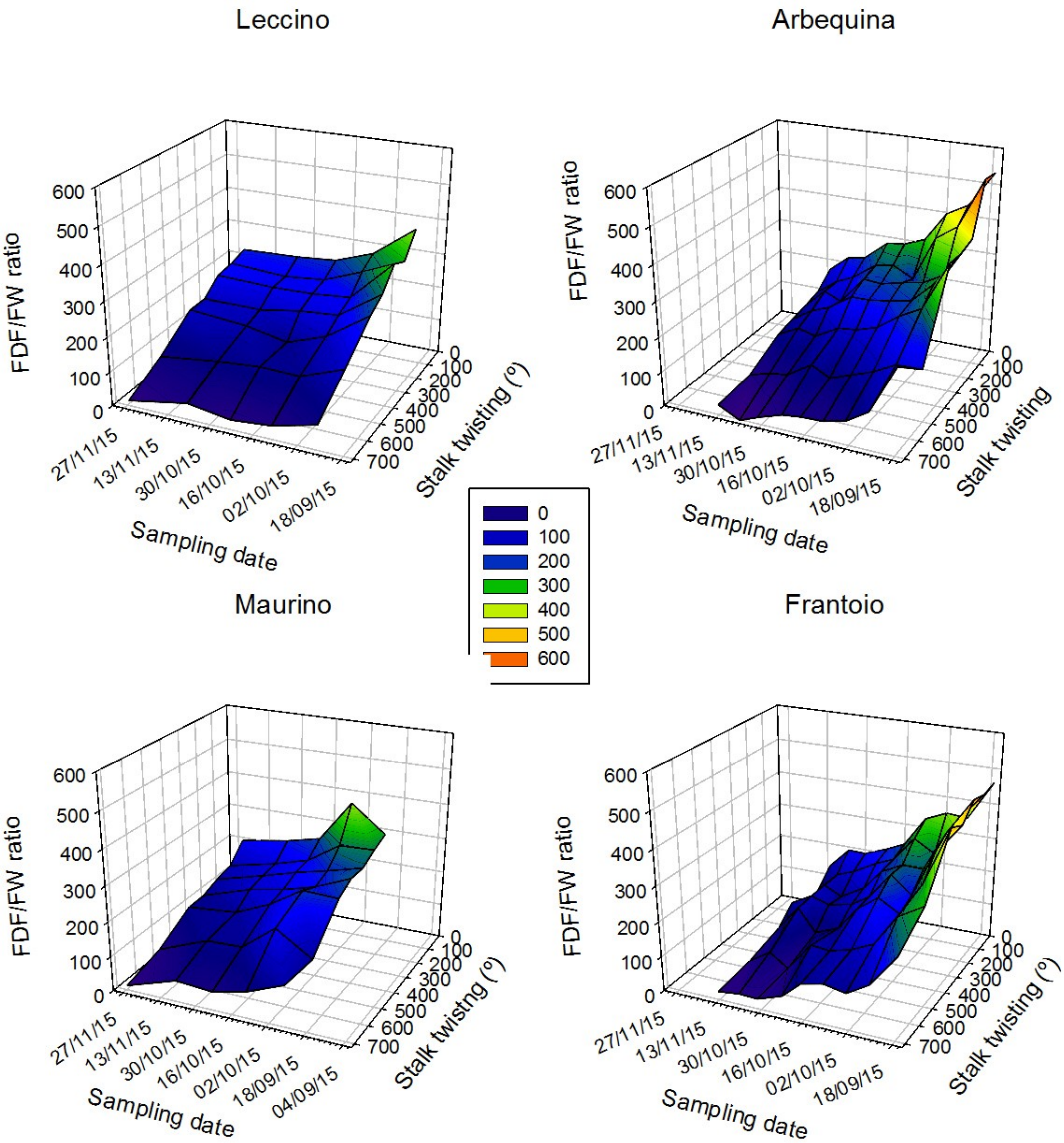

Fig. 44. Fruit detachment force to fruit fresh weight ratio (FDF/FW) evolution along ripening process for different stalk twisting angles and different cultivars.

Currently, for olive and other fruit crops, fruit ripening influence on harvesting process is measured by FDF (Zipori, Dag, Tugendhaft, & Birger, 2014) and FDF/FW ratio, (Polat, Acar, Bilim, Saglam, & Erol, 2011) applying only traction forces to the fruit stalk. Each harvesting machine can cause a different stalk twisting angle depending on the machine-tree interactions (Castillo-Ruiz et al., *2016*). Once mean twisting angle is known, it would be possible to get more reliable estimation of expected harvesting efficiency on the base of FDF and FDF/FW ratio at the expected stalk twisting interval. This methodology could be useful to predict a harvest efficiency over 85 % particularly for early harvesting, considering that it takes place when FDF/FW ratio goes under 2.3 N (about 230 g) (Farinelli, Tombesi et al., 2012). Further research is required to explain how other forces such as bending or inertial forces influence fruit detachment in olives and other crops as well as how climatic conditions affect FDF and FDF/FW evolution.

Conclusions

Olive stalk resistance against pulling forces was reduced when stalk twisting was applied in some olive cultivars. At the same time, FDF and FDF/FW ratio were reduced along the ripening process. Combined pulling and twisting forces could provide a better estimation of the real fruit susceptibility to detachment. Jaen ripeness index, fruit firmness and oil content on a dry matter basis could be used along with FDF at different twisting angles, as predictors for optimal harvesting period. Since earliest sampling dates, all cultivars showed FDF values under 3 N at stalk twisting angles over 180 º, except for Leccino, that required wider angles (up to 360 º). Finally, FDF/FW ratio provided less variability data and also took into account inertial forces during harvesting process using trunk shakers.

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CAPÍTULO 8.1. CONCLUSIONES

Para adaptar los árboles a la recolección mecanizada mediante la poda es recomendable atender a tres cuestiones principales: En primer lugar, la adaptación de las dimensiones del árbol a la cosechadora, principalmente al sistema de recepción empleado. En segundo lugar, es importante adaptar la estructura del árbol al sistema de recolección empleado, para maximizar el derribo de fruto. Y en tercer lugar, una adecuada maniobrabilidad de la cosechadora, ayuda a reducir los tiempos accesorios, y maximiza la capacidad de trabajo de la máquina, junto con un diseño de plantación adaptado al sistema de recolección empleado. Además se han identificado zonas de la copa que resultan más favorables para la recolección mecánica tanto por su situación como por su producción de fruto y calidad del aceite. Finalmente, la adaptación de la estructura del árbol a la cosechadora, mejora la eficiencia de derribo en olivar tradicional.

Los distintos trabajos realizados, conducen a las siguientes conclusiones parciales en cada uno de los artículos:

- El empleo de un sistema de seguimiento remoto y una metodología de análisis de tiempos de trabajo en olivar, permite manejar un gran volumen de datos de forma económica y en tiempo real. Por tanto es una alternativa muy interesante tanto desde el punto de vista de la investigación, como desde el punto de vista de la gestión de explotaciones. (Capítulo 4, artículo 1).
- Las cosechadoras pueden proporcionar una mayor capacidad de trabajo en ha/h, mientras que los sistemas de recolección descompuestos presentan mayores rendimientos de campo. (Capítulo 4, artículo 1).
- El diseño de plantación debe adecuarse a la cosechadora, tanto en el ancho de calle como en la longitud de línea. En cuanto a la forma de parcela y el ángulo entre la línea de árboles y la calle de servicio deben ser lo más regulares posibles para favorecer el trabajo de la máquina. (Capítulo 4, artículo 1).
- Las distintas zonas de la copa no producen una cantidad homogénea de frutos ni de aceite. La localización del fruto es un factor clave para determinar la facilidad o dificultad de acceso para su recolección mecanizada en función de la tecnología de derribo empleada (Capítulo 5, artículo 2).
- La localización del fruto condiciona sus características físicas (Peso y fuerza de retención del fruto), químicas (rendimiento graso y contenido en polifenoles) y el estado de maduración. El objetivo de un sistema de recolección mecanizada debe ser recoger la mayor cantidad de fruto posible con la mayor calidad posible, para ello, hay zonas de la copa como la parte exterior o la zona superior que por su facilidad de acceso y por la calidad de sus frutos deben considerarse

como zonas prioritarias para la acción de cualquier sistema de cosecha mecánica (Capítulo 5, artículo 2).

- La poda de formación y la poda de producción permiten adaptar los árboles a la recolección mecanizada sin causar un impacto apreciable en la producción o la calidad del fruto. En este sentido, en olivar intensivo, la cruz debe superar 1 m de altura y las ramas interiores deben reducirse al máximo, ya que son poco accesibles para los sacudidores de copa y para los sistemas de ayuda al derribo que se emplean junto con los vibradores de troncos (Capítulos 5 y 7.1, artículo 2 y estudios adicionales).
- Se ha desarrollado una metodología de medida de la porosidad de copa basada en la medida de la radiación transmitida. Dicho sistema ha sido evaluado y ensayado en diversas condiciones, y ha mostrado una precisión y repetibilidad adecuada bajo ángulos cenitales iguales o inferiores a 30 º. Este método demuestra que la porosidad de copa y la radiación transmitida se encuentran relacionadas, aunque las variaciones de porosidad no han generado diferencias en producción (Capítulo 6 y 7.1, artículo 3 y estudios adicionales).
- El sistema de poda aplicado influye sobre la porosidad de la copa, aunque no se correlaciona con la cantidad de restos eliminados, debido a la gran variabilidad de los cortes aplicados. En cuanto a la cantidad de restos de poda eliminados, la poda anual genera un mayor peso que las podas bienales, apreciándose diferencias entre variedades (Capítulos 6 y 7.1. artículo 3 y estudios adicionales).
- El sistema de poda empleado no debe influir en la producción total de los árboles, aunque sí debe reducir la producción en aquellas zonas de la copa que sean más difíciles de recoger por parte de la cosechadora, como la zona interior en el caso de que el sistema de derribo sea un sacudidor de copa (Capítulos 5 y 7.1, artículo 2 y estudios adicionales).
- La adaptación de los árboles mediante la poda al sistema de recolección empleado ha permitido mejorar el porcentaje de derribo, aunque no ha influido sobre los daños ocasionados a los árboles. La adaptación del árbol a la cosechadora debe ir acompañada de una adaptación de la cosechadora al árbol, para mejorar los procesos de recolección y poda de forma conjunta (Capítulos 6 y 7.1, artículo 3 y estudios adicionales).
- El proceso de derribo del fruto no se realiza exclusiva–mente por tracción, sino que además está influido por esfuerzos flectores y torsores. El esfuerzo torsor incide en la reducción de la fuerza de retención del fruto a lo largo de todo el periodo de maduración. Sin embargo, el efecto del esfuerzo torsor varía en función de la variedad (Capítulo 7.2, estudios adicionales).
- La adaptación del árbol a través de la poda, de la cosechadora al árbol, el diseño de plantación, así como la mejora de los sistemas de derribo, son factores clave

para la adaptación, diseño y desarrollo de las futuras cosechadoras de olivar (Capítulos 4, 7.1 y 7.2, artículo 1 y estudios adicionales).

CAPÍTULO 8.2. CONCLUSIONS

Three main issues should be addressed to adapt olive trees to mechanical harvesting by pruning. Firstly, tree dimensions should be adjusted to the harvester, mainly, to the catch frame system. Secondly, tree structure should be adapted to harvesting system in order to achieve high harvesting efficiency. Finally the harvester must have an adequate manoeuvrability along with an adapted orchard layout to reduce transport times enlarging harvester effective field capacity. Moreover target canopy areas for mechanical harvester have been identified attending ease of access, fruit yield and oil quality. Furthermore, tree structure adaption to harvester improved harvesting efficiency for traditional olive orchards.

Performed tests lead to these partial conclusions

- Remote tracking system and analysis methodology for adquired data make possible to manage large data sets in real time and at low cost. Therefore remote tracking is an interesting alternative both for researchers and olive growers (Chapter 4, paper 1).
- Harvesters are able to provide higher effective field capacity (ha/h) than non integral harvesting systems although they achieve higher field efficiency than harvesters (Chapter 4, paper 1).
- Orchard layout should be adjusted to the harvester regarding alley width and row length. In relation to field shape and angle between the headland and row, they must be as regular as possible to favour the harvester labour (Chapter 4, paper 1).
- Canopy location influences fruit and oil quantity. Fruit location is a key factor to determine if harvesting system could access, depending on fruit detachment technology (Chapter 5, paper 2).
- Fruit location determines fruit physical properties (fresh weight and fruit retention force), chemical features (oil yield and polyphenol content) and ripening. The aim of a harvesting system should be to harvest the maximum quantity of fruit achieving the highest quality. To meet these requirements, some canopy locations such as outer and higher canopy volume should be the main target for mechanical harvesting systems (Chapter 5, paper 2).
- Growth and crop tree pruning make possible to adapt trees to mechanical harvesting without yield or fruit quality reduction. It would be advisable to establish the junction between scaffolds at 1 m height above the soil. In addition, inner branches should be cut considering that they are difficult to access by canopy shakers and it is also difficult to harvest using long poles along with trunk shakers (Chapters 5 and 7.1, paper 2 and additional studies).

- A methodology to measure crown porosity based on radiation transmittance was developed and tested. This methodology has been tested under different conditions showing high accuracy and repeatability when zenith angles were below 30º. This methodology demonstrates that crown porosity and radiation transmittance are related, although porosity did not influence yield. (Chapter 6 and 7.1, paper 3 and additional studies).
- Pruning system influences crown porosity, although it does not fit with pruning fresh weight due to high variability between pruning cuts. Annual pruning produces higher pruning fresh weight than biennial pruning, finding significant differences between cultivars (Chapters 6 and 7.1, paper 3 and additional studies).
- Pruning system should not influence yield, altough canopy structure must be modified to reduce fruit production in those canopy locations more difficult to harvest. In case of harvesting by canopy shakers, inner fruit set should be reduced (Chapters 5 and 7.1, paper 2 and additional studies).
- Tree adaption to harvesting system by pruning has improved harvesting efficiency, although debris production has not been influenced by pruning system. Tree adption to the harvester should be performed along with harvester adaption to the tree structure in order to improve both, harvesting and pruning operations (Chapters 6 and 7.1, paper 3 and additional studies).
- Fruit detachment process is not only conditioned by traction forces but also by bending and torsional effects. Torsional forces have reduced fruit retention forces regardless of ripening process. However, torsional forces influenced fruit detachment, and it varied depending on cultivars (Chapter 7.2, additional studies).
- Tree adaption by pruning, harvester adaption to the tree, orchard layout, and fruit detaching tecnologies improvement, are key factors to face new developments for olive harvesters (Chapters 4, 7.1 and 7.2, paper 1 and additional studies).

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