UNIVERSIDAD DE SEVILLA

DEPARTAMENTO DE CRISTALOGRAFÍA,
MINERALOGÍA Y QUÍMICA AGRÍCOLA

SOIL WATER REPELLENCY AS CONDITIONED BY LAND USE MANAGEMENT. SHORT- AND LONG-TERM EFFECTS

MED_Soil
Research Group

FUEGORED
Red temática nacional
Efectos de los Incendios
Forestales sobre los Suelos

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Memoria que presenta D. Jorge García Moreno para optar al Grado de Doctor por la Universidad de Sevilla

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El autor

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Los directores

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

Miguel de Unamuno

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SUMMARY

Water repellency (WR) is a property of some soils that reduces infiltration rates, enhances runoff generation and increases soil erosion risk. Although wildfires are considered a triggering factor, the characteristics of plant residues and soil properties may contribute to the development of soil WR. Because of its impacts, soil WR must be considered when modeling soil erosion risk and hydrological processes. Although the study of this property has increased during the last two decades, there are still many gaps in the knowledge of this property. Soil water repellency has been studied in relation to wildfires, certain vegetation types, soil and climates. Nevertheless, there are not many data about the natural baseline in natural soils not affected by wildfires or in managed soils (mainly, cropped soils). This research tries to shed light on some of these aspects, studying the natural soil water repellency in different types of Mediterranean woodlands, the relation between organic carbon, water repellency and soil stability to slaking under different crops and management types at aggregate and intra-aggregate scales and the impact of conservative management practices in the long-term.

A brief review of the current knowledge is carried out in Chapter 1, paying attention to the physical and chemical principles of soil water repellency and highlighting its main characteristics and impacts. The main objectives of this research are briefly enounced in chapter 2.

In chapter 3, the study of natural baseline of soil water repellency in different types of Mediterranean woodlands is studied. Although many studies on water repellency from Mediterranean soils exist, relatively few studies have contributed to the knowledge of the natural baseline of soil water repellency in wide areas. The objective of this paper is to study the natural background soil water repellency in Mediterranean soils from south-western Spain under three representative forest types (pines, eucalypts and holm oaks) and its relation with plant cover (trees, shrubs and herbaceous plants) and soil properties. Field sampling was carried out in summer 2013 in 15 areas from Huelva (SW Spain) under the studied forest types. Vegetation cover (trees, shrubs and herbaceous plants) was determined using transects at each case. The water drop penetration time test was used for assessing soil water repellency, and main soil properties were determined (texture, pH, organic C, N, extractable P, exchangeable base cations - Ca^{2+}, Mg^{2+}, K^+ and Na^+ - and cation exchange capacity). According to results, soil WR was observed in all areas, increasing according to the sequence soils under holm oaks < eucalypts < pines. The severity of soil water repellency was always higher under the canopy of trees and usually decreased in bare areas, although bare soils under pine forest showed a proportion of slight to strong water-repellent cases. Severity of water repellency from soils under eucalypts and holm oaks increased with the presence of shrubs and herbaceous plants, but similar levels were not reached out of the tree-covered areas. Soils under vegetation in pine forests were always water-repellent, and wettability was observed only in some bare areas, suggesting a high potential of pines for induction of water repellency. Soil pH and the proportion of clay showed negative correlations with soil water repellency. A negative correlation between WR class and the proportion of exchangeable K^+ was found, suggesting that K deficiency for trees and shrubs restricts the input of hydrophobic substances in soil.

The relation between organic carbon, water repellency and soil stability to slaking under different crops and management types at aggregate and intra-aggregate scales is studied in chapter 4. In this section, the distribution of organic C and intensity of water repellency in soil aggregates with different size and in the interior of aggregates from Mediterranean soils under different crops (apricot, citrus and wheat) and management (conventional tilling and no tilling/mulching) is carried out. For this, undisturbed aggregates were sampled and carefully divided in size fractions (0.25-0.5, 0.5-1, 1-2, 2-5, 5-10 and 10-15 mm) or peeled to obtain separated aggregate layers (exterior, transitional and interior). Organic C content in the fine earth fraction of soils under different crops did not show important variations, although it increased significantly from conventionally tilled to mulched soils. The distribution of organic C content in aggregates with different size varied among soils under different crops, generally increasing with decreasing size. At the intra-aggregate level, organic C concentrated preferably in the exterior layer of aggregates from conventionally tilled soils, probably because of recent organic inputs or leachates. In the case of mulched soils, higher concentrations were observed, but no significant differences among aggregate regions were found. The intensity of water repellency, determined by the ethanol method, did not show great variations among crops, but increased significantly from conventionally tilled to mulched soils. Coarser aggregates were generally wettable, while finer aggregates showed slight water repellency. Regardless of variations in the distribution of organic C in aggregate layers from conventionally tilled soils, great or significant differences in the distribution of water repellency at the intra-aggregate level were not found in any case. Finally, the intensity of water repellency was much more important than the concentration of organic C in the stability to slaking of aggregates.

The impact of conservative management practices in the long-term is studied in chapter 5. Application of crop residues to cultivated soils combined with no tillage are management practices used to improve water management, increase soil fertility, crop production and soil erosion control. Conservative practices as mulching and no-tillage increase soil organic matter input in soils and contribute to reduce the soil hydrological response, but also increase soil water repellency. Water repellency is a property of soils that reduces infiltration rates. In this research, we have studied the effect of no-tillage and mulching at different rates (1-4, MR1; 5-8, MR2; and 9-12 Mg ha^{-1} year^{-1} wheat straw residues application, MR3) versus conventional tillage with no mulching, during a range of treatment periods (1-15 years) in Southern Spain. Soil water repellency (SWR) and organic matter content were analyzed and rainfall simulations were performed to study the impact of management in the hydrological soil response (time to ponding, Tp; time to runoff, Tr; and runoff rate). Subcritical SWR developed in MR1 soils, and slight SWR was observed in MR2 and MR3 soils after a few years of treatment. Subcritical or slight SWR induced significant changes in Tp and Tr, which increased mainly in MR1 soils, but increased SWR observed in MR2 and MR3 soils reduced the positive impact of organic matter and contributed to accelerate ponding and runoff flow.

RESUMEN

La repelencia al agua es una propiedad de algunos suelos que reduce las tasas de infiltración, incrementando la generación de escorrentía y el riesgo de erosión del suelo. Aunque los incendios forestales se consideran un factor desencadenante, se sabe que la hidrofobicidad es una de las características de los residuos vegetales y que algunas propiedades del suelo pueden contribuir a su desarrollo. Debido a sus impactos, la repelencia al agua del suelo debe ser considerada cuando se modela el riesgo de erosión del suelo y los procesos hidrológicos. Aunque el estudio de esta propiedad se ha incrementado durante las últimas dos décadas, todavía hay muchas lagunas en el conocimiento que se tiene de ella. La repelencia al agua del suelo se ha estudiado en relación con los incendios forestales, ciertos tipos de vegetación, suelos y climas. Sin embargo, no hay muchos datos sobre la hidrofobicidad natural en suelos no afectados por el fuego o en suelos cultivados. Este trabajo de investigación trata de arrojar luz sobre algunos de estos aspectos, como el estudio de la repelencia al agua del suelo bajo diferentes tipos de bosque mediterráneo, la relación entre el contenido en carbono orgánico, la estabilidad estructural y la repelencia al agua, tanto a nivel de agregados como a escala más detallada, así como el impacto de las prácticas de conservación a largo plazo.

Una breve revisión de los conocimientos actuales se lleva a cabo en el capítulo 1, prestando atención a los principios físicos y químicos de la repelencia al agua del suelo y destacando sus principales características e impactos. Los principales objetivos de esta investigación son enunciados del brevemente en el capítulo 2.

En el capítulo 3 se estudia la línea de base natural de la repelencia al agua del suelo bajo diferentes tipos de bosque mediterráneo. Aunque existen muchos estudios sobre la repelencia al agua en suelos mediterráneos, relativamente pocos estudios han estudiado este fenómeno a escalas amplias. El objetivo de este trabajo es estudiar el fondo natural repelencia al agua del suelo en suelos mediterráneos de la provincia de Huelva (suroeste de España) bajo tres tipos bosque representativos de este área (pinar, eucaliptal y encinar), su relación con la cobertura vegetal (incluyendo vegetación arbórea, arbustiva y herbáceas) y las propiedades del suelo. El muestreo de campo se llevó a cabo en el verano de 2013 en 15 áreas de Huelva, bajo los tipos de bosques estudiados. La cubierta vegetal se caracterizó en cada caso mediante transectos. La prueba de tiempo de penetración de la gota de agua se utilizó para evaluar la persistencia de la repelencia al agua, y se determinaron las principales propiedades del suelo (textura, pH, C orgánico, N, P extraíble, cationes básicos intercambiables – Ca^{2+}, Mg^{2+}, K^{+} y Na^{+} – y la capacidad de intercambio catiónico). Los resultados obtenidos mostraron que la repelencia al agua está presente bajo todos los tipos de vegetación considerados, aumentando de acuerdo con la secuencia encinar<eucaliptal<pinar. La persistencia de la repelencia al agua

del suelo fue siempre mayor bajo la cobertura de árboles (frente a arbustos o plantas herbáceas) y por lo general disminuyó en las zonas desnudas de vegetación, aunque los suelos desnudos bajo pinar mostraron una cierta proporción de observaciones de repelencia ligera a fuerte. La severidad de la repelencia al agua de los suelos bajo eucaliptos y encinas aumentó con la presencia de arbustos y plantas herbáceas, si bien niveles similares no se llegaron a encontrar fuera de la cobertura arbórea. Los suelos cubiertos por vegetación en los bosques de pino siempre mostraron repelencia al agua excepto en algunas zonas desprovistas de vegetación, lo que sugiere que el pinar posee un alto potencial para la generación de hidrofobicidad. El pH del suelo y la proporción de arcilla mostraron correlaciones negativas con repelencia al agua del suelo. Por otra parte, se encontró una correlación negativa entre la hidrofobicidad y la proporción de K^+ intercambiable, lo que sugiere que la deficiencia de K limita el aporte de sustancias hidrofóbicas en el suelo por parte de la vegetación leñosa.

La relación entre el carbono orgánico, la repelencia al agua y la estabilidad estructural de suelos bajo diferentes tipos de cultivo y tipos de manejo, tanto a nivel de agregados como en el interior de los mismos, se estudia en el capítulo 4. Ahí se analiza la distribución de C orgánico y de la hidrofobicidad en agregados de suelos mediterráneos bajo diferentes cultivos (albaricoque, cítricos y trigo) y tipos de manejo agrícola (laboreo convencional y no laboreo/mulching), tanto en agregados de suelo de diferente tamaño como en su interior. Para ello, se seleccionaron agregados no alterados y se separaron cuidadosamente en grupos según su tamaño (0.25 a 0.5. 0.5 a 1. 1-2. 2-5. 5-10 y 10-15 mm). En el caso de los agregados más gruesos (10-15 mm), además, se separaron las capas externa, de transición e interior mediante un procedimiento de abrasión mecánica. El contenido de C orgánico en la fracción tierra fina (< 2 mm) de suelos bajo diferentes cultivos no mostró variaciones importantes, aunque sí fue significativamente más alto en suelos con mulch que en suelos bajo laboreo convencional. La distribución de C orgánico en agregados con diferente tamaño varió entre suelos según el cultivo, pero en general aumentó en los agregados más finos. A nivel intra-agregado, el C orgánico se concentró preferentemente en la capa exterior de los agregados de suelo bajo laboreo convencional. Sin embargo, es posible que esto se debiese a aportes o lixiviados orgánicos recientes. En el caso de suelos bajo mulch, se observaron concentraciones más altas, pero no se encontraron diferencias significativas entre las diferentes zonas del agregado. La intensidad de la repelencia al agua, determinada mediante el método del etanol, no mostró grandes variaciones entre suelos bajo diferentes cultivos, pero sí aumentó de forma significativa en el caso de los suelos bajo prácticas de conservación. De modo general, los agregados más gruesos eran fácilmente humectables, mientras que los agregados más finos mostraron una ligera repelencia al agua. Independientemente de las variaciones en la distribución de C orgánico en el interior de los agregados de suelo bajo laboreo convencional, en ningún caso se encontraron diferencias en la intensidad de la hidrofobicidad en el interior de los agregados. Finalmente, también se concluyó que la estabilidad estructural de los agregados de los suelos estudiados depende mucho más de la intensidad de la repelencia al agua que de la concentración de C orgánico.

El impacto de las prácticas de tratamiento conservador en el largo plazo se estudia en el capítulo 5. La aplicación de los residuos de cultivos a los suelos cultivados combinados con siembra directa son prácticas utilizadas para mejorar la gestión del agua, aumentar la fertilidad del suelo, la producción de cultivos y el control de la erosión del suelo. Prácticas de conservación como el mulching o el no laboreo no sólo ayudan a aumentar el contenido de materia orgánica en los suelos y contribuyen a reducir la respuesta hidrológica del suelo, sino que también aumentan la repelencia al agua del suelo. En esta investigación se ha estudiado el efecto del no laboreo y la adición de diferentes tasas de mulching (1-4 -MR1-, 5-8 -MR2- y 9-12 Mg ha^{-1}año^{-1} de paja de trigo -MR3) frente al laboreo convencional durante diferentes períodos de tratamiento (1-15 años). Para ello, se analizó la repelencia al agua y el contenido de materia orgánica de los diferentes suelos seleccionados y se realizaron experimentos de simulación de lluvia con el objetivo de estudiar el impacto del manejo del suelo en su respuesta hidrológica, determinando en cada caso el tiempo de encharcamiento, Tp, el tiempo de generación de escorrentía, Tr, y la tasa de escorrentía). Los suelos MR1 mostraron repelencia al agua subcrítica, mientras que MR2 y MR3 mostraron ligera repelencia al agua sólo después de algunos años de tratamiento. La repelencia subcrítica o ligera debida al manejo del suelo indujo cambios en Tp y Tr, especialmente en MR1. Por otro lado, el aumento en la intensidad de la repelencia al agua en MR2 y MR3 redujo el impacto positivo de la adición de materia orgánica y acortó considerablemente el tiempo de generación de escorrentía, aumentando así el riesgo de erosión.

1 INTRODUCCIÓN

La repelencia al agua es una propiedad de los suelos que inhibe o reduce la tasa de infiltración del agua en el suelo (Doerr et al., 2000). El retraso en la infiltración del agua en el suelo tiene consecuencias hidrológicas y geomorfológicas importantes (Doerr et al., 2000). Algunos de los primeros estudios y observaciones sobre esta propiedad fueron descritos por Schreiner y Edmund (1910) en suelos agrícolas en California (EEUU). Esta inhibición o reducción de la tasa de infiltración se puede producir durante períodos de tiempo que pueden oscilar desde unos pocos segundos hasta horas, días o semanas (Doerr y Shakesby, 2009; Jordán et al., 2013).

En las últimas décadas ha cobrado notoriedad para la comunidad científica, que está viendo como esta propiedad de los suelos no es algo excepcional y que por el contrario, se debe a multitud de factores que se están estudiando en la actualidad. Aunque haya estudios desde el principio del siglo XX (Schreiner y Edmund, 1910; Shantz y Piemeisel, 1917), son muy escasos, y es ahora cuando el estudio de esta propiedad está cobrando importancia a nivel mundial (DeBano, 1981; Doerr et al., 2000; Letey et al., 2000; Jordán et al., 2013; Moore y Blackwell, 1998; Wallis y Horne, 1992). Se ha demostrado la existencia de esta propiedad en diferentes tipos de suelo y bajo diferentes climas y tipos de vegetación de todo el mundo (DeBano, 2000a; Doerr et al., 2000; Wallis y Horne, 1992).

Al disminuir la tasa de infiltración en la superficie del suelo (Figura 1), la repelencia al agua contribuye a reducir el tiempo de generación de escorrentía y a intensificar el flujo superficial, lo que tiene a su vez tiene consecuencias importantes como el aumento del riesgo de erosión, la irregularidad en el frente de mojado y el desarrollo de vías de flujo preferencial o el lavado acelerado de nutrientes y agroquímicos en el caso de sistemas agrícolas (Imeson et al., 1992; Shakesby et al., 1993, Ritsema et al., 1993, 1997; Doerr y Shakesby, 2009).

La repelencia al agua puede estar relacionada con los microorganismos del suelo, la vegetación, el contenido de materia orgánica (Doerr et al., 2000; Doerr y Shakesby, 2009) y la composición, el contenido de agua del suelo, los incendios forestales y otras características como la acidez (Mataix-Solera y Guerrero., 2007; Rodriguez-Alleres et al., 2007; Zavala et al., 2009a), textura, estructura (Mataix et al., 2009), mineralogía de las arcillas (Guerreo et al., 2001, Mataix- Solera y Doerr, 2004; Arcanegui et al., 2008) y otros (Doerr et al., 2000). Aunque todavía no se conocen con exactitud las sustancias capaces de inducir la repelencia al agua en los suelos y es muy difícil establecer una única causa que la produzca ya que son múltiples los factores bióticos y abióticos que la producen.

Figura 1. Gotas de agua sobre la superficie de un agregado repelente al agua tras un incendio forestal en Gorga (Alicante, 2011). Fotografía: Lorena M. Zavala.

1.1 PRINCIPIOS FÍSICOS-QUÍMICOS DE LA REPELENCIA Y SU RELACIÓN CON LAS PROPIEDADES DEL SUELO

A la hora de estudiar los principios físico-químicos de la repelencia al agua, es conveniente, primero detenerse en algunas de las propiedades del agua, para así entender mejor los procesos que ocurren durante el contacto entre las fases sólida y líquida. Hillel (1998) da mucha importancia a los dos enlaces de hidrógeno, que está unido al oxígeno mediante enlaces primarios. Las moléculas así formadas se unen entre sí por medio de enlaces secundarios del oxígeno, formando una especie de retícula que Hillel (1998) llama “polímero” de moléculas unidas por enlaces de hidrógeno. Los enlaces primarios son más fuertes que los enlaces secundarios. Así, según la geometría estructural y la distribución de los electrones en la molécula, según Hillel (1998), los enlaces de hidrógeno se forman y permanecen sólo bajo unas condiciones geométricas específicas.

El grado de afinidad o repelencia al agua de un objeto viene determinado por las propiedades químicas de su superficie externa. El agua se expande cuando se reorganiza sobre una superficie lisa hidrofílica y aparece formando gotas aisladas cuando la superficie es hidrofóbica (Adam, 1963). Basta una capa monomolecular adsorbida de compuestos orgánicos polares para cambiar las propiedades de una superficie sólida (Figura 2). En la práctica, una pequeña proporción en el suelo de compuestos orgánicos hidrófobos es suficiente para inducir repelencia al agua, y muchos autores han hecho hincapié en la capacidad de los ácidos húmicos de inducir repelencia al agua en el suelo, aunque el contenido de materia orgánica del agua del suelo repelente es muy baja.

La afinidad o repelencia entre las superficies de agua y sólidos son originadas por las fuerzas atractivas (adhesión) y la atracción entre las moléculas de agua (cohesión). Para comprender mejor esas fuerzas, es necesario considerar algunas propiedades moleculares del agua.

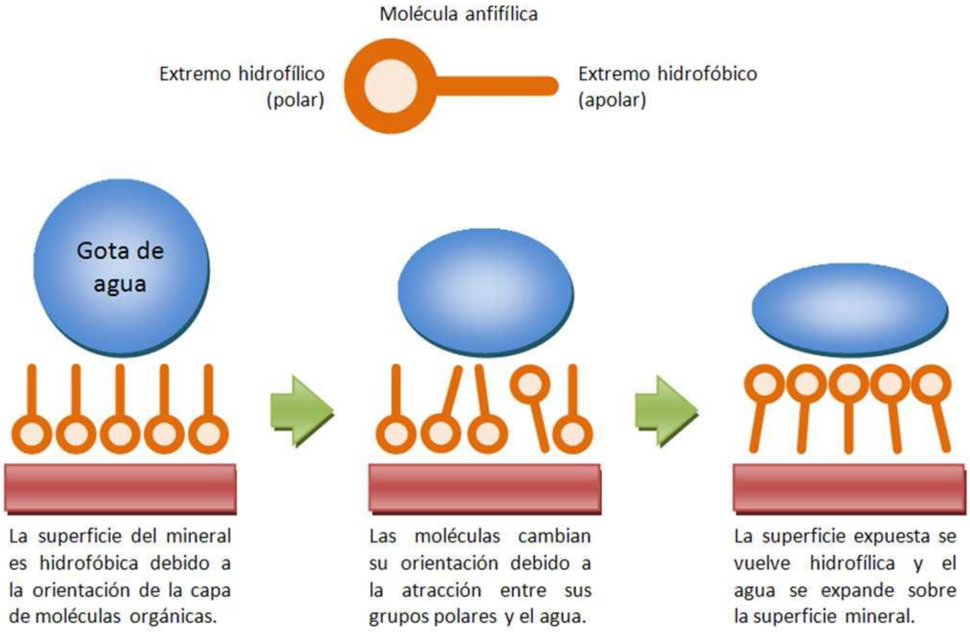


Figura 2. Representación esquemática de una molécula de carácter anfílico (parte superior) y secuencia de cambios en la orientación de moléculas anfílicas sobre una superficie mineral en contacto con el agua (Jordán et al., 2010a).

Una molécula de agua está compuesta de un átomo de oxígeno con una carga parcial negativa y dos átomos de hidrógeno con una carga parcial positiva, unidos entre sí con una posición angular de 105°, lo que otorga a la partícula una fuerte estructura dipolar (Parker, 1987). La atracción entre polos con carga parcial positiva (hidrógeno) y negativa (oxígeno) causa que las moléculas de agua formen estructuras que se mantienen unidas por puentes de hidrógeno. Los enlaces de hidrógeno que puede formar la molécula de agua son resistentes a la reorganización, lo que favorece esta propiedad frente a otras superficies que puedan ofrecer oxígenos expuestos con lo que poder formar uniones entre sí (Kramer, 1974). El agua se adhiere a la mayoría de las superficies naturales, pero la fuerte dipolaridad de la molécula de agua también produce fuerzas relativamente fuertes que pueden neutralizar la atracción entre las cargas superficiales. Así, dentro de un líquido, la suma de fuerzas que actúan una molécula individual es cero. Como consecuencia de esta fuerza, las moléculas de la superficie experimentan una atracción hacia el interior (tensión superficial) que tiende a reducir la superficie del cuerpo de agua y la distancia entre las moléculas en su interior. La suma de las fuerzas que actúan en la superficie del líquido se llama "tensión superficial". La mayoría de los líquidos tienen una tensión superficial entre 20 y 40 10^{-3} N m^{-1} a 20 °C. Sin embargo, en el caso del agua, esta tensión es excepcionalmente alta, llegando hasta 72.75 10^{-3} N m^{-1} (Parker, 1987). Con el incremento de la temperatura, la tensión superficial de los líquidos se reduce. Al pasar de 10 a 30 °C, por ejemplo, la tensión superficial del agua en contacto con el aire pasa de 74.22 a 71.18 dinas cm^{-1} (Stephens, 1996). La tensión superficial aumenta también con la presencia de sales en solución, ya que los electrolitos incrementan las fuerzas de cohesión en el seno del líquido.

Los mismos principios pueden aplicarse a las superficies de los sólidos, aunque su naturaleza inhibe la deformación esférica. La tensión superficial para sólidos varían entre 0.5 y 5 N m^{-1}, aumentando proporcionalmente con su estabilidad y su punto de fusión. Cuando un líquido moja una superficie sólida se extiende sobre ella, de modo que las fuerzas de cohesión entre las moléculas del líquido se debilitan, pues parte de ellas se transforman en fuerzas de adhesión en la interfase líquido-sólido. En este caso, las fuerzas de adhesión son superiores a las de cohesión. Si las fuerzas de cohesión son dominantes, el líquido tenderá a asumir una forma esférica en forma de gota. De este modo, las superficies con una tensión superficial mayor a 72,75 10^{-3} N m^{-1} pueden considerarse como hidrofílicas. Normalmente, los minerales tienen una tensión superficial mucho más alta que la del agua y, por lo tanto, son superficies hidrofílicas, mientras que algunas sustancias orgánicas, tales como las ceras o los polímeros orgánicos, pueden tener una tensión superficial con valores energéticos menores a 72,75 10^{-3} N m^{-1}, y, por lo tanto, son hidrofóbicos

(Zisman, 1964). Según Tschapek (1984), excepto en el caso del sílice deshidroxilado, todas las partículas minerales del suelo presentan un carácter hidrofílico, ya que su superficie está normalmente recubierta por iones asociados y grupos polares hidroxílicos, lo que causa afinidad por las moléculas de agua.

Cuando se coloca una gota de un líquido sobre la superficie de un sólido, cada fase presente (sólida, líquida o gaseosa) posee su propia tensión superficial. Como resultado, en el punto de la triple interfase se forma un ángulo de contacto cuyo valor dependerá de las propiedades de cada fase (Jaramillo, 2004). Según la ley de Young-Laplace, el ángulo de contacto sólido/agua es mayor de 90º cuando la superficie sólida es hidrofóbica, y cuando el ángulo es menor a 90 º la superficie es hidrofílica (Figura 3), lo que tradicionalmente se ha mantenido como criterio en el caso de los suelos. Por otro lado, se ha demostrado que la infiltración puede ocurrir incluso con ángulos mayores de 90º (Shirtcliffe et al., 2006), especialmente en el caso de un suelo, formado por partículas discretas de distinta forma, tamaño y naturaleza química. De este modo, la idea comúnmente aceptada durante décadas de que un líquido puede infiltrarse sólo cuando el ángulo de contacto es menor de 90º es falsa en el caso de sustratos física y químicamente similares a la arena, y, por lo tanto, en el de los suelos. Suelos formados mayoritariamente por partículas de arena (tamaño entre 0.05 y 2 mm) o suelos muy repelentes al agua con suficiente porosidad, el agua puede ocupar este espacio, pero no será capaz de recubrir las partículas minerales de manera individual, mientras que en el caso de partículas hidrofílicas, éstas podrán ser recubiertas fácilmente por la lámina de agua.

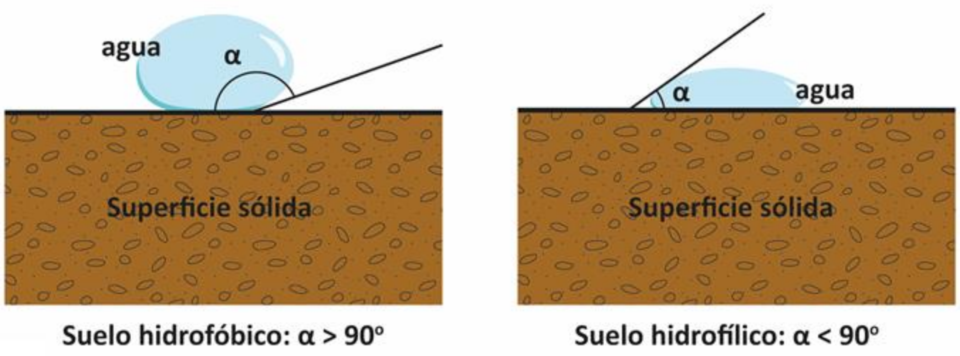


Figura 3. Representación esquematizada del ángulo de contacto entre una superficie sólida y líquida (a partir de Jaramillo, 2004).

1.2 EFECTOS Y CONSECUENCIAS DE LA REPELENCIA AL AGUA EN EL SUELO

La repelencia al agua es una característica de los suelos con importantes consecuencias para el crecimiento vegetal, hidrología superficial y subterránea, y para el riesgo de erosión del suelo. Al reducirse la infiltración del agua en el suelo y aumentar la escorrentía superficie se produce una pérdida de nutrientes, un mal desarrollo radicular, deficiencias en la germinación de semillas, lavado sustancias solubles, incremento del riesgo de erosión de suelo o incremento de la estabilidad de agregados (Wallis y Horne, 1992; Hendrickx et al., 1993; Ritsema y Dekker, 1995; Blanco-Canqui y Lal, 2009). Desde un punto de vista hidrológico y geomorfológico, cuando el agua se infiltra a través de grietas o poros en la superficie de un suelo repelente al agua se generan diferentes zonas con distinto grado de humedad o incluso zonas total y permanentemente secas, incluso durante la estación húmeda (Dekker y Ritsema, 2000). Esto se debe a la aparición de las vías de infiltración o flujo preferencial en los horizontes del suelo (Figura 4). Cuando la superficie de un suelo es repelente al agua, al facilitarse el encharcamiento frente del agua de lluvia se genera un flujo superficial hortoniano. Los suelos repelentes al agua están asociados con el flujo preferencial (Jamison, 1945; Bond, 1964; Gilmour, 1968; Nissen et al., 1999). Se llama flujo preferencial (Figura 4), al movimiento vertical del agua a través de diversos conductos formados por grietas, macroporos, galerías excavadas, huecos de antiguas raíces o discontinuidades de texturas de suelo por las que el agua va surcando por gravedad. Así, el flujo preferencial forma vías más o menos permanentes, de distinto tamaño y variación de grados de humedad que acaban afectando al crecimiento de las plantas y permiten un paso más rápido de agua y solutos que generan grandes riesgos de erosión y contaminación (Dekker y Ritsema, 1994). El flujo se podrá producir de manera amplia o de forma localizada según se presenten estas discontinuidades en la superficie y en el suelo el mosaico de hidrofobicidad/hidrofilia (Jordán et al., 2010a).

Como consecuencia del movimiento del agua a través del flujo preferencial, se presentan situaciones en las que en un suelo no se moje, ya que el agua discurre a través de estos canales de macroporos y grietas disminuyendo así, el riesgo de erosión (Debano, 1971; Burch et al., 1989; Walsh et al., 1995). Un estudio realizado sobre suelos volcánicos en México por Jordán et al. (2009), mostró la existencias de la vías de flujo preferencial analizado el frente mojado. Los suelos con distintos grados de repelencia mostrarón una gran irregularidad en sus frentes mojados con una gran variación en la penetración del agua en función de la textura, la densidad aparente, la frecuencia de macroporos y la humedad. De una forma totalmente contraria se comportarón los suelos con bajo o nulo grado de repelencia

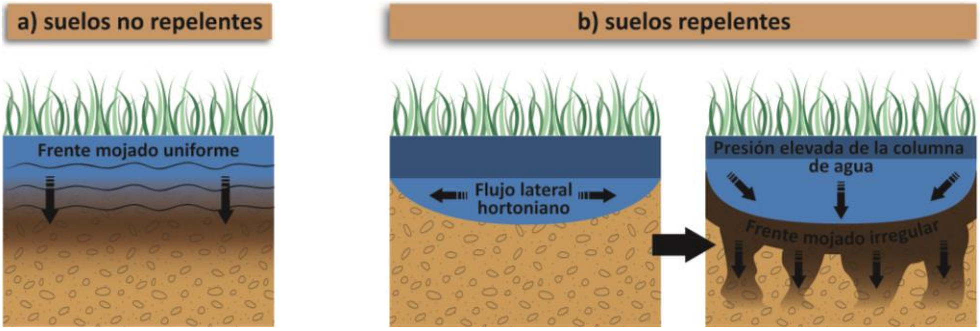


Figura 4. Aparición de infiltración o flujo preferencial en el perfil del suelo.

apareciendo su frente mojado muy regular, homogéneo y con una pareja velocidad de penetración (Figura 5).

Por otro lado, una acumulación de agua sobre un suelo repelente al agua fluirá como escorrentía superficial en caso de encontrarse en una zona con pendiente o acumularse en zonas donde la pendiente es menos acentuada, provocando en la zona un aumento de la presión de la presión hidrostática hasta valores críticos sobre distintos un puntos del suelo que hacen que el agua termine infiltrándose, redistribuyéndose la humedad (Wallak y Jortzick, 2008). Así, la disminución de las tasas de infiltración del agua en el suelo como consecuencia de la repelencia tiene consecuencias hidrológicas y geomorfológicas inmediatas, a las que hay que añadir consecuencias sobre el crecimiento y supervivencia de las plantas.

Al disminuir la tasa de infiltración en la superficie del suelo, la repelencia al agua contribuye a reducir el tiempo de generación de escorrentía y a intensificar el flujo superficial, lo que tiene a su vez otras consecuencias importantes como el aumento del riesgo de erosión, la irregularidad en el frente de mojado y el desarrollo de vías de flujo preferencial o el lavado acelerado de agroquímicos en el caso de sistemas agrícolas. No obstante, la repelencia al agua no siempre tiene efectos negativos, ya que puede favorecer el incremento en la estabilidad estructural (Blanco-Canqui et al., 2007) o el secuestro de carbono (Urbanek et al., 2007).

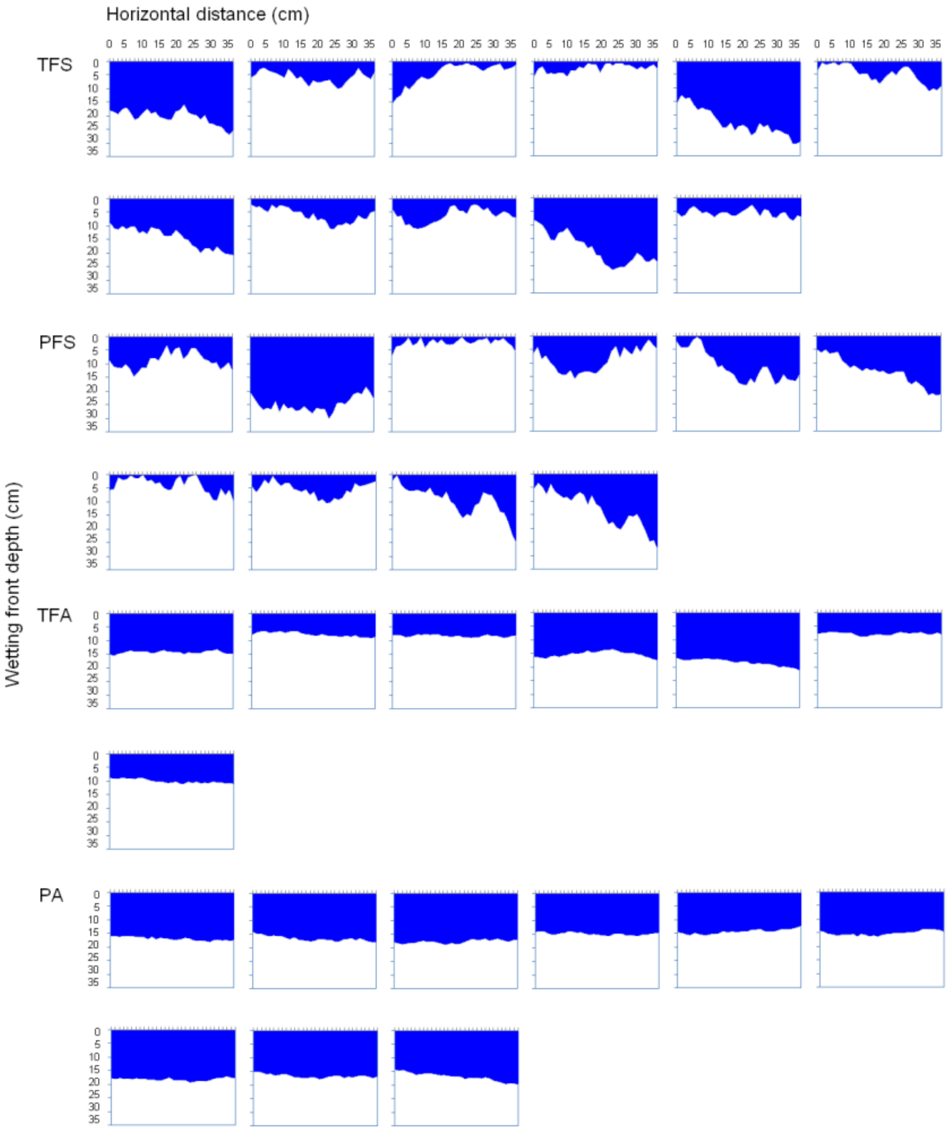


Figura 5. Frentes de mojado tras experimentos de simulación de lluvia (90 mm h-1) en suelos repelentes al agua bajo bosque de *Abies*, *Pinus* y *Quercus* desarrollados sobre lavas (TFS), suelos repelentes al agua bajo *Pinus* y *Quercus*, desarrollados sobre lavas y sedimentos piroclásticos (PFS), suelos hidrófilos bajo *Abies*, *Pinus* y *Quercus* desarrollados sobre cenizas (TFA) y suelos hidrófilos desnudos desarrollados sobre cenizas volcánicas (PA) (Jordán et al., 2009).

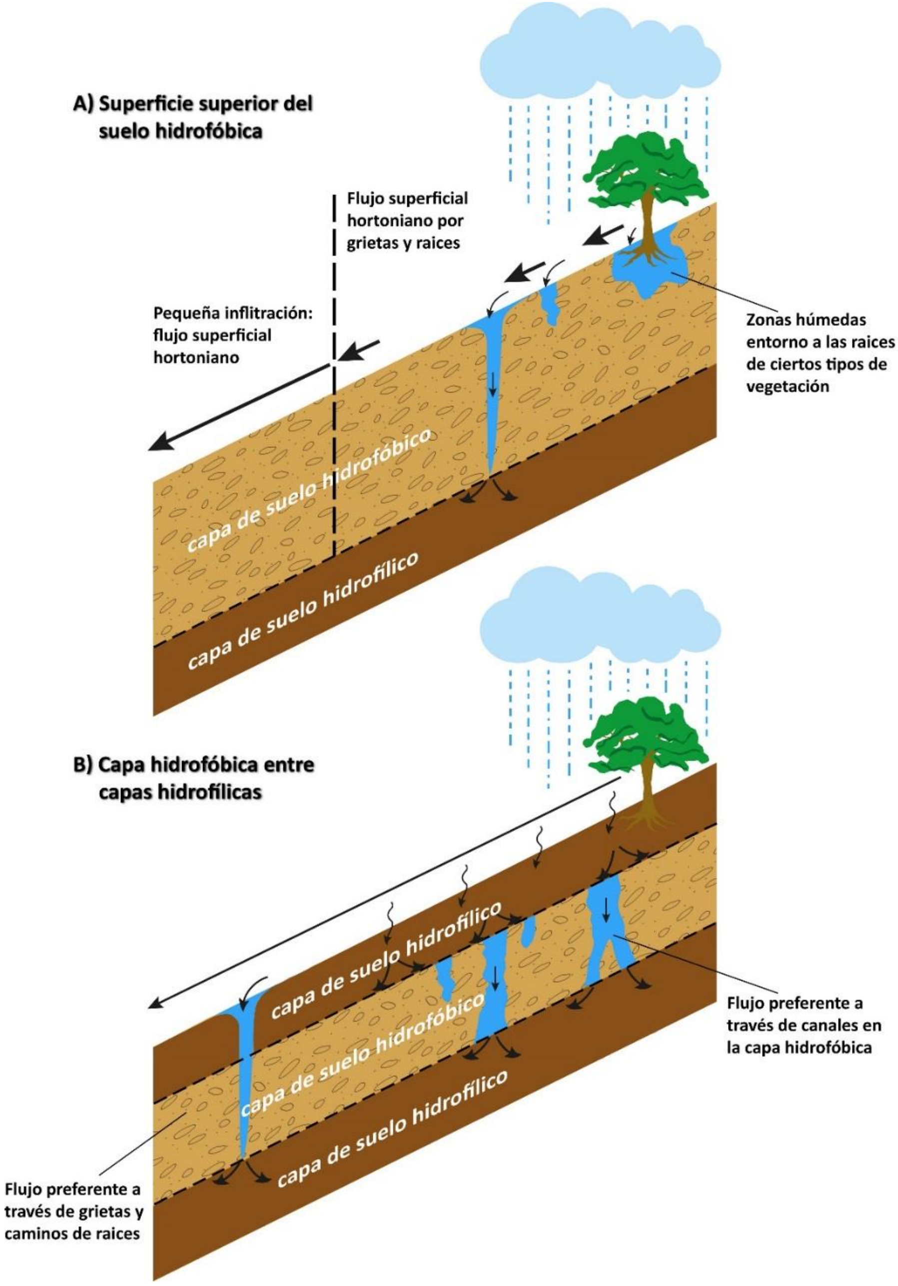


Figura 6. Esquema de una posible respuesta hidrológica de un suelo con una capa hidrofóbica localizada en la superficie (A), o una capa hidrofóbica entre dos capas hidrofílicas (B). A partir de Doerr et al. (2000).

En un estudio sobre repelencia y la pérdida de suelo en el área del eje Neovolcánico de México realizado con simulación de lluvia, Jordán et al. (2009) observaron, tras analizar la relación entre la repelencia y la respuesta hidrológica, que la tasa de escorrentía superficial en los suelos repelentes al agua era mayor que en los suelos hidrofílicos.

El aumento de flujo superficial y la reducción de la capacidad de infiltración son debidos, en gran parte, al impacto del agua sobre el suelo (Van Dam et al., 1990). Cuando la superficie de suelo que soporta la presión del agua se excede se producirá el flujo superficial. Según sea la distribución del agua sobre la superficie y las distintas formaciones que haya en capa del suelo (como grietas, caminos a través de raíces, madrigueras, zonas mas hidrofóbicas y zonas mas hidrofílicas), se producirá un fujo superficial de forma generalizada o de forma más localizada en zonas puntuales (Figura 6A). Por otro lado, muy a menudo ocurre que debajo de una capa hidrofílica o de una capa de cenizas se encuentra una capa hidrofóbica. Cuando esta capa hidrofóbica llega a un estado de saturación, se produce la infiltración del agua a través vías y canales de flujo preferencial abiertos en la capa hidrofóbica llegando a una segunda capa hidrofílica situada por debajo de la capa hidrofóbica (Figura 6B). Este agua puede permanecer aquí almacenada en la capa hidrófilica y evaporarse más tarde o puede ser absorbida por las plantas. También puede perderse por escorrentía cuando llegue a saturarse y moverse ladera abajo si la zona es de pendiente (Doerr et al., 2000). El flujo superficial hortoniano generado sobre capas de suelo repelentes al agua se pueden infiltrar por grietas, canales de raíces y macroporos, o bien al llegar a una zona hidrofílica (Figura 6B) (Doerr et al., 2000).

1.3 SUSTANCIAS HIDROFÓBICAS EN EL SUELO

La identificación de los compuestos específicos que causan la repelencia al agua ha sido uno de los objetivos de las investigaciones en las últimas décadas (Franco et al., 1995; McIntosh y Horne, 1994). Aunque aún no se posee un conocimiento exhaustivo de todas las sustancias capaces de inducir hidrofobicidad en los suelos (Doerr et al., 2000; Doerr et al., 2009), sí se sabe que, de forma natural el suelo contiene en su composición sustancias hidrofóbicas. La mayoría de tales sustancias son abundantes en los ecosistemas y son liberadas al suelo, como, por ejemplo, los hidrocarburos alifáticos, lixiviados de horizontes orgánicos, exudados de raíces o de la fauna del suelo, hongos y otros microorganismos, o directamente como restos orgánicos.

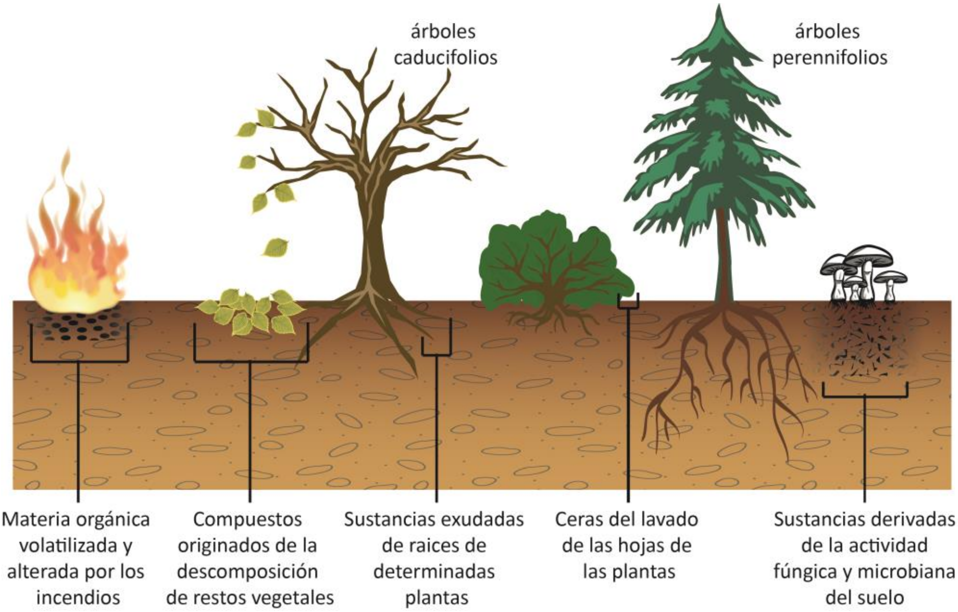


Figura 7. Fuentes de los principales compuestos orgánicos con propiedades hidrofóbicas en el suelo. A partir de Doerr et al. (2000).

Las principales sustancias orgánicas capaces de inducir repelencia al agua en los suelos pueden dividirse en dos grupos principales: hidrocarburos alifáticos y sustancias polares con estructura anfifílica. Los primeros están formados por cadenas hidrocarbonadas largas. Se trata de compuestos no polares y son insolubles en agua. El segundo grupo está formado por cadenas hidrocarbonadas que poseen un extremo polar hidrofílico y otro extremo hidrofóbico (Figura 7). A pesar de ser generalmente solubles en agua, las moléculas anfifílicas pueden formar recubrimientos hidrofóbicos (Doerr et al. 2000; Horne y McIntosh, 2000). Se cree que ambos grupos pueden inducir repelencia al agua en los suelos, pero las moléculas polares (por ejemplo: ácidos grasos y determinadas ceras, como ésteres y sales de ácidos grasos) parecen ser los principales constituyentes de las cubiertas hidrofóbicas sobre partículas minerales, como han observado varios autores (Doerr et al., 2000; Graber et al., 2009).

Entre las formas químicas más frecuentes se encuentran alcanos y alquenos (procedentes de bacterias, hongos, algas y plantas superiores), terpenoides (algunas ceras de plantas), monocetonas (de bacterias y plantas superiores), dicetonas (de eucaliptos), poliéster de ácidos grasos (de coníferas). No obstante, la presencia de estos compuestos no implica siempre la repelencia al agua del suelo, ya que se ha demostrado que cantidades apreciables de estos compuestos también pueden encontrarse en suelos de carácter hidrofílico (Doerr et al., 2000; Graber et al., 2009).

La repelencia al agua del suelo se ve muy influenciada por el tipo de vegetación presente y puede ser inducida en muchos casos. Las plantas contienen compuestos hidrofóbicos en su estructura que pasan al superficie del suelo (Jaramillo., 2004) por descomposición de la materia orgánica al morir (McGhie y Posner, 1981), por exudados de la raíz (Dekker y Ritsema, 1996) o el mismo ciclo de la vida del vegetal al renovar las hojas o mediante el lavado por las aguas desde las superficies vegetales (Doerr et al., 2000; DeBano, 2000a). Existen estudios en los que se ha detectado la relación de la repelencia con cierto tipo de vegetación, como bajo ciertas especies de pinos (Hubbert et al., 2006; Jordán et al., 2009; Lewis et al., 2006; Mataix-Solera y Doerr, 2004), en eucaliptos, en alcornoques (Jordán et al., 2008; Sevink et al., 1989), en brezos y otras especies de matorral mediterráneo (Giovannini et al., 1987; Martínez-Zavala y Jordán., 2009). El principal motivo de la aparición de repelencia bajo este tipo de vegetación se debe principalmente a los compuestos de exudados de sus tejidos, como resinas, ceras y compuestos aromáticos (Doerr et al., 1998; Doerr et al., 2000). En un estudio de McGhie y Posner (1980) en el que evaluaron la repelencia bajo eucalipto, y para ello molieron la hojarasca procedente de una superficie con plantaciones de eucaliptos y la mezclaron con distintas proporciones de dos tipos de arena gruesa y fina calentadas previamente a 500 ^{o}C. La hojarasca hizo incrementar el ángulo repelencia en los dos tipos de arena, observándose a su vez mayor grado de hidrofobicidad en la muestra formada por arena más gruesa (Jaramillo, 2004). En otro estudio, Jordán et al. (2008) encontraron bajos niveles de repelencia al agua en suelos bajo bosques mixtos de *Quercus suber* y *Olea europaea*, frente a otros tipo de vegetación presente por la zona y con el mismo clima, estas diferencias pueden deberse a la naturaleza química de los compuestos orgánicos liberados por especies como *Olea europaea*.

La acumulación de compuestos orgánicos como hidrocarburos alifáticos y compuestos anfílicos, son responsables de la aparición de repelencia en los suelos (Doerr et al., 2000). Horne y Mclntosh (2000) realizaron un estudio sobre suelos arenosos que habían desarrollado hidrobicidad en Nueva Zelanda, extrajeron por diferentes métodos los componentes del suelo e identificaron, la presencia de lípidos neutros, alcanos y triglicéridos, lípidos grasos, ácidos grasos de cadena larga y una fracción soluble con carácter anfílico (Tabla 1).

Tabla 1. Ejemplo de algunas sustancias hidrofóbicas y su origen (Doerr et al., 2000).

Compuestos y sustancias	Origen/Fuente
Alcanos	Bacterias, hongos, algas, plantas superiores
Alquenos	Bacterias, hongos, algas, plantas resultados
Terpenoides	Algunas ceras de plantas
Monocetonas	Bacterias, plantas superiores (por ejemplo: eucaliptos y especies herbáceas)
Dicetonas	Plantas superiores (por ejemplo: eucaliptos y especies herbáceas)
Poliéster de ácidos grasos	Plantas superiores (por ejemplo: pinos)

DeBano (1991) sugirió que el calentamiento de suelos no repelentes al agua que contuviesen más del 2-3% de materia orgánica siempre induciría repelencia al agua. En el suelo, las partículas orgánicas tienden a ser absorbidos en forma de pequeños glóbulos, de modo que una determinada cantidad de glóbulos puede recubrir completa o parcialmente los granos minerales del suelo. Dependiendo de la proporción de sustancias hidrófobas en la materia orgánica, se originará o no la repelencia al agua en ese suelo.

La concentración de estas sustancias de naturaleza hidrofóbica en el suelo depende del tipo de vegetación y las características del suelo (Zavala et al., 2009a), observándose a veces una distribución en mosaico de esta propiedad (Figura 8). Franco et al. (2000) encontraron compuestos hidrofóbicos con una composición química similar a la encontrada para materiales de *Eucaliptus sp.* Así, la repelencia al agua en suelos pude estar asociada a unas determinadas especies vegetales, pero, en realidad no se puede decir con rotundidad que una sola especie sea la causante de la hidrofobicidad en los suelos.

Aunque las plantas mas comúnmemnte asociadas a la repelencia son las plantas perennes, principalmente árboles con gran cantidad de resinas, ceras y aceites aromáticoscomo como eucaliptos y pinos. Tambien se ha observado un aumento de la repelencia con gramíneas herbáceas de la familia Poáceas como *Agrostis spp.* (Karnok et al., 1993; York, 1993). Esto puede resultar un problema a tener en cuenta en zonas como campos de golf donde se siembran especies de este tipo y se pueden generar numerosos puntos con una mala infitración que pejudiquen el estado de la hierba para el juego. También de la familia de las Poáceas, McIntosh y Horne (1994)

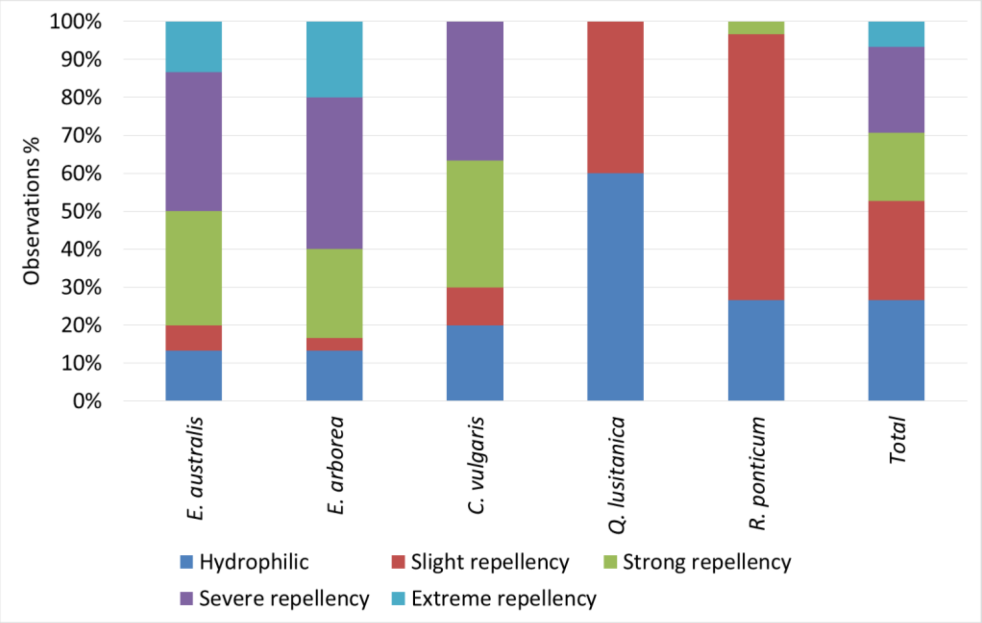


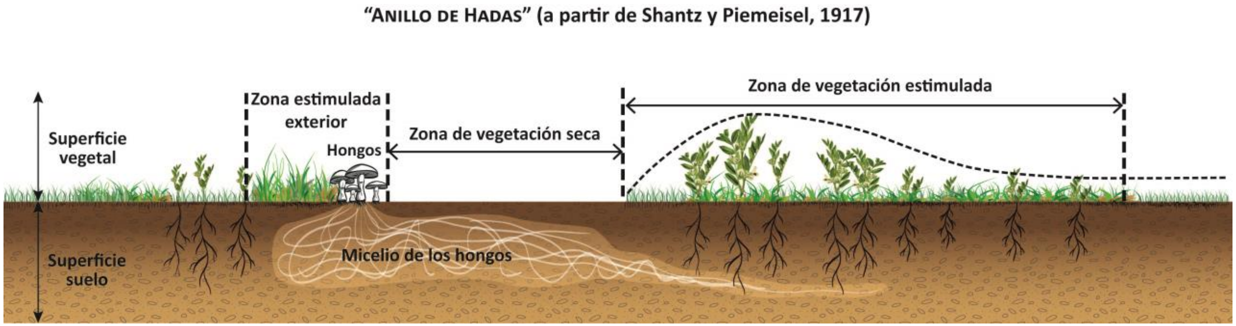
Figura 8. Clases de repelencia al agua observada bajo diferentes especies vegetales en el Parque Natural Los Alcornocales (Cádiz). A partir de Zavala et al. (2009a).

observaron la aparición de repelencia al agua en suelos bajo *Spinifex hirsitus.* En zonas cultivadas de Australia también se ha observado repelencia bajo cultivos de leguminosas de la familia Fabaceae *Lupinus cosentinii* (Doerr et al., 2000; Carter et al., 1994).

Puede resultar que la incorporación de estas sustancias hidrofóbicas sea una estrategia de economización del agua que las plantas han ido desarrollando a lo largo de su evolución para la supervivencia y subsistencia de las mismas, del mismo modo que producen compuestos alelopáticos para influir en el crecimiento, supervivencia o reproducción de otros organismos (Doerr et al., 2000; Moore y Blackwell, 1998).

Del mismo modo, la repelencia al agua está siendo relacionada con microorganismos y hongos que se encuentran en el suelo asociados junto a los distintos tipos de vegetación. La influencia de los hongos en el desarrollo de la repelencia en el suelo ha sido estudiada por diversos autores (Dekker y Ritsema, 1996; York y Canaway, 2000; Pottorf, 2003) aunque no está muy claro si existe una influencia directa. Estudios citados por Debano (2000a) sugieren que la causa de la aparición de la repelencia en distintas zonas está ligada a los hongos. Se observó por primera vez con la aparición de los llamados "anillos de hadas" (Schantz y Piemeisel, 1917; Figura 9), que es un término que se vincula a la aparición de anillos concéntricos secos, dentro de los cuales se observa un alto crecimiento de las plantas (generalmente pasto). Estos anillos fueron vinculados a diversas fuentes naturales y sobrenaturales, como caminos cerrados creados para el baile de hadas, truenos, relámpagos, torbellinos, hormigas, topos y orina de animales (Debano, 2000a). Cuando se producen estos anillos se puede ver un área de vegetación seca en la parte superior de la superficie de donde tiene lugar el crecimiento el micelio de los hongos en el interior del suelo. Los anillos de hadas son muy llamativos a simple vista ya que también se presentan como anillos concéntricos de crecimiento anormal de pasto sobre la misma superficie de suelo (Figura 10). La zona de crecimiento exuberante es la que presenta los hongos, que dan lugar a la fructificación de setas siguiendo el círculo (Jaramillo, 2004).

Los anillos más frecuentes son los definidos por círculos de pasto seco o severamente dañado por la sequía sin presencia de setas fructificadas o carpóforos en la superficie del terreno. Este tipo de anillos son muy frecuentes en zonas con césped deportivo y parques que con anterioridad había un pastizal o bosque, que hace que se encuentren unas condiciones óptimas para el desarrollo del hongo por la materia orgánica acumulada. Es en estos lugares de abundante material de origen vegetal como hojarasca, raíces muertas o madera donde se estimulan la aparición de los hongos (Jaramillo, 2004). Estos anillos fueron estudiados por York y Canaway (2000) en campos de golf de Inglaterra, que vieron una alta repelencia en las zonas donde predominaba el hongo *Marasmius oreades*. Ocurre con más frecuencia que los anillos se observen en suelos de textura arenosa, de baja fertilidad y con baja capacidad de almacenamiento de agua (Jaramillo, 2004). Sobre un suelo arenoso en Holanda, Dekker y Ritsema (1996) estudiaron la humedad de un anillo de hadas de 12 metros de diámetro. Al interior de anillo concéntrico con pasto normal como cobertura le seguía un anillo hacia fuera con vegetación más exuberante y otro en el que se encontraban los carpóforos del hongo. Tras dos semanas de lluvia (precipitación de 66 mm) la parte externa del círculo se humedeció hasta una profundidad de 20 cm, la parte de los hongos llegó a los 3 cm y la de vegetación exuberante a 10 cm (Jaramillo, 2004).



"ANILLO DE HADAS" (a partir de Shantz y Piemeisel, 1917)

Figura 9. Ilustración esquemática del "anillo de hadas" propuesta por Shantz y Piemeisel en 1917 (Jaramillo, 2004).

Figura 10. Anillos de hadas en Landmannalaugar (Islandia). Fotografía: Petr Brož, bajo licencia Creative Commons Attribution 3.0 Unported.

Sin embargo, McGhie y Posner (1980) no observaron relación importante entre la repelencia y los hongos. En un estudio en el que vieron que con *Penicillum* y *Aspergillus* (hongos trabajados por ellos) no produjeron repelencia sobre arena lavada.

1.4 LA HIDROFOBICIDAD EN SUELOS AGRÍCOLAS Y FORESTALES

La hidrofobicidad al agua en el suelo es causada por ciertos compuestos orgánicos que se encuentran en la materia orgánica recubriendo las partículas minerales y agregados (Franco et al., 2000; Mataix-Solera y Doerr, 2004), asociada a menudo con especies particulares de plantas, hongos y otros microorganismos del suelo, aunque esto no significa que estas especies siempre actúan con la misma intensidad o en la misma dirección (Doerr et al., 2000). La forma en la que varias especies de plantas favorecen o no la hidrofobicidad tiene que ver con la cantidad y tipo de residuos orgánicos acumulados en el suelo, como exudados de la raíz (Dekker y Ritsema, 1996), lavados de compuestos a partir de hojas de plantas (Doerr et al., 2000; DeBano, 2000a) o de los productos de la descomposición de la materia orgánica (McGhie y Posner, 1981).

Así, como hemos visto, diferentes tipos de vegetación, tanto arbustiva y arbórea, se han relacionado con la presencia de hidrofobicidad en los suelos (Doerr et al., 2000). En el sur de California, Holzhey (1969) estudió la repelencia al agua en distintos tipos y formas de vegetación. En las zonas arbustivas con escasa capa de hojarasca observaron la menor repelencia, y en las zonas también arbustivas pero de bosque compuesto de *Arctostaphylos sp., Ceunothus sp., Querciis dumosa* y *Rhamnus crocea* la mayor repelencia.

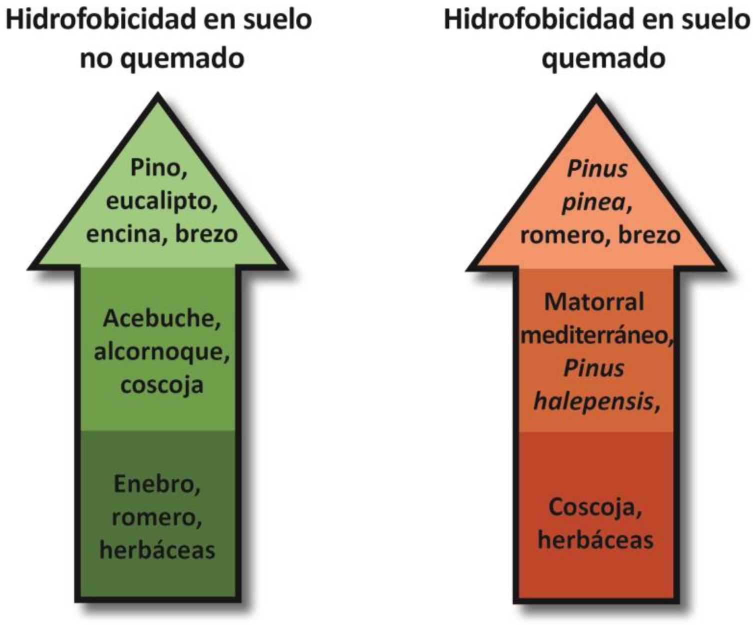


Figura 11. Hidrofobicidad en función de las especies vegetales: en suelos quemados y suelos no quemados. A partir de varios autores.

La hidrofobicidad se ha estudiado con especial énfasis en los suelos bajo coníferas y eucaliptos, especialmente después de un incendio. Sin embargo, el número de trabajos sobre otros tipos de vegetación de matorral mediterráneo es todavía baja (Martínez-Zavala y Jordán-López, 2009). En las zonas de clima mediterráneo, en condiciones microclimáticas húmedas o zonas subhúmedas, la abundante producción de biomasa y la acidez del suelo son factores que desencadenan la hidrofobicidad. A su vez, cómo tantos factores de influencia hidrofobicidad del suelo se determina por la vegetación (Figura 11).

La repelencia es un fenómeno común en suelos forestales, en suelos arenosos y en suelos afectados por incendios, mientras que los suelos agrícolas han sido asumidos tradicionalmente como humectables (Wallis y Horne, 1992). Sin embargo, en las últimas dos décadas, varios autores han observado la presencia de hidrofobicidad en suelos cultivados. En Holanda el 75% de los prados herbáceos y suelos cultivados presentan repelencia al agua (Dekker y Ritsema, 1994) y 5 millones de hectáreas en el sur de Australia son superficies de suelo repelente al agua que suponen pérdidas para la producción agrícola (Bodí et al., 2012). Aunque, hay que tener en cuenta que la repelencia en suelos de uso agrario no siempre van a mermar la producción y va a depender mucho, de lo extrema o ligera que sea la repelencia sobre el suelo. En este sentido deben ir encaminados los estudios hoy en día de la comunidad científica. Así, la repelencia al agua y sus respuestas hidrogeológicas en suelos agrícolas puede tener efectos positivos y negativos para el cultivo. En este sentido, por un lado, suelos con un alto grado de hidrofobicidad incrementa los riesgos de pérdidas de nutrientes y plaguicidas por lixiviación. También una reducción de la infiltración de agua produce una disminución de la habilidad de almacenamiento de agua por parte de las raíces (Blanco y Lal, 2009; Debano, 2000; Clothier et al., 2000). Pero, por otro lado, una repelencia moderada y ligera puede ser beneficiosa en los procesos conjuntos del suelo y el cultivo. Ya que puede llegar a incrementar la estabilidad de los agregados y su fuerza. Así mismo el secuestro de carbono puede verse favorecida a largo plazo, principalmente en suelos no labrados (Blanco y Lal, 2009; Urbanek et al., 2007). Una rápida entrada de agua sobre la superficie del suelo puede provocar el estallido de los agregados (slaking) debido a la compresión y posterior salida del aire contenido en el interior de los poros (Ojeda et al., 2008). Así que prácticas conservadoras para suelos agrícolas como el no laboreo incrementan el secuestro de carbono orgánico pueden generar al suelo propiedades de repelencia al agua. Hallet et al. (2001a) en un estudio sobre suelo franco-limoso observaron que suelos con no laboreo eran más repelentes que suelos arados. Blanco-Canqui et al. (2007), en un estudio sobre unos suelos cultivados con maíz y durante un largo periodo sin labranza (44 años), observó el doble de repelencia respecto al suelo labrado. Por el contrario Eynard et al. (2004)

no encontraron diferencias significativas en cuanto a la repelencia entre suelos labrados y no labrados en suelos francos, franco-limosos, franco-arcillo-limosos y arcillosos.

Blanco-Canqui y Lal, (2009) observaron la medida de la repelencia en suelos cultivados con una leguminosa (*Glycine max L.*) y no labrados durante un largo tiempo (entre 4 y 30 años) y un suelo contiguo con laboreo combinando el arado de vertedera con el arado de cincel. En 8 de los 11 suelos, analizando la repelencia en los primeros 5 cm, el no laboreo indujo a la repelencia retrasando la entrada de agua en 3 segundos. Estos resultados están relacionados con la abundante biomasa generada procedente de los cultivos presentes en la superficie del suelo y al aumento de la actividad de todos los microorganismos que tras la descomposición de los restos vegetales generan componentes hidrófobos. Tambien se encontraron unas poblaciones más abundantes macroorganismos como lombrices de tierra (*Lumbricus terrestres L.*) en las zonas de no laboreo frente a las de laboreo.

Especialmente en caso de suelos agrícolas o naturales no afectados por el fuego, tiene especial importancia un adecuado manejo unido a un aporte de fracción orgánica ya que los suelos de la cuenca mediterránea, por sus condiciones edafoclimáticas y la intensa mineralización, presentan normalmente un bajo contenido en materia orgánica (Mataix-Solera y Guerrero, 2007; García y Hernandez, 1996; García et al., 1996, 2002). A lo largo de los años, ha sido una práctica habitual la aplicación de residuos orgánicos a través del estiércol de ganado. Esta práctica ha ido desapareciendo a finales del siglo XX con el abandono del uso de animales para trabajar la tierra y la separación geográfica y física de las zonas agrícolas y ganaderas y al aumento del uso masivo de los fertilizantes químicos (Mataix-Solera y Guerrero, 2007).

Todo esto ha llevado a un continuo deterioro de los suelos que tuvo como consecuencia un descenso en la productividad de los cultivos que llevó a retomar este tipo de prácticas agrícolas. La adición de residos orgánicos proporciona al suelo un incremento de todas sus propiedades físicas, aumentando, así la estabilidad estructural (Caravaca et al., 2002; Roldán et al., 1994, 1996; Guerrero et al., 2001; Vázquez et al., 1996), la porosidad y aireación (García-Orenes et al., 2005), la capacidad de retención de agua (Mays et al., 1973), un aumento de las poblaciones microbianas que están implicadas en la agregación de partículas (Roldán et al., 1994) y una multitud de procesos que contribuyen a la riqueza del propio suelo. La utilización de enmiendas orgánicas no sólo se restringe a los suelos cultivados, sino a zonas forestales y áreas en restauración (Arcenegui et al., 2007; Mataix-Solera et al., 2007).

La repelencia al agua en suelos agrícolas, es una propiedad que en los últimos años está siendo muy estudiada por la comunidad científica (Blanco-Canqui y Lal, 2009; Blanco-Canqui et al., 2009; Blanco-Canqui, 2011; Urbanek et al., 2007; González-Peñaloza et al., 2012; Rodríguez-Alleres M, 2007; Hallet et al., 2001a), aunque entre los primeros estudios sobre repelencia al agua están los realizados en suelos agrícolas por Jamison (1943, 1946) y Wander (1949). Uno de los primeros estudios sobre suelos agrícolas repelentes al agua fue publicado por Chan (1992) que observó la aparición de repelencia al agua en un suelo bajo no laboreo.

Hasta la década de los noventa, los suelos agrícolas eran generalmente considerados humectables (Wallis y Horne, 1992). Aunque según Blanco-Canqui (2011), la repelencia al agua es cada vez más reconocida como un atributo influyente del suelo bajo diferentes escenarios de uso y manejo en todo el mundo (DeBano, 2000a; Doerr et al., 2000). Así, muchos autores han observado que las prácticas de manejo del suelo pueden inducir repelencia al agua en suelos cultivados (Blanco-Canqui, 2011; Blanco-Canqui y Lal, 2009). Las prácticas de manejo del suelo en áreas cultivadas pueden influir en la aparición y distribución la repelencia (Wallach et al., 2005; Urbanek et al., 2007).

A pesar de que la repelencia al agua es poco común en suelos cultivados, la utilización de un determinado manejo, como la fertilización orgánica, puede inducir repelencia al agua (Cerdà y Doerr, 2007). En otro estudio, en Israel, se observó que, tras un periodo de riego con aguas residuales durante 20 años, se indujo repelencia al agua en el suelo (Wallach y Jortzick, 2008; Wallach et al. 2005). El aumento la repelencia al agua en los suelos bajo no laboreo se ha observado, por ejemplo, por Blanco-Canqui y Lal (2009), Blanco-Canqui et al. (2009), Chan (1992), González-Peñaloza et al. (2012), Hallett et al. (2001a), Pikul et al. (2009), Simon et al. (2009) y Roper et al. (2013).

Blanco-Canqui y Lal (2009) describieron la repelencia al agua como un fenómeno común en los suelos después de las prácticas de conservación a largo plazo. Tanto Blanco-Canqui y Lal (2009) como González-Peñaloza et al. (2012) han puesto de relieve la importancia de los diferentes grados de la repelencia al agua del suelo en relación con la respuesta hidrológica de los suelos cultivados bajo prácticas de conservación. Por el contrario, otros autores han informado de poca o ninguna influencia del no laboreo en las prácticas de repelencia (Eynard et al., 2004).

Como ya se ha mencionado (pág. 24), en muchos casos la repelencia al agua en el suelo se desarrolla a través de la acumulación de compuestos ácidos hidrófobos de exudados de raíces y plantas (Dekker y Ritsema, 1996; Doerr et al., 1998) y derivados de la descomposición de la materia orgánica (McGhie y Posner, 1981).

Todos estos compuestos hidrofóbicos se van incorporando al suelo y van cubiendo la superficie de los agregados. Rodriguez-Alleres et al. (2007) realizaron un estudio en La Coruña y Pontevedra (en el noroeste de España) sobre el efecto en la repelencia al agua en relación al contenido de carbono orgánico utilizando diferentes tamaños de partículas de suelos ácidos con altos contenidos de materia orgánica y bajo diferentes cultivos (maíz y pastizales por un lado, y bosques de pinos y eucaliptos por otro). La distribución de la repelencia al agua se encontró muy relacionada con el contenido de materia orgánica. En las zonas muestreadas de suelo bajo cultivo de maíz y pastizal se relacionó la repelencia con las fracciones del suelo más finas (<0.05 mm) aunque de forma global el suelo se mostró humectable ya que las partículas gruesas no mostraban hidrofobicidad. Por el contrario, en los suelos de bosques de pinos (*Pinus pinaster*) y bosques de eucaliptos (*Eucalyptus globulus*) si se encontró una mayor severidad de la repelencia en todas las fracciones de tamaño, si bien, menor en la fracción más gruesa (2-1 mm). Este alto grado de repelencia al agua en suelos forestales está relacionado con el alto contenido y las propiedades de la materia orgánica. Mientras que Crockford et al. (1991) y González-Peñaloza et al. (2013) han asociado la repelencia a partículas más gruesas, otros autores como Doerr et al. (1996) han observado que tanto las partículas de fracción fina como partículas de fracción gruesas eran hidrofóbicas (o incluso más hidrofóbicas las finas).

Bodí et al. (2014) realizaron un estudio en la Sierra de Enguera (provincia de Valencia) en el que cuantificaron la repelencia en el suelo bajo distintos tipos de manejos agrícolas y con distintos usos. En su estudio, los suelos con cubierta vegetal manifestaban repelencia al agua, mientras que todos los suelos tratados con herbicidas y los labrados se consideraron hidrofílicos. Comparados con suelos forestales, los resultados obtenidos manifiestan que la repelencia al agua aparece más frecuentemente en suelos forestales antes que en los agrícolas. Y prácticamente es inexistente en suelos labrados, ya que la mecanización del suelo produce la destrucción de los agregados, favoreciendo la mineralización de los compuestos orgánicos y reduciendo así el grado de repelencia al agua (Crockford et al., 1991).

1.5 RELACIÓN ENTRE LA REPELENCIA AL AGUA DEL SUELO Y DEL FUEGO

Los incendios forestales producen una serie de efectos sobre el suelo que dependen tanto de factores intrínsecos, como sus propiedades físicas y químicas, o extrínsecos, como la vegetación, y de la intensidad del incendio. La principal característica post-incendio es la drástica disminución de la cobertura vegetal del suelo, que lo sitúa en un estado vulnerable frente a la precipitación, incrementando el riesgo de erosión, aunque no es este el único efecto. Aunque la hidrofobicidad aparece de forma natural en muchos tipos de suelos (Doerr et al., 2000; Doerr et al., 2006a; Doerr et al., 2009), diversos estudios muestran que existe una cierta relación entre el fuego y la repelencia al agua del suelo (DeBano et al., 1970; DeBano, 2000b; DeBano et al., 2005) o de la ceniza (Bodí et al., 2012; Cerdá y Doerr, 2008; Pereira et al., 2013; Zavala et al., 2009b) (Figura 12). ¿Cómo afecta el fuego a la repelencia al agua del suelo? Existen varios modelos que ayudan a entender mejor este proceso. En la Figura 13 se representa, de forma esquematizada, el modelo que DeBano (1981) propuso para entender con claridad el efecto del fuego sobre la redistribución de sustancias hidrofóbicas en el suelo.

Figura 12. Gota de agua sobre una capa de ceniza repelente al agua tras un incendio experimental en Almadén de la Plata (Sevilla) en 2013. Fotografía: F.A. González-Peñaloza.

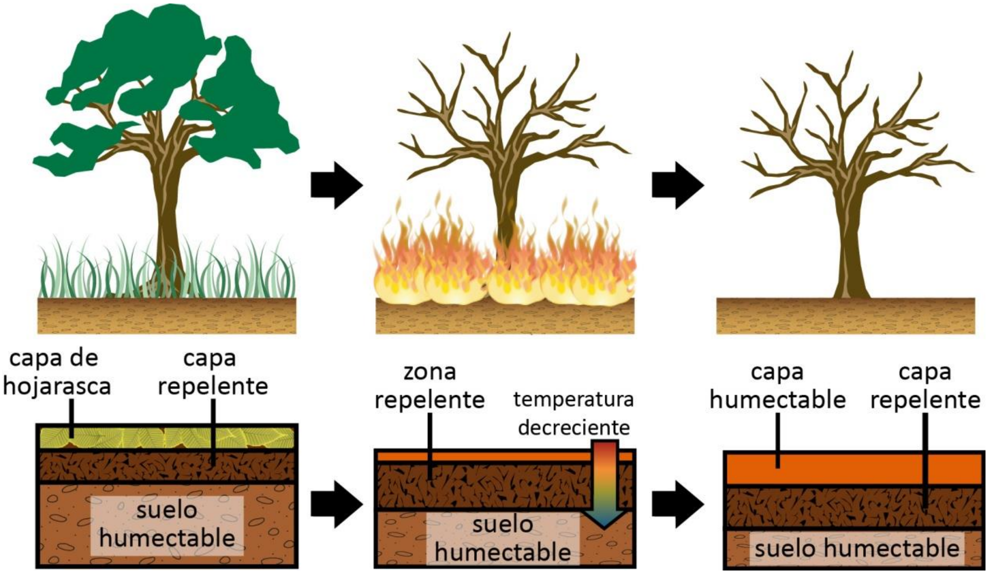


Figura 13. Efecto del fuego sobre la hidrofobicidad del suelo (a partir de DeBano, 1981). Izquierda: antes del fuego, las sustancias hidrofóbicas se encuentran en la capa de hojarasca y el primer horizonte de suelo mineral. Centro: El fuego quema la capa de vegetación causando el desplazamiento y la concentración de las sustancias hidrofóbicas a través de gradientes de temperatura. Derecha: después del fuego, una capa de suelo repelente al agua permanece en el horizonte inferior del área quemada.

El paso del fuego transforma súbitamente el aspecto y el funcionamiento del ecosistema allí donde se produce, y deja una herencia que lo afectará durante años de diversas formas dependiendo de múltiples factores. Dependiendo de su intensidad, el fuego puede inducir, incrementar, destruir o no tener ningún efecto sobre el carácter hidrofóbico del suelo (Doerr et al., 2004; Doerr et al. 2006b).

Varios autores (DeBano, 1966; DeBano y Krammes, 1966; DeBano et al. 1970; Savage, 1974) han observado que el fuego puede inducir repelencia al agua sobre suelos que previamente no la presentaban. Factores como la temperatura alcanzada (Granged et al., 2011a; Robichaud y Hungerford, 2000; Zavala et al., 2010), la cantidad y tipo de hojarasca consumida (Doerr et al., 2000; Rodríguez-Alleres., 2007) y la humedad del suelo (Doerr y Shakesby, 2009; Granged et al., 2011b; Ritsema et al., 1997) antes de producirse el incendio, pueden intensificar o reducir la repelencia al agua. El calentamiento de suelos no repelentes con un contenido en materia orgánica del 2-3% puede inducir la aparición de la repelencia al agua (DeBano, 1991). La aparición de repelencia en suelos incendiados surge cuando la temperatura del incendio llega a los 200 °C (Osborn et al., 1964). Sin embargo, a temperaturas superiores a 450-500 °C, la hidrofobicidad puede ser destruida como consecuencia de la combustión de sustancias orgánicas (DeBano et al., 1976; Nakaya, 1982).

Durante la combustión, las substancias orgánicas hidrofóbicas en la hojarasca y en la superficie del suelo se volatilizan durante el incendio. Una pequeña parte de esta cantidad de material es desplazada en profundidad, siguiendo el gradiente térmico hasta condensarse de nuevo a pocos centímetros bajo la superficie (Figura 14). La profundidad de este frente repelente al agua no es sólo dependiente de la temperatura alcanzada, sino también de las características del suelo, tales como la humedad en el momento del incendio o la textura (Huffman et al. 2001; Robichaud y Hungerford, 2000). Aunque, independientemente de la intensidad o severidad del fuego y de las características del suelo, rara vez supera los 6-8 cm de profundidad

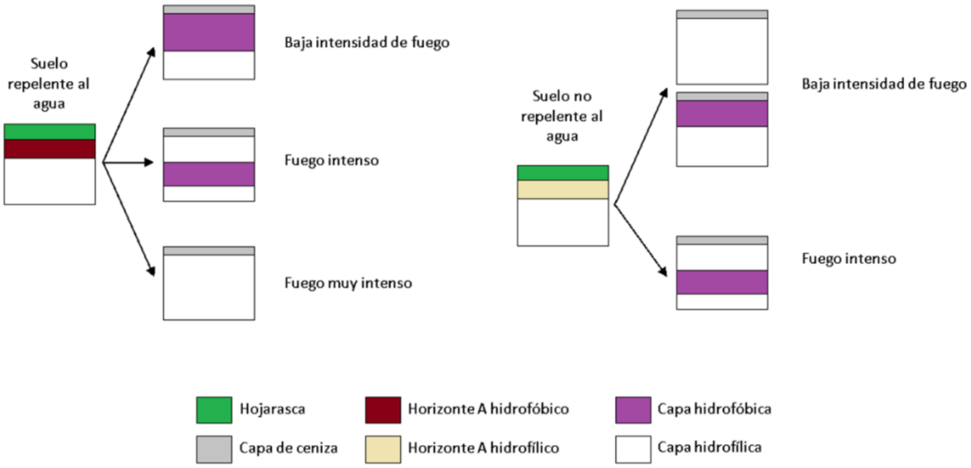


Figura 14. Esquema del efecto del fuego sobre la hidrofobicidad en suelos previamente hidrofóbicos e hidrofílicos en función de la severidad del fuego.

(Henderson y Golding, 1983; Huffman et al. 2001). Robichaud y Hungerford (2000) observarón la redistriución de las sustancias hidrofóbicas en el suelo sometido a distintos rangos de temperatura. La temperatura alcanzada, la cantidad de y tipo de hojarasca y la humedad del suelo antes del incendio pueden intensificar o reducir la repelencia. Durante el incendio se produce la volatilización de la mayoría de substancias orgánicas hidrofóbicas presentes en la hojarasca y superficie del suelo. Todas estas substancias se desplazan verticalmente siguiendo un gradiente térmico hasta que se condensan unos centímetros más abajo (Huffman et al., 2001).

Dependiendo de la severidad (grado de afectación producido por el fuego) e intensidad (es la tasa en kWm^{-1} a la que se libera la energía desprendida por el fuego) del fuego (Pausas, 2012), las temperaturas que se alcanzan en el suelo durante un incendio son muy variadas. El suelo no es un buen conductor del calor, por lo que a una gran profundidad la temperatura es mucho menor aunque la temperatura de las llamas sean muy altas (Debano et al., 1998). Varios autores (Debano et al., 1979; García-Corona et al., 2004; Mataix-Solera y Guerrero, 2007; Robichaud y Hungerford, 2000) han obsevado, en experimentos de laboratorio, el comienzo de la destrucción de repelencia en la superficie del suelo alcanzando temperaturas de 250 y 350 ^{o}C. En un estudio, Debano y Krammes (1966) observaron que se destruía la repelencia al agua en suelos sometidos a temperaturas entre 480 y 540 ^{o}C durante 25 minutos (Tabla 2). Tambien observaron que después de 5 minutos a 600 ^{o}C, la repelencia al agua en el suelo era extrema. Sin embargo, a partir de los 800 ^{o}C comienza a disminuir la repelencia llegando a ser el suelo hidrofílico de nuevo a los 900 ^{o}C (durante 10 minutos).

Además de los mecanismos de concentración de sustancias hidrofóbicas debidos a los procesos de volatilización y condensación que ocurren durante el fuego, autores como Giovannini (1994) sugieren que la hidrofobicidad puede originarse durante las reacciones químicas que se producen en el incendio a causa de a pirolisis y la reordenación de estas partículas y substancias que dan como resultado unas sustancias más fuertemente hidrofóbicas.

Tabla 2. Umbrales térmicos y algunos de los efectos en el suelo (Mataix-Solera y Guerrero, 2007).

Temperatura (ºC)	Componentes minerales	Materia orgánica
1400	Fusión de arenas y limos (>1400 ºC)	
1200	Volatilización del calcio (1240 ºC)	
800-1200	Fusión de la arcilla (>800 ºC)	Pédida de S (>800 ºC) (oxidación del S
700	Colapso de la estructura cristalina	Pédida de P (>700 ºC)
600	Máxima pérdida de K y P (oxidación de enlaces metálicos)	Pérdida del 50% N (300-600 ºC)
500	Transformación de óxidos gaseosos de Fe y Al (400-500 ºC)	Aparición de cenizas Materia orgánica pirolizada (250-500 ºC) Destrucción de la hidrofobicidad (450-580 ºC)
400	Pérdida de agua estructural de la arcilla (>420 ºC)	Combustión de la materia orgánica (400-450 ºC)
300		Destilación de la materia orgánica (200-315 ºC)
200		Cambios en la materia orgánica Aparición de hidrofobicidad
150		Muerte de semillas, bacterias, hongos (50-120 ºC)
100	Pérdida de agua	Deshidratación (60-100 ºC)
50		Muerte de las plantas (40-70 ºC)

2 OBJETIVOS

El principal objetivo del presente trabajo es investigar algunos de los factores que condicionan la intensidad y la distribución de la repelencia al agua en suelos mediterráneos, considerando tanto los suelos naturales como las prácticas agrícolas de conservación, que diversos autores han puesto de manifiesto como responsables de la hidrofobicidad en suelos cultivados.

Dado que la repelencia al agua en los suelos es una propiedad clave cuyo análisis permite entender mejor las respuestas hidrológicas y los procesos erosivos en los suelos, este trabajo nace con la finalidad de obtener un mayor conocimiento del estudio de los tipos de vegetación que pueden favorecer la aparición de repelencia al agua y su relación con los distintos tipos de suelo.

Por lo tanto, en este trabajo se plantean los siguientes objetivos:

a) Investigar la distribución y la intensidad de la repelencia al agua en suelos bajo diferentes tipos de sistemas forestales mediterráneos, representativos de amplias zonas en el sur de España (bosque de eucaliptos, encinas y pinos), y de manera específica:
    i) Estudiar la relación entre la repelencia al agua de suelos bajo cobertura arbórea, de matorral o herbácea, y
    ii) Estudiar la relación existente entre la repelencia al agua del suelo y algunas de sus propiedades químicas (acidez, contenido en materia orgánica, concentración de N, P, carbonato de calcio y capacidad de intercambio catiónico) o físicas (textura) consideradas importantes en el desarrollo de la hidrofobicidad.

b) Estudiar la relación entre repelencia al agua, contenido en carbono orgánico y estabilidad estructural en suelos bajo diferentes tipos de manejo agrícola (albaricoque, cítricos y trigo) y diferentes tratamientos (laboreo convencional y acolchado) a escala de agregado, y de manera específica:
    i) Estudiar el contenido de carbono orgánico y la intensidad de la repelencia al agua en agregados de diferentes tamaños.
    ii) Estudiar la distribución de carbono orgánico y de grado de repelencia al agua en diferentes regiones de agregados de suelo.
    iii) Estudiar la estabilidad estructural de los agregados del suelo en relación con el contenido de carbono orgánico y la intensidad de la repelencia al agua en suelos bajo diferentes cultivos (albaricoque, cítricos y trigo) y diferentes tratamientos (laboreo convencional y acolchado sin laboreo).

c) Estudiar el impacto de las prácticas de conservación en la repelencia al agua de suelos agrícolas previamente humectables sobre los procesos hidrológicos y geomorfológicos. De manera específica, los objetivos de esta investigación son:

i) Estudiar el desarrollo de la repelencia al agua en suelos bajo acolchado y no laboreo en suelos del sur de España después de un período de 15 años.
ii) Estudiar la relación entre la repelencia al agua y el contenido en materia orgánica del suelo bajo prácticas de conservación.
iii) Estudiar el impacto de la hidrofobicidad en la respuesta hidrológica de los suelos agrícolas bajo prácticas de conservación.

3 NATURAL SOIL WATER REPELLENCY IN DIFFERENT TYPES OF MEDITERRANEAN WOODLANDS

3.1 BACKGROUND

Water repellency (WR) is a natural property of soils that reduces infiltration rates and, in consequence, enhancing runoff flow generation and increasing erosion risk (Doerr et al., 2000; Jordán et al., 2013). Soil WR has been reported in many geographic areas under a range of climatic conditions, vegetation types and soils (Doerr et al., 2000). Although biunique correspondence is difficult to establish (since many biotic and abiotic factors are involved), some plant species seem to be linked to the occurrence of WR in soils (Doerr et al., 1998; Scott, 2000). Plant species most commonly associated with WR are evergreen trees with a considerable amount of resins, waxes or aromatic compounds in their composition, as eucalypts and pines (Arcenegui et al., 2008; Hubbert et al., 2006; Lewis et al., 2006; Mataix-Solera and Doerr, 2004; Mataix-Solera et al., 2007; Martínez-Zavala and Jordán López, 2009). But WR has been also found in soils under shrub species in temperate areas (Mallik and Rahmann; 1985; Giovannini et al., 1987; Jordán et al., 2008; Jordán et al. 2010; Martínez-Zavala and Jordán López, 2009; Zavala et al., 2009b), oaks (Cerdà et al., 1998; Jordán et al., 2008; Mataix-Solera et al., 2007) and deciduous trees (Reeder and Jurgensen, 1979; Buczko et al., 2002).

Although wildfires are a major cause of WR, soil properties and the characteristics of the parent material may also condition the severity of WR in soils (Lozano et al., 2013; Mataix-Solera et al., 2013). Soil acidity (Hurrass and Schaumann, 2006; Mataix-Solera et al., 2007; McGhie and Posner, 1980; Zavala et al., 2009a), soil texture (DeBano, 1991; de Jonge et al., 1999; Doerr et al., 1996; González-Peñaloza et al., 2013; Rodríguez-Alleres et al., 2007), aggregates (Doerr et al., 1996; Jordán et al., 2011a;Kawamoto et al., 2007; Mataix-Solera and Doerr, 2004) and soil mineralogy (Dlapa et al., 2004; Lichner et al., 2006; Mataix-Solera et al., 2008; McKissock et al., 2000; Ward and Oades, 1993) are also important factors.

Soil WR inhibits or decreases the rate of infiltration, increasing runoff and erosion in forest (Doerr et al., 2000; Jordán et al., 2008; Shakesby et al., 2000) or cropped soils (García-Moreno et al., 2013; González-Peñaloza et al., 2012). Soil WR also induces uneven wetting patterns and the formation of preferential flow paths (de Rooij, 2000; Jordán et al., 2009; Granged et al., 2011a; Zavala et al., 2009b). Some important consequences of uneven wetting are the accelerated leaching of nutrients and increased contamination risk (Leighton-Boyce et al., 2005; Ritsema and Dekker, 1994).

Because of the impacts of soil WR in geomorphological and hydrological processes, information on the natural severity of soil WR is necessary for adequate soil planning and management. Some authors have studied the natural background of soil WR in soils under coniferous forest (*Pinus*, *Picea* and *Pseutotsuga* species) in USA (Doerr et al., 2009; Pierson et al., 2008), in Mexico (Jordán et al., 2009), in Europe (Dekker and Ritsema, 1994; Capriel et al., 1995), in South Africa (Scott, 2000) and in Australia (Blackwell, 2000; Roberts and Carbon, 1972). Background levels of soil WR from Mediterranean areas in Spain have also been reported by Cerdá and Doerr (2007), Cerdà et al. (1998), Jordán et al. (2008; 2009), Mataix-Solera et al. (2007), Rodríguez-Alleres et al. (2012), Schnabel et al. (2013) and Zavala et al. (2009a).

However, the knowledge of soil WR baseline presents some gaps in areas where this is a key property for the understanding of the hydrological and erosional response of soils. The objectives of this research are i) to study the occurrence and severity of soil WR in forest soils representative of wide areas in southern Spain (eucalypts, holm oaks and pines), ii) to study the relation between soil WR and tree, shrub and herbaceous cover in these areas and iii) to study the relation existing between soil WR and chemical (pH, organic C, N, P, CO_3Ca and cation exchange capacity) and textural soil properties.

3.2 MATERIAL AND METHODS

3.2.1 STUDY AREA

This research has been carried out during summer 2013 in fifteen areas from the province of Huelva (SW Spain), representative of the main types of woodlands in the area: eucalypts (*Eucaliptus globulus* and *E. camaldulensis*), pines (*Pinus pinea*) and holm oaks (*Quercus rotundifolia*). Pine woodlands are dominated by *P. pinea* and *P. halepensis*. Shrubs under pine and eucalypts are commonly formed by brooms (as *Genista hirsuta*), gorse (*Ulex* sp.), Spanish lavender (*Lavandula stoechas*), flax-leaved daphne (*Daphne gnidium*), dwarf palms (*Chamaerops humilis*) and rock rose (*Cistus ladanifer*, *C. salvifolius* or *C. crispus*). While eucalypts and pines form woodlands with a dense tree canopy, most holm oaks included in this study are dehesas, a savanna-like agrosylvopastoral system with sparse oaks and used mainly for grazing. Dominant tree species is holm oak (*Q. rotundifolia*), although it can be mixed with cork oaks (*Q. suber*) in some areas. Shrubs are commonly formed by rockrose (*C. ladanifer*), dwarf palms (*C. humilis*), myrtles (*Myrtus communis*), mastics (*Pistacia lentiscus*), Kermes oaks (*Q. coccifera*) and buckthorn (*Rhamnus oleoides*).

Table 1 shows the main characteristics of the studied plots, including geographical location, main vegetation type, soil type, lithology, slope, mean annual rainfall and conservation practices (if existing). Lithology includes metamorphic rocks (phyllites and slates) and volcanic rocks (Bellinfante et al., 2005). When present, conservation practices observed included no till and contour plowing.

Elevation of selected plots is variable, ranging between 68 and 500 masl, and slope ranged between 3 and 40%. Annual rainfall data (mean annual rainfall between 1984 and 2009) were extracted from the Andalusian Climate Database (Regional Andalusian Government). Mean annual rainfall increased irregularly with latitude, and varied between 485 and 889 mm.

3.2.2 ASSESSMENT OF VEGETATION COVER

During August 2012, fifteen plots 15 m × 15 m were established at each study area. At each plot, four 10 m long east-to-west oriented transects were placed at each plot. At each transect, plant cover (tree, shrub or herbaceous cover) was recorded every 2.5 m as 1 (present) or 0 (not present). The final number of observations was 15 plots × 4 transects × 4 points = 240. Tree, shrub and herbaceous cover were expressed as the percentage of observations (points) at each plot. The amount of bare soil was calculated as the percentage of points where no type of cover was recorded at each plot. Bare soil included rock fragments and rocky outcrops.

3.2.3 ASSESSMENT OF SOIL WATER REPELLENCY

Soil WR assessment was carried out under field conditions along vegetation transects every 2.5 m during august 2012, after a period of 40-45 days without rainfall. Persistence of SWR was analysed by the water drop penetration time (WDPT) test (Wessel, 1988).

At each point, litter was gently removed by hand and 10 drops of distilled water were placed on the soil surface and time for complete infiltration was recorded. The average time was considered representative for each case and soil was classified as wettable (WDPT ≤ 5 s), slightly water repellent (5 s < WDPT ≤ 60 s), strongly water repellent (60 s < WDPT ≤ 600 s), severely water repellent (600 s < WDPT ≤ 3600 s) and extremely water repellent (WDPT > 3600 s). Water drops were applied with an automatic micropipette onto the soil surface from a height of approximately 5 mm to avoid excess kinetic energy affecting soil-droplet interactions.

Table 1. Characteristics of the studied plots: longitude and latitude (decimal degrees), vegetation type, lithology, elevation (masl), slope (%), mean annual rainfall (rainfall, mm) and conservation practices.

Study area	Longitude	Latitude	Vegetation	Lithology	Elevation	Slope	Rainfall	Conservation practices
1	-7.466	37.558	Eucalypts	Slates	260	12	485	Contour plowing
2	-7.382	37.717	Holm oaks	Slates	240	4	526	No till
3	-7.339	37.423	Eucalypts	Slates	68	3	516	Contour plowing
4	-7.331	37.721	Holm oaks	Slates	110	8	543	No
5	-7.234	37.575	Eucalypts	Slates	220	30	564	Contour plowing
6	-7.243	37.837	Pines	Phyllites	252	15	665	No
7	-7.214	37.681	Holm oaks	Slates	255	7	594	No
8	-7.223	37.867	Pines	Phyllites	260	12	691	No
9	-7.208	37.920	Holm oaks	Slates	160	20	763	No
10	-7.099	37.378	Pines	Slates	100	8	489	No
11	-7.108	37.600	Eucalypts	Slates	200	4	585	No
12	-7.110	37.764	Holm oaks	Volcanic rocks	290	5	637	No
13	-7.098	37.824	Pines	Phyllites	500	40	672	No
14	-6.944	37.549	Eucalypts	Slates	70	4	731	No
15	-6.882	37.800	Pines	Volcanic rocks	160	5	889	No

3.2.4 SOIL ANALYSIS AND CLASSIFICATION

Soil samples were collected at the center of each plot between 0 and 5 cm depth or to bedrock if it was closer to the soil surface. Soil samples were transported in plastic bags to the laboratory for soil analysis dried at laboratory room temperature (25 ^oC) to constant weight and sieved (2 mm) to eliminate coarse soil particles. All samples were analysed by triplicate, and mean values were considered as representative for each case.

Soil acidity (pH) was determined in 1:2.5 soil: water extracts. Organic carbon (OC) content was determined by oxidation with acid-dichromate potassium and titration of dichromate excess with ferrous sulfate (Walkley and Black, 1934). Total N was determined by Kjeldahl digestion (Bremmer and Mulvaney, 1982). Extractable P was determined in soil extracts ($CaCl_2$ 0.01 M) using the Mo-blue method (Olsen and Sommers, 1982). Cation exchange capacity was determined by the $BaCl_2$-compulsive exchange procedure (Rhoades, 1982). Exchangeable cations were determined by the ammonium acetate method (Thomas, 1982).

For texture analysis, air-dried soil subsamples were pre-treated with H_2O_2 (6%) to remove organic matter and soluble salts, dried in the oven to obtain the initial weight, dispersed with a sodium hexametaphosphate solution, and mechanically shaken. The sand fraction (0.05-2 mm) was removed from the suspension by wet sieving and then fractionated by dry sieving; the fine silt (0.002-0.02 mm) and clay (<0.002 mm) fractions were determined by the pipet method (USDA, 2004). Coarse silt (0.02-0.05 mm) was calculated as the difference between 100% and the sum of the sand, clay, and fine silt percentages. Coarse elements (> 2 mm) were separated by dry-sieving and expressed as percentage of soil weight.

For soil classification, soil profiles were described and sampled according to FAO (2006), and analyses were carried out using the laboratory methods cited above. Soils were classified in soil types (reference groups) according to IUSS Working Group WRB (2006).

3.2.5 DATA ANALYSIS

Data analysis included regressions, correlations (Spearman rank correlation coefficient) and analysis of variance (Kruskal-Wallis ANOVA). When the Kruskal

Table 2. Soil characterization (mean values; standard deviation, SD; coefficient of variation, CV%; maximum and minimum values): soil type (IUSS Working Group WRB, 2006), pH; organic carbon (OC,%); N-Kjeldahl (N, %); P (ppm); CO_3Ca (%); exchangeable cations (Ca^{2+}, Mg^{2+}, Na^+ and K^+; cmol(+)kg^{-1}); cation exchange capacity (CEC, cmol(+)kg^{-1}) base saturation (BS,

Plot	Soil type	pH	OC	N	P	CO_3Ca	Ca^{2+}	Mg^{2+}	Na^+	K^+	CEC	BS	Sand	Silt	Clay	Texture	CE
1	Leptic Regosols	5.60	0.27	0.00	5.99	0.00	0.745	0.053	0.087	0.164	5.362	19.56	41.78	35.54	22.68	Loam	4.67
2	Dystric Leptosols	5.60	0.08	0.01	2.96	0.00	0.850	0.049	0.162	0.611	5.830	28.68	40.97	38.22	20.81	Loam	3.39
3	Lithic Leptosols	5.40	4.12	0.14	6.25	0.00	6.473	0.368	0.513	0.164	13.716	54.81	68.83	12.98	18.19	Sandy loam	4.27
4	Leptic Regosols	6.40	5.67	0.04	3.86	0.00	4.099	1.424	0.314	0.431	15.292	40.99	61.56	21.07	17.37	Sandy loam	3.99
5	Leptic Regosols	5.70	1.22	0.01	7.55	0.00	1.040	0.020	0.370	0.417	7.596	24.32	49.51	39.02	11.47	Loam	2.07
6	Leptic Regosols	5.30	0.26	0.00	0.50	0.00	0.742	0.083	0.079	0.235	5.273	21.60	40.30	37.50	22.20	Loam	4.58
7	Dystric Leptosols	5.70	0.08	0.01	0.48	0.00	0.868	0.095	0.100	0.561	5.828	27.87	41.90	37.10	21.00	Loam	3.39
8	Leptic Regosols	5.70	1.00	0.01	31.51	0.00	1.789	0.534	0.359	0.196	7.090	40.59	55.81	23.65	20.54	Sandy clay loam	2.72
9	Lithic Leptosols	7.50	0.91	0.06	10.22	0.45	0.982	0.073	0.099	0.173	1.327	100.00	55.14	22.19	22.67	Sandy clay loam	0.22
10	Eutric Regosols	4.80	0.66	0.17	3.58	0.00	1.041	0.604	0.681	0.155	2.482	99.96	44.00	40.75	15.25	Loam	5.56
11	Lithic Leptosols	4.80	2.53	0.01	8.96	0.00	2.235	1.010	0.527	0.489	7.011	60.78	38.12	44.94	16.94	Loam	3.76
12	Dystric Leptosols	6.30	1.67	0.12	4.43	0.00	11.761	12.346	0.381	0.589	30.094	83.33	30.79	50.42	18.79	Silt loam	1.32
13	Lithic Leptosols	5.20	0.91	0.17	8.78	0.00	1.106	0.048	0.294	0.153	16.041	9.98	52.68	40.41	6.91	Sandy loam	1.82
14	Lithic Leptosols	5.20	4.29	0.14	0.48	0.00	3.337	0.319	0.477	0.174	13.914	30.95	68.31	13.29	18.40	Sandy loam	4.10
15	Lithic Leptosols	5.40	0.87	0.45	16.27	0.00	1.228	0.112	0.148	0.196	4.427	38.04	62.40	20.60	17.00	Sandy loam	1.83
Mean		5.64	1.64	0.09	7.45	0.03	2.553	1.143	0.306	0.314	9.419	45.43	50.14	31.85	18.01	-	3.18
SD		0.68	1.73	0.12	7.90	0.12	3.012	3.126	0.190	0.179	7.353	28.72	11.65	11.76	4.32	-	1.47
CV%		12.10	105.95	133.76	106.03	387.30	117.98	273.62	62.04	57.09	78.07	63.22	23.23	36.94	23.98		46.27
Max		7.50	5.67	0.45	31.51	0.45	11.761	12.346	0.681	0.611	30.094	100.00	68.83	50.42	22.68	-	5.56
Min		4.80	0.08	0.00	0.48	0.00	0.742	0.020	0.079	0.153	1.327	9.98	30.79	12.98	6.91	-	0.22

Wallis null hypothesis was rejected, post-hoc pairwise comparisons were performed to assess significant differences between groups. All computations were performed using Statgraphics Centurion XVI (StatPoint, 1982-2011).

3.3 RESULTS

3.3.1 SOIL PROPERTIES

A summary of soil characteristics is shown in Table 2. Most soils were slightly to strongly acid, with pH varying between 4.8 and 6.4, except soil from plot 9 (pH 7.5). OC content varied in a wide interval, with values ranging from 0.08 to 5.67% (mean value 1.64 ± 1.73%). Nitrogen content varied between 0.00 and 0.17%, except one sample which reached 0.45%. Phosphorous content was highly variable, with values between 0.48 and 31.51 ppm (7.45 ± 7.90 ppm, on average). CO_3Ca content was 0.00 for all soil plots except for plot 9 (CO_3Ca 0.45%), where soil acidity was neuter (pH 7.5). The content of exchangeable Ca^{2+}, Mg^{2+}, Na^+ and K^+ is poor for most soil plots. Ten of fifteen soil plots shows CEC below 10 cmol(+) kg^{-1}, and mean CEC was 9.419 ± 7.353 cmol(+) kg^{-1}. Base saturation varied between 9.98 and 100.00%, but 10 of 15 soil profiles showed base saturation below 50%. Soil texture is characterized by a relatively low clay content (18.01 ± 4.32%, on average), varying between sandy loam and silt loam or loam.

The main characteristic of studied soils is the limited depth and poor development. Soil types ranged between Dystric or Lithic Leptosols and Eutric or Leptic Regosols and many soils were shallower than 20 cm. The A horizon is limited to a few millimeters and is often directly contacting the bedrock. Consequently, organic matter, roots and biological activity is condensed in a shallow surface layer. These soil types are common in south western Spain (Schnabel et al., 2013; Zavala, 2001).

3.3.2 VEGETATION COVER

Vegetation cover determined at each plot is displayed in Table 3. On average, tree cover decreased from plots under eucalypts (75.0 ± 6.3%) to plots under holm oaks (28.8 ± 21.0). In contrast, average shrub and herbaceous cover were higher in plots under holm oak woodland (31.3 ± 19.8% and 37.5 ± 23.8%, respectively). Tree cover varied between 68.8 and 81.3% (eucalypts), 6.3 and 62.5% (holm oaks) and 31.3 and 87.5% (pines). Shrub cover varied between 12.5 and 25% (eucalypts), 12.5 and 50% (holm oaks) and 6.3 and 31.3% (pines). On average, herbaceous cover showed

Table 3. Dominant vegetation and plant cover (%) for each plot. Mean value ± standard deviation is displayed for each cover type.

Plot	Vegetation	Tree cover	Shrub cover	Herbaceous cover	Bare soil
1	Eucalypts	68.8	12.5	12.5	18.8
2	Holm oaks	31.3	31.3	37.5	31.3
3	Eucalypts	75.0	25.0	25.0	25.0
4	Holm oaks	62.5	43.8	25.0	12.5
5	Eucalypts	68.8	25.0	25.0	18.8
6	Pines	31.3	12.5	0.0	62.5
7	Holm oaks	6.3	18.8	0.0	75.0
8	Pines	56.3	12.5	31.3	18.8
9	Holm oaks	25.0	12.5	43.8	43.8
10	Pines	87.5	6.3	0.0	12.5
11	Eucalypts	81.3	12.5	6.3	18.8
12	Holm oaks	18.8	50.0	50.0	25.0
13	Pines	68.8	31.3	31.3	12.5
14	Eucalypts	81.3	12.5	25.0	18.8
15	Pine forest	43.8	6.3	18.8	37.5
All plots		53.8 ± 25.7	20.9 ± 13.3	22.1 ± 15.8	28.8 ± 18.7

values very close to shrub cover, although herbaceous cover from some plots under pines (6 and 10) and holm oaks (7) was 0.0%. Although a few small areas showing herbaceous vegetation were observed, they were not recorded in transects. On average, bare soil surface under each vegetation type was 20 ± 2.8% (eucalypts), 28.8 ± 21.5% (pines) and 37.5 ± 23.8% (holm oaks). The bare soil surface varied between 12.5% (plots 4 under holm oaks, and 10 and 13 under pines) and 75% (plot 7, under holm oaks).

3.3.3 SOIL WATER REPELLENCY

Figure 1 shows the proportion of observations for each class of WR under different vegetation types. When considering all vegetation types together, the proportion of observations was 28.3 (wettable), 30.0 (slight WR), 26.7 (strong WR), 8.8 (severe WR) and 6.3% (extreme WR). For different vegetation types, the proportion of wettable points varied between 7.5 (pines) and 47.5% (holm oaks). Slight (35.0%) to strong WR (17.5%) was recorded under holm oaks. In contrast, WDPTs observed under eucalypts and pines were longer. Soils under eucalypts showed severe to

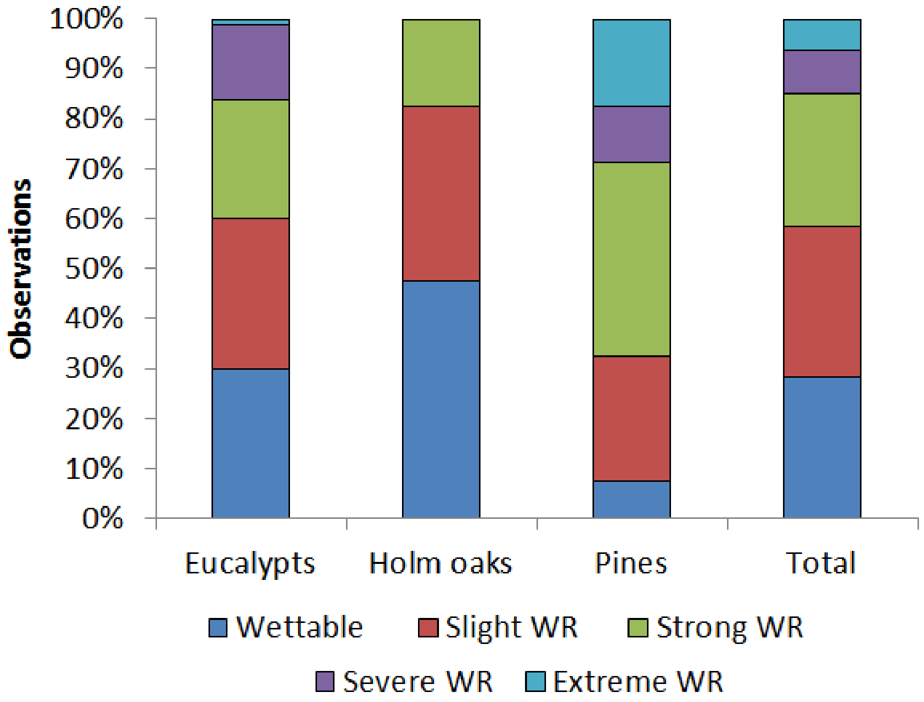


Figure 1. Number of observations of soil water repellency classes from eucalypt, holm oak, pine and all plots.

extreme WR, 16.3%. Under pines, the proportion of severe to extremely water-repellent points increased to 18.8%.

Table 4 shows the results of the Wilcoxon-Mann-Whitney U test for paired comparisons between soil WR under different vegetation types. Significant differences were between for WR from soils under eucalypts and holm oaks (p = 0.00081), eucalypts and pines (p = 0.00006) and holm oaks and pines (p = 0.00000).

Table 4. Results of the Wilcoxon-Mann-Whitney U two-sample test for mean WDPT class from different pairs of vegetation types.

Vegetation type	N	W	p
Eucalypts - holm oaks	80	2269.0	0.00081
Eucalypts - pines	80	4344.5	0.00006
Holm oaks - pines	80	5257.0	0.00000

Figure 3 shows the number of observations of soil WR classes from soils under eucalypt, holm oak and pine plots under different types of plant cover: tree, shrub and herbaceous cover (T+S+H), tree and shrub cover (T+S), tree and herbaceous cover (T+H), tree cover (T), shrub and herbaceous cover (S+H), shrub cover (S), herbaceous cover (H) and bare soil. In plots from eucalypt and pine woodlands, soil WR was generally more severe under the canopy of trees. Water repellency classes from eucalypt plots under the canopy of trees (T) were wettable, slight or strong (9, 17 and 13 records, respectively). Soils under combinations of tree with other strata showed strong (T+S+H, 3 records), slight to severe (T+H, 9) and strong to extreme WR (T+S, 9). In contrast, WR from bare soil points were wettable (13 records) or slightly water repellent (3). T-plots under pines showed strong (22 records), severe (6) and extreme (7). Soil points under the canopy of trees in combination with shrubs and herbaceous plants showed extreme (T+S+H, 1 observation), severe to extreme (T+S, 7) and strong to severe WR (T+H, 3). Soil points under shrubs, herbaceous plants or combinations showed slight and strong WR (6 and 5 records, respectively). Bare soil points from pine woodlands were wettable or slightly water repellent (21 of 23 records). In contrast to soil plots under eucalypt and pine woodlands, plots under holm oaks did not show extreme or severe WR. Slight to extreme WR was observed under the canopy of trees or trees combined with shrubs and/or herbaceous plants (T, T+S, T+H or T+S+H). Under shrubs and herbs (S, H or S+H), soil was wettable (8 records) or slightly water repellent (19 records). In this case, 100% bare soil points were wettable.

Significant Spearman rank correlation coefficients between soil WR (determined as mean WDPT class), tree, shrub and herbaceous cover, bare soil cover and soil properties are shown in Table 5. . Soil WR (WDPT class) showed a positive correlation with tree cover ($r = 0.5768$) and negative correlations with bare soil ($r = -0.5614$), pH ($r = -0.5374$), exchangeable K^+ ($r = -0.6813$) and clay content

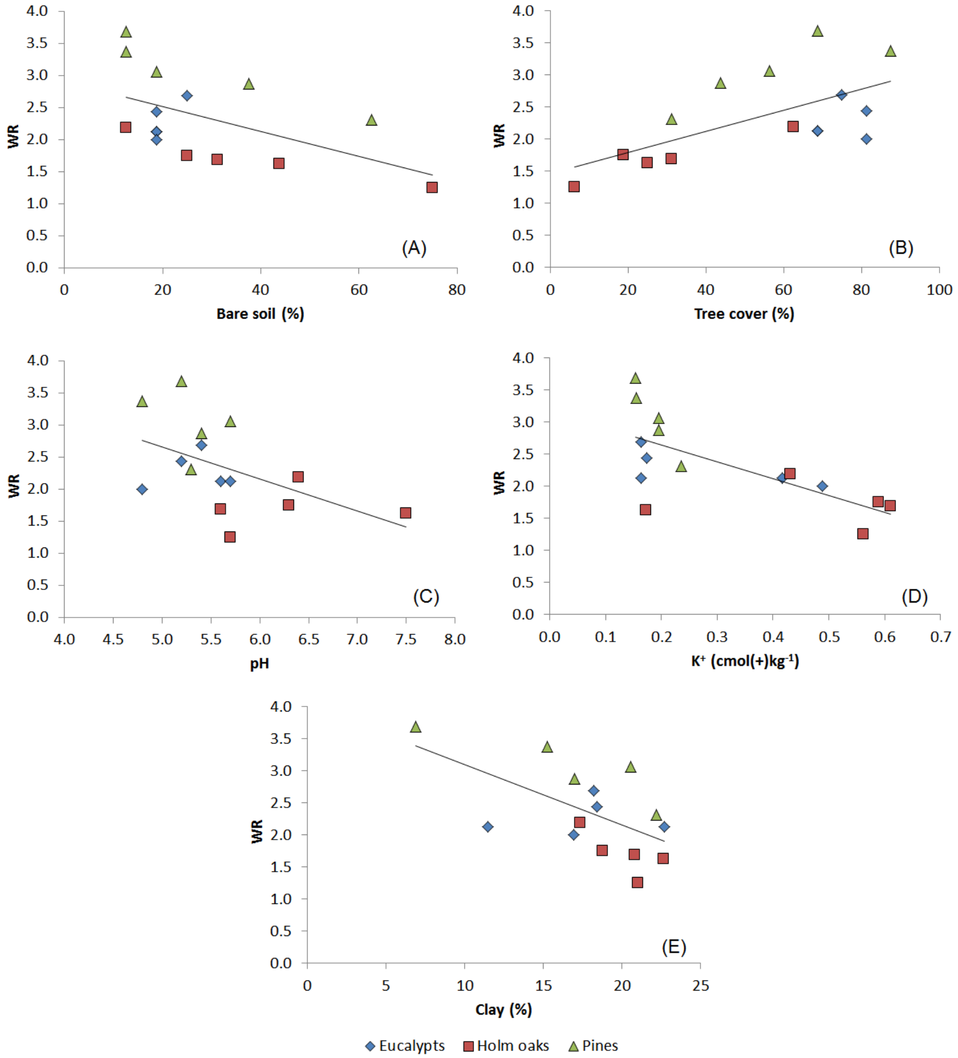


Figure 2. Regressions between soil WR (mean WDPT class) and other variables (bare soil percentage, tree cover, pH, exchangeable K and clay content): (A) WR = 2.903 - 0.019 × Bare soil (%), R2 = 0.2722, p = 0.0461; (B) WR = 1.490 + 0.0160 × Tree cover (%), R2 = 0.3631, p = 0.0174; (C) WR = 5.186 - 0.502 × pH, R2 = 0.2498, p = 0.0578; (D) WR = 3.162 - 2.576 × K+ (cmol(+) kg-1), R2 = 0.4537%, p = 0.0059; (E) WR = 4.051 - 0.094 × clay (%), R2 = 0.3526%, p = 0.0196.

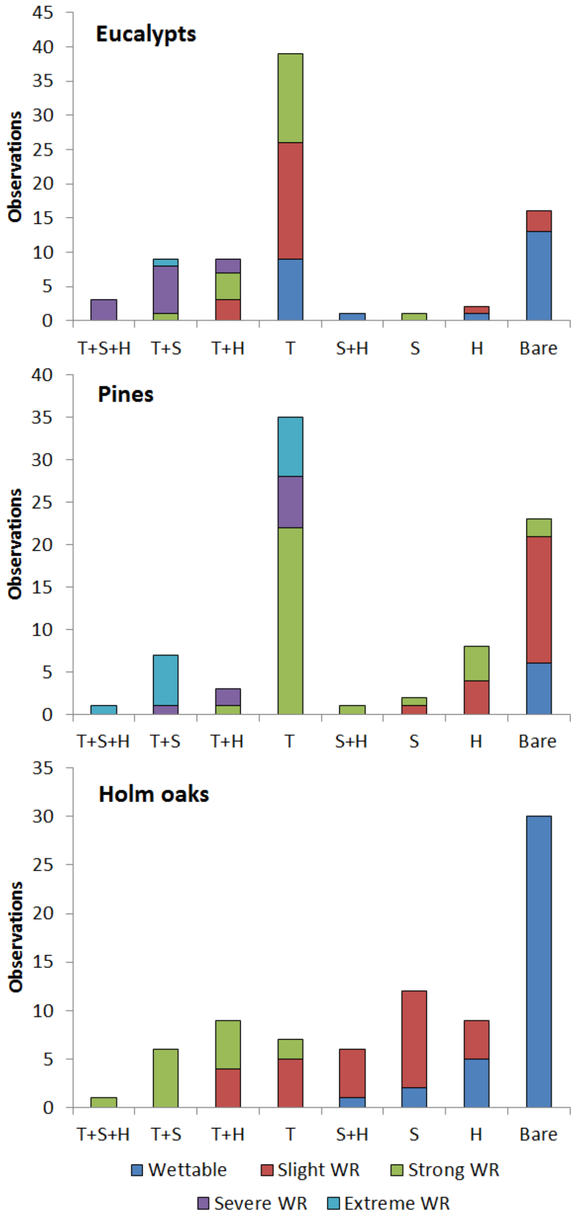


Figure 3. Number of observations of soil water repellency classes from eucalypt, holm oak and pine plots. Tree, shrub and herbaceous cover (T+S+H), tree and shrub cover (T+S), tree and herbaceous cover (T+H), tree cover (T), shrub and herbaceous cover (S+H), shrub cover (S), herbaceous cover (H) and bare soil (Bare).

Table 5. Spearman rank correlation coefficients between soil water repellency (mean WDPT class, WDPTc), tree (TC), shrub (SC) and herbaceous cover (HC), bare soil cover (BSc), and soil properties: pH; organic carbon (OC); N-Kjeldahl (N); P (ppm); CO_3Ca; exchangeable cations (Ca^{2+}, Mg^{2+}, Na^+ and K^+); cation exchange capacity (CEC) base saturation (BS); sand, silt and

	WDPTc	TC	SC	HC	BSC	OC	N	CO_3Ca	Ca^{2+}	Mg^{2+}	Na^+	Sand
TC	0.5768											
HC			0.5484									
BSC	-0.5614	-0.7292										
pH	-0.5374	-0.6917	0.449									
Ca^{2+}						0.8587	0.5471					
Mg^{2+}									0.7214			
Na^+		0.6661			-0.5517	0.619			0.7107	0.5536		
K^+	-0.6813	-0.5414										
CEC			0.762			0.644		-0.5916	0.6679			
BS (%)								0.5916	0.525	0.6964		
Sand							0.5379					
Silt												-0.8357
Clay	-0.5416	-0.5781			0.6248		-0.5744				-0.6571	
CE		0.5454		-0.6921								

(r = -0.5416). No significant correlations were found between soil WR and other chemical or physical soil parameters. The linear regressions between soil WR (determined as mean WDPT class) and these variables are shown in Figure 2.

Soil WR decreases when the proportion of bare soil surface increases. The ANOVA p-value for soil WR/bare soil percentage (p = 0.0461) shows that there is a statistically significant relationship between both variables. R^2 coefficient indicates that the model explains 27.2% of the variability in mean WDPT class. The correlation coefficient (r = -0.5218) indicates a moderately strong relationship between variables. The regression between soil WR and tree cover shows that WR increases with tree cover. The ANOVA p-value for soil WR/tree cover (p = 0.0174) shows that there is a statistically significant relationship between both variables. According to R^2 coefficient, the equation explains 36.3% of the variability in mean WDPT class. In contrast, no significant regressions were found for soil WR and shrub (R^2 = 0.0048, p = 0.4343) or herbaceous plant cover (R^2 = 0.0099, p = 0.7246).

The rest of soil variables showing significant Spearman correlation coefficients with soil WR (pH, exchangeable K concentration and clay content) decrased when soil WR increased (Table 5). Clay content and exchangeable K^+ showed moderate R^2 coefficients (R^2 = 0.3526, p = 0.0196 and R^2 = 0.4537, p = 0.0059, respectively). Soil acidity (pH), in contrast, regression did not show a significant relationship between both variables (R^2 = 0.2498, p = 0.0578).

3.4 DISCUSSION

Very few studies have been carried out about the characterization of soil WR background over large areas (Schnabel et al., 2013). In this study, background soil WR in undisturbed soils has been characterized at regional scale in fifteen experimental plots through the province of Huelva (SW Spain), including a range of vegetation types, main soil types and substrates. Results may be representative of other Mediterranean areas under similar climate, vegetation and soil characteristics.

A range of soil WR severity has been found in the three vegetation types studied in this research. This demonstrates that a natural background of soil WR exists in the studied area, independently of other factors as wildfires. This is in agreement with previous research from other authors who have found a WR baseline in sols under different vegetation and climate types (Buczko et al., 2002; Buczko et al., 2005; Buczko et al., 2006; Doerr and Thomas, 2000; Doerr et al., 2003; Cerdà and Doerr, 2007; Cerdá et al., 1998; Jordán et al., 2008; Jordán et al., 2009; Martínez-Zavala and Jordán-López, 2009; Mataix-Solera et al., 2007; Rodríguez-Álleres et al., 2012; Schnabel et al., 2013; Zavala et al., 2009a).

3.4.1 SOIL WATER REPELLENCY UNDER DIFFERENT VEGETATION SPECIES

Different severities of soil WR have been observed in soils under different forest species. Although many studies have reported an intense relationship between soil WR and plant species, this relation is not biunique, since many other factors are involved: fungi, microbial activity, root activity, wildfires, soil management, soil moisture, soil temperature, etc. (Doerr et al., 2000).

Slight to severe WR observed in soils under eucalypts and pines in our research is in agreement with previous research (Doerr et al., 1998; Doerr et al., 2003; Mataix-Solera et al., 2007; Shakesby et al., 1993). Soil WR has been traditionally associated with tree species as pines or eucalypts because of resins, waxes and other organic substances in their tissues (Mataix-Solera and Doerr, 2004) that may induce soil WR in soils. Substances capable of inducing severe water repellency in soils have been found in tissues and litter from pines and eucalypts (Atanassova and Doerr, 2011; de Blas et al., 2010; Doerr et al., 1998; Franco et al., 1995). Water repellency has also been associated with Mediterranean shrublands as heaths (Jordán et al., 2008), Kermes oak and rosemary (Mataix-Solera et al., 2007).

Soils under holm oak woodlands showed slight to severe WR under tree canopy. This range of variation is agreement with other studies about oak species (Cerdà et al., 1998; Jordán et al., 2008; Mataix-Solera et al., 2007). WR found in soils under oaks may be induced both by the organic matter content and quality. Hydrophobic compounds have been observed forming part of the composition of leaves and other tissues in oak species (Conde et al., 1998; Ito et al., 2002; Salminen et al., 2004). Under shrubs or herbaceous cover, soil WR decreased, while 100% samples from bare soils were wettable. Cerdà et al. (1998) studied the soil hydrological response in dehesas from Extremadura (SW Spain) under drought conditions and observed that soil WR increased under the tree canopy (*Q.ilex*), in comparison to open areas or between-tree areas. They observed that the proportion of soil samples showing WDPT < 60 s increased between areas under the canopy of trees (4%) and between-tree areas (40%). Also in dehesas, Schnabel et al. (2013) observed that bare soils were mostly wettable in more than 90% cases, with WR increasing under shrubs and, more intensely, under the tree canopy. In holm oak sparse woodlands, Cerdà et al. (1998) found that soil WR from between-tree areas was more severe than in our results. This may be easily explained, as they measured soil WR after an intense drought period. Soil WR may vary strongly with soil moisture, as reported in other areas (Benito et al., 2003; Zavala et al., 2009a). Although Schnabel et al. (2013) used the ethanol percentage method for assessing soil WR, their results are much closer to ours.

In general, our results show that soil WR increases according to this sequence: bare areas < shrubs and herbs < tree-covered areas. Similar results have been achieved in other Mediterranean areas. In SW Spain, Zavala et al. (2009b) found that most of soil samples from areas under sparse herbs were wettable, with WR increasing progressively under the canopy of shrublands and pines. They observed that soil properties as pH, OC content, sand and clay content or bulk density were significantly correlated with soil WR, although many of these factors were not important within vegetation types. Higher levels of soil WR found under the canopy of trees clearly states that organic inputs from tree litter are the main cause of hydrophobicity. Although the number of observations is small, it is surprising that trees + shrubs combinations showed WR classes similar to those observed under trees. This is especially surprising in soils from eucalypt woodlands, where severe and extreme WR was observed, while soils under tree canopy varied between wettable and strongly water repellent. All soils from holm oak woodlands under T+S and T+S+H cover were strongly water repellent (n = 7), in contrast to soils exclusively under trees, which were slightly (5 samples) and strongly water repellent (2 samples). Although it is necessary to conduct more detailed analysis of the effect of specific species in the development of soil hydrophobicity in the study area, it is possible that these apparently confusing results are due to the limited number of samples under some cover types. Regressions between mean WR class and trees, shrubs, herbs or proportion of bare soil may help to support this, as no significant regressions were found between shrub or herbaceous cover and WR. Less severe WR under shrubs (S and S+H plots) than under trees (T, T+S, T+H and T+S+H plots) found in this research is in contrast with results reported by other authors, who have observed different results in function of studied species. Jordán et al. (2008), for example, found that soil WR increased according to the series cork oaks and olive trees < cork oaks < grassland < heathland. These results were explained as the consequence of hydrophobic substances in plant residues, especially important under heathlands. Zavala et al. (2009a) also observed that WR from soils under heathland was much more severe than under eucalyptus, pines, cork oaks or olive trees. Severity of WR in Jordán et al. (2008) and Zavala et al. (2009a) under oaks, pines and eucalypts was similar to our results.

3.4.2 SOIL WATER REPELLENCY AND SOIL CHARACTERISTICS

According to the observed coefficients of variation (Table 2), soil properties varied within narrow intervals except organic C (CV = 105.95%), N (133.76%), P (103.03%) and exchangeable Ca and Mg (117.98 and 273.62%, respectively. CO_3Ca content showed the highest CV (387.30%), but this may be explained easily, as 14 from 15 values were 0.00%. Consequently, soils of the area are acid, relatively poor in soil OC (only 5 from 15 observations showed values above 1%), poor in nutrients and predominantly sandy loam to loam. Some of these properties are thought to induce the occurrence of WR in soils, as soil acidity or high sand content, while others are thought to favor wettability, as reduced soil OC (Doerr et al., 2000; Wallis and Horne, 1992).

In this research, soil WR (mean WDPT class) is significantly correlated with exchangeable K (Spearman rank correlation coefficient -0.6813), pH (-0.5374) and clay content (-0.5416). Harper et al. (2000) stated that these types of relationships are qualitative more than quantitative, and when used in an exploratory manner they can help to provide hypotheses for further experimental studies. Total N, available P and exchangeable Ca, Mg, Na and K concentrations from studied soils varied in a wide range, showing CVs between 57.09 and 387.30%, but most values are low. Total N, for example showed 8 from 15 values below 0.1%; Ca and Mg, which are usually dominant exchangeable bases, showed very low concentrations. Under those conditions, the amount of exchangeable K may be used as an indicator of the soil nutrient status. In 8 from 15 cases, the proportion of K in the cation exchange complex was higher than the proportion of Mg (Table 2). In the studied soils, exchangeable K showed a significant correlation with soil WR (-0.6813) and tree cover (-0.5414). Deficiencies of K have been reported in acid poor soils for eucalypts (Merino et al., 2003) or pines (Martins et al., 2009). So, it may be speculated that water-repellent tree covered soils show a deficit of K, which increases in areas were the proportion of perennial ligneous plants decreases.

Although a significant relationship between sand content and WR was not found, results show that WR clearly decreased when clay content increased. This is in agreement with previous results by different authors. The occurrence of WR is more frequent in coarse-textured than in fine-textured soils (DeBano, 1991; Blackwell, 1993; Giovannini and Lucchesi, 1983; Woche et al., 2005). Many authors have observed that just a relatively small amount of hydrophobic organic matter is required for coarse soil particles to develp WR (DeBano, 1981; Giovannini and Lucchesi, 1983; Blackwell, 1993). In contrast, some studies have found that WR may develop also in soils with considerable clay contents (Doerr et al., 1996; Doerr et al., 2000; Jordán et al., 2009). Zavala et al. (2009a) observed that soils under different types of vegetation from SW Spain (including pines, eucalypts and cork oaks) showed more severe WR in fine- than in coarse-textured soils. Also, in soils under pines and eucalypts from South Africa, Scott (2000) found that WR was not associated with soil texture. Different authors have reported that aggregate size was much more important than soil texture (Harper et al., 2000; Jordán et al., 2011a). Franco et al. (1995) suggested that hydrophobic substances interact with aggregates rather than with soil particles. Harper et al. (2000) suggested that clay, more than sand content is related with the development or inhibition of soil WR. Our results demonstrate that, in the studied sandy loam - sandy soils, WR is inversely related to clay content, confirming the hypotheses by Harper et al. (2000). Although relationship between the development of WR and aggregate fractions is necessary, these results may be valid for similar soils under the same climate and vegetation types.

Although most soils were slightly to strongly acid, a significant correlation was found for soil pH and WR, which increased with soil acidity. Although regression between soil WR and pH was not highly significant ($p = 0.0578$), pH increased from soils under pines and eucalypts and soils under holm oaks, where severity of soil WR was lower. Few studies have systematically investigated the relationship between soil WR and soil pH, soil WR has been demonstrated to be conditioned by soil pH (Diehl et al., 2010). Previous research has shown that soil acidity may condition the severity of soil WR under pines, oaks and eucalypts (Mataix-Solera et al., 2007; Zavala et al., 2009a) in Mediterranean Spanish areas. Chen and Schnitzer (1978) found that wettability may be conditioned by the ratio between humic (soluble at $pH > 6.5$) and fulvic acids (soluble at any pH). Consequently, Zavala et al. (2009a) suggested that increased preferential leaching of humic acids (soluble at $pH > 6.5$) may increase wettability in neuter to alkaline soils under humid conditions. Soil pH can also condition the development of soil WR by controlling fungi and microbial activity, which is able to enhance or decrease soil WR (Doerr et al., 2000; Franco et al., 2000; Hubbert et al., 2006) by releasing or degrading hydrophobic or hydrophilic substances. Recently, Schnabel et al. (2013) found no relationship between soil pH and WR in rangelands under different land management types. In their work, the range of variation of soil acidity in their work was similar to that observed in our case. In contrast, they only studied soils under oaks. Consequently, it can be suggested that, although alkaline conditions may favor soil wettability (Diehl et al., 2010) in laboratory experiments, many interactions among different factors take place under filed conditions, and indirect effects of pH on soil WR may exist via vegetation species, organic matter and soil microbiota.

Although it is well accepted that organic compounds cause WR, relatively low OC contents observed in soils showing even severe and extreme WR clearly demonstrates that the amount of soil organic matter needs not necessarily be related to soil WR. Although positive correlations between soil organic matter and WR have been found by different authors (Mataix-Solera et al., 2007; Varela et al., 2005; Zavala et al., 2009a), others have observed that humic acids may induce soil WR even when the organic matter concentration is low (Jungerius and de Jong, 1989). This is in agreement with results reported in other Mediterranean areas. Zavala et al. (2009a) observed significant relationship between WR and OC content in soils under cork oak, eucalypts and pines, but soils under heaths and olive trees showed high and low WR respectively, independently of soil OC content.

4 ORGANIC CARBON, WATER REPELLENCY AND SOIL STABILITY TO SLAKING UNDER DIFFERENT CROPS AND MANAGEMENTS: A CASE STUDY AT AGGREGATE AND INTRA-AGGREGATE SCALES

4.1 INTRODUCTION

Water repellency (WR) is a soil property that inhibits or delays water infiltration during periods of time varying between a few seconds and days or weeks. Inhibited or delayed infiltration rates contribute to enhanced runoff flow, often increasing soil erosion risk (Doerr et al., 2000; Shakesby et al., 2000). Other important consequences are irregular soil wetting patterns, the development of preferential flow paths and accelerated leaching of nutrients (Blackwell, 2000; Leighton-Boyce et al., 2005; Ritsema and Dekker, 1994).

Although low inputs of hydrophobic organic substances and high mineralization rates lead to low degrees of WR in cropped soils, it has been reported that conservative agricultural practices (reduced or no tilling, mulching treatments, etc.) may induce the development of soil WR (Blanco-Canqui and Lal, 2009; Buczko et al., 2006; García-Moreno et al., 2013; González-Peñaloza et al., 2012). New evidences show that subcritical or slight WR are common states for many soils (Bodí et al., 2013; Buczko et al., 2006; Goebel et al., 2005; Hallett et al., 2001a; Lozano et al., 2013; Urbanek et al., 2007; Zavala et al.,2014).

Many authors have studied the impact of WR at catchment, slope or plot scales (DeBano, 2000; Doerr et al., 2000; Jordán et al., 2013). Nevertheless, comparatively few studies have been carried out at particle or aggregate scale. Some researchers have reported variations in persistence or intensity of WR among aggregates with different size. Intra-aggregate heterogeneity of physical, biological and chemical properties have been reported by Dexter (1988), Horn (1990), Horn et al. (1994) and, more recently, by Fan et al. (2013) and Urbanek et al. (2007). This heterogeneity conditions the transport of substances, microbial activity and biochemical processes, including changes in the amount, distribution and chemical properties of organic matter (Urbanek et al., 2007). Soil WR does not only have negative consequences. Some authors have reported positive relationships with, for example, aggregate stability (Mataix-Solera and Doerr, 2004) or carbon sequestration rates (Piccolo and Mbagwu, 1999).

Studies focused on the intra-aggregate distribution of OC and WR are necessary to shed light on the soil processes at a detailed scale. The objectives of this research are to study [i] the OC content and the intensity of WR in aggregates of different sizes. [ii] the intra-aggregate distribution of OC and the intensity of WR and [iii] the structural stability of soil aggregates relative to the OC content and the intensity of WR in soils under different crops (apricot, citrus and wheat) and different treatments (conventional tilling and mulching).

4.2 METHODS

4.2.1 EXPERIMENTAL DESIGN AND SOIL SAMPLING

Soil samples were collected from an experimental area in the province of Sevilla (Southern Spain). Climate is Mediterranean type, with warm dry summers and moderately wet cool winters. According to data from the nearby weather station Las Cabezas (25 masl; 37º 1' N, 5º 53' W), mean temperature is 17.6 ºC, with monthly mean temperature ranging between 9.8 (January) and 26.0 ºC (August). Annual mean rainfall is 449.4 mm, with mean monthly rainfall ranging between 0.9 (July and August) and 79.3 mm (November). Soils in the studied area are developed from calcareous sandstone, and are classified as Luvic Calcisols and Calcic Luvisols (WRB, 2006). For this study, soil plots under different crops were selected (apricot, citrus and wheat). At each case, two management types were considered: conventional tillage with moldboard plow and mulching (no-tilling and addition of wheat residues at rates varying between 5 and 8 Mg ha^{-1} year^{-1}).

At each sampling site, soil blocks (50 cm long × 50 cm wide × 10 cm deep) were carefully collected to avoid disturbance of aggregates as much as possible and transported to the laboratory. At field moist condition, undisturbed soil aggregates were separated. Individual aggregates were arranged in paper trays and air-dried during 7 days under laboratory standard conditions. After air-drying, part of each sample was separated for different analyses: [i] part of the original samples was reserved for soil chemical and physical characterization; [ii] part of the aggregates were carefully measured with a caliper and separated in different size classes (0.25-0.5, 0.5-1, 1-2, 2-5, 5-10 and 10-15 mm) for determination of WR and OC content; [iii] aggregates 10-15 mm in size were selected for obtaining aggregate layers and determination of WR and OC content; finally, [iv] aggregates about 10 mm in size were selected for assessing stability to slaking, WR and OC content.

4.2.2 SEPARATION OF AGGREGATE LAYERS

Part of coarser aggregates were selected for obtaining aggregate layers. Aggregate layers were separated using the soil aggregate erosion abrasion chamber described by Park and Smucker (2005), shown in Figure 4-A. For this purpose, single air-dried aggregates (10-15 mm) were placed in the abrasion chamber and rotated in a rotary shaker at 400 rpm. The eroded material fell through a 340 μm sieve and was collected in a retainer base chamber. During each experiment, the eroded material

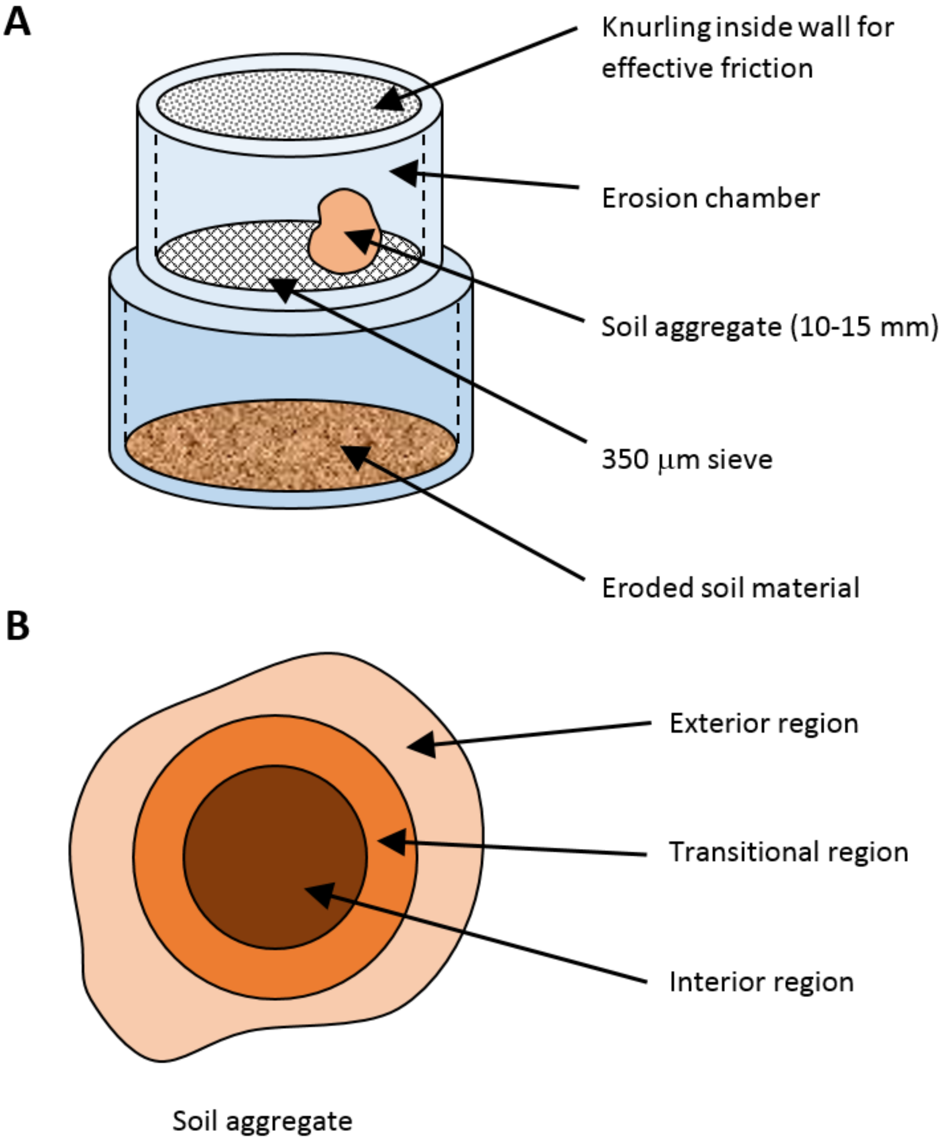


Figure 4. (A) Diagram of the soil aggregate erosion chamber system (re-drawn from Park and Smucker, 2005). (B) Layers obtained by abrasion of soil aggregates.

was weighted periodically to obtain the exterior and transitional layers. Eroded material corresponding to these layers (Figure1-B) was collected when the percentage of eroded mass reached 33.3 ± 2 and 66.7 ± 2%, respectively (Park and Smucker, 2005).

4.2.3 SOIL ANALYSES

Part of air-dried soil samples were sieved (2 mm) to eliminate coarse soil particles and homogenized. Soil OC (OC) content was determined by the modified Walkley-Black method (USDA, 2004). Soil acidity (pH) was measured in aqueous soil extracted in de-ionised water (1:2.5 soil:water). Total nitrogen was measured by the Regular Macro-Kjeldahl method and C/N ratio was calculated.

For texture analysis, air-dried soil subsamples were pre-treated with H_2O_2 (6%) to remove organic matter and soluble salts, dried in the oven to obtain the initial weight, dispersed with a sodium hexametaphosphate solution, and mechanically shaken. The sand fraction (0.05-2 mm) was removed from the suspension by wet sieving and then fractionated by dry sieving; the fine silt (0.002-0.02 mm) and clay (<0.002 mm) fractions were determined by the pipet method (USDA, 2004). Coarse silt (0.02-0.05 mm) was calculated as the difference between 100% and the sum of the sand, clay, and fine silt percentages.

The intensity of WR was assessed using the ethanol percentage test (EPT). Drops (0.5 μL) of decreasing ethanol concentrations (increasing surface tensions) were applied onto the soil surface with a micro-pipet until one of the drops balled out in the first 5 seconds after application. This allows the classification of the soil into a surface tension category between two ethanol concentrations. EPT classes were classified as in Doerr (1998): [1] very wettable (0.0 % ethanol), [2] wettable (3.0%), [3] slightly water repellent (5.0%), [4] moderately water repellent (8.5%), [5] strongly water repellent (13.0%), [6] very strongly water repellent (24.0%) and [7] extremely water repellent (36.0%).

In order to study the relation between stability to slaking, WR and OC, 90 air-dried aggregates (about 10 mm in size) selected per treatment (mulched or conventional tillage) and crop (apricot, citrus and wheat). Every set of aggregates was randomly divided in three groups (n = 30) for assessing stability to slaking, WR and OC, respectively. For analysing stability to slaking, selected aggregates were placed on a 1.5-mm sieve and immersed in distilled water (20 mm depth) during 5 min, and the time for 50% loss of structural integrity was recorded. If structural integrity of aggregates is maintained after 5 min, immersion was repeated 5 times and the soil

Table 6. Criteria for classification of stability to slaking (Herrick et al., 2001).

Slaking class	Criteria for each slaking class
0	50% of structural integrity is lost immediately after immersion.
1	50% of structural integrity is lost 5 s after immersion.
2	50% of structural integrity is lost 5-30 s after immersion.
3	50% of structural integrity is lost 30-300 s after immersion or <10% of soil material remains on the sieve after 5 immersion cycles.
4	10-25% of soil material remains on the sieve after 5 immersion cycles.
5	25-75% of soil material remains on the sieve after 5 immersion cycles.
6	>75% of soil material remains on the sieve after 5 immersion cycles.

material remaining on the sieve was dried and weighted. Stability to slaking was determined according to Herrick et al. (2001) (Table 6).

4.2.4 DATA ANALYSIS

The normal distribution of data was assessed using the Shapiro-Wilk test. When data fitted the normal distribution, data analysis included basic data descriptions (means and standard deviations, ANOVA). When data did not fit the normal distribution, non-parametric tests were applied (Wilcoxon test for comparison of median values, Spearman rank correlation coefficient). Differences between the intensity of WR in aggregate layers were assessed using the Kruskal-Wallis and the median Mood's test, and it was considered that significant differences existed when confirmed at least by one of these tests. All computations and graphical displays were performed using SPSS (IBM Corp., 2013).

Table 7. Characterization of studied soils in the 0-10 cm layer. SD: standard deviation.

Crop	Treatment	pH	Organic C (%)	Sand (%)	Silt (%)	Clay (%)
Apricot	Conventional tillage	7.0	1.55	7.4	69.4	23.2
Apricot	Mulch	7.1	4.60	10.2	66.7	23.1
Citrus	Conventional tillage	6.9	1.40	11.2	60.6	28.2
Citrus	Mulch	7.1	5.25	11.7	65.4	22.9
Wheat	Conventional tillage	7.2	1.35	8.7	63.7	27.6
Wheat	Mulch	7.2	4.85	8.9	68.6	22.5
Mean ± SD		7.1 ± 0.1	3.2 ± 1.9	9.7 ± 1.6	65.7 ± 3.3	24.6 ± 2.6

4.3 RESULTS

4.3.1 CHARACTERIZATION OF STUDIED SOILS

The results of soil characterization (0-10 cm) is shown in Table 7. Studied soils are neutral (pH 7.1 ± 0.1, on average), with OC content varying between 1.35 and 1.55% (conventional tillage) and 4.60 and 5.25 (mulched soils). Soil texture varied between silt loam and silty clay loam, with average sand and clay contents 9.7 ± 1.6 and 24.6 ± 2.6%, respectively.

4.3.2 ORGANIC C CONTENT AND WATER REPELLENCY IN AGGREGATE SIZE FRACTIONS

Soil OC content from aggregate size fractions showed significant differences according to crop, treatment and size (Table 8). On average, OC content varied between 1.50 ± 0.88 (wheat) and 2.00 ± 0.93% (apricot). Mulching increased OC content from 1.00 ± 0.35 (conventional tillage) to 2.49 ± 0.57% (mulched soils). OC content varied with size, with maximum value between 1.91 ± 0.90 and 2.20 ± 1.105 (size fractions 0.5-1 and 0.25-0.5 mm, respectively).

Figure 5 shows the distribution of OC content from soils under different crop and treatment per size fractions. The distribution of OC content from different crops under conventional tillage did not show any particular behaviour, with values ranging between 0.62 ± 0.25 (wheat, 5-10 mm) and 1.41 ± 0.23% (apricot, 0.25-0.5 mm), on average. In contrast, OC content decreased whit increasing size in mulched soils under all crops. In this case, OC content varied between 2.44 ± 0.11 (5-10 mm)

Table 8. Results of the ANOVA for organic C content by factors crop, treatment and size fraction. At each group, mean values followed by the same letter did not show significant differences.

Factor	Group	N	Mean ± standard deviation	ANOVA, p-value
Crop	Apricot	60	2.00 ± 0.93 b	0.0062
	Citrus	60	1.74 ± 0.89 ab	
	Wheat	60	1.50 ± 0.88 a	
Treatment	Conventional tillage	90	1.00 ± 0.35	0.0000
	Mulch	90	2.49 ± 0.57	
Size fraction	0.25-0.5 mm	30	2.20 ± 1.10 b	0.0159
	0.5-1 mm	30	1.91 ± 0.90 ab	
	1-2 mm	30	1.66 ± 0.77 a	
	10-15 mm	30	1.42 ± 0.72 a	
	2-5 mm	30	1.69 ± 0.86 a	
	5-10 mm	30	1.49 ±0.76 a	

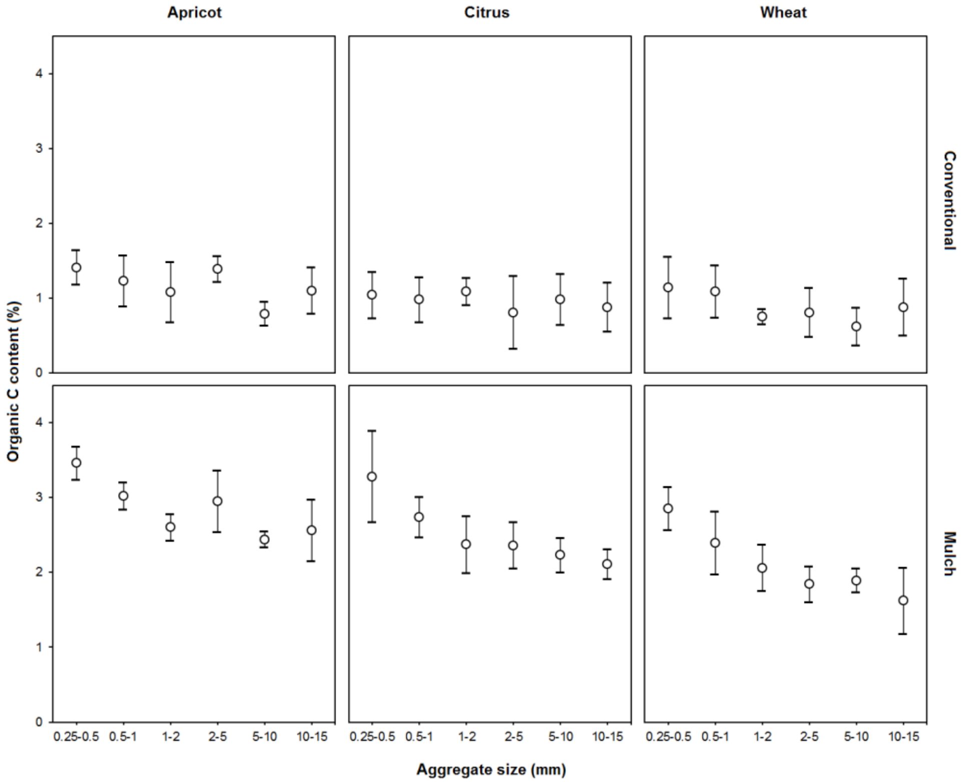


Figure 5. Mean OC content from each size fraction for soils under each crop (columns) and treatment (rows). Vertical bars show ± standard deviation.

and 3.46 ± 0.22% (0.25-0.5 mm) under apricot, 2.11 ± 0.2 (10-15 mm) and 3.28 ± 0.61% (0.25-0.5 mm) under citrus and 1.62 ± 0.44 (10-15 mm) and 2.85 ± 0.29 % (0.25-0.5 mm) under wheat.

The intensity of WR did not show significant differences among crops, but varied significantly per treatment and size fraction (Table 9). Figure 6 shows the distribution of EPT values from soils under different crop and treatment per size fractions. The intensity of soil WR decreased with increasing size under all crops and treatments. Median EPT values generally varied between 2 (fractions between 2 and 15 mm) and 3 (fractions between 0.25 and 2 mm), shifting from slightly water repellent to wettable between size fractions 1-2 and 2-5 mm. In contrast, median EPT values from mulched soils under wheat were 2 (10-15 mm), 4 (1-2, 2-5 and 5-12) and 5 (0.25-0.5 and 0.5-1 mm).

4.3.3 INTRA-AGGREGATE DISTRIBUTION OF ORGANIC C

The distribution of OC content from aggregate layers varied with soil treatment. Table 10 shows the results of the ANOVA for OC content of soil samples from each crop and treatment for different aggregate layers. On average, OC content in aggregate layers from conventionally tilled soils varied between 0.34 ± 0.13 (interior layer of aggregates from conventionally tilled soils under citrus) and 2.97 ± 0.52% (transitional layer of aggregates from mulched soils under apricot). In aggregates from soils under conventional tillage, the distribution of OC content decreased strongly between the exterior and interior layers. In citrus cropped conventionally tilled soils, for example, OC content decreased by 30.10%. In contrast, mulched soils did not show intra-aggregate variations, with average OC contents of 2.93 ± 0.50 (apricot), 2.75 ± 0.69 (citrus) and 2.27 ± 0.61% (wheat).

4.3.4 INTRA-AGGREGATE DISTRIBUTION OF WATER REPELLENCY

In general, the intensity of soil WR from aggregate layers of soil samples under different crops and treatments varied between EPT = 1 (very wettable) and 4 (moderately water repellent). The range of EPT values was 1-3 (median 2-2.5) in conventionally tilled soils) and 1-4 (median 2-3) in mulched soils. Table 11 shows the results of the Kruskal-Wallis and Mood’s median tests. Results show that significant differences among EPT median values from different layers were found only in aggregates from conventionally tilled soils under wheat and mulched soils under apricot. In the first case, median EPT varied between 2 (interior and transitional layers) and 2.5 (exterior layer). Although this difference is considered

Table 9. Results of the Kruskal-Wallis analysis of EPT data by factors crop, treatment and size fraction.

Factor	Group	N	Median	Minimum	Maximum	Kruskal-Wallis, p-value
Crop	Apricot	60	3	2	4	> 0.05
	Citrus	60	3	2	4	
	Wheat	60	3	2	5	
Treatment	Conventional tillage	90	2	1	3	0.0000
	Mulch	90	4	2	5	
Size fraction	0.25-0.5 mm	30	3.5	3	5	0.0000
	0.5-1 mm	30	3.5	3	5	
	1-2 mm	30	3	2	5	
	10-15 mm	30	2	1	3	
	2-5 mm	30	2.5	2	4	
	5-10 mm	30	2.5	2	4	

Table 10. Results of the ANOVA for organic C content (OC%, mean ± standard deviation) of soil samples from each crop and treatment for different aggregate layers. Mean values followed by different letters showed significant differences for the same use and treatment. N=30 for each case.

Crop	Treatment	Layer	OC%	ANOVA, p-value
Apricot	Conventional tillage	Exterior	1.25 ± 0.38 c	< 0.0001
		Transitional	0.94 ± 0.29 b	
		Interior	0.59 ± 0.20 a	
	Mulch	Exterior	2.93 ± 0.49 a	> 0.05
		Transitional	2.97 ± 0.52 a	
		Interior	2.88 ± 0.50 a	
Citrus	Conventional tillage	Exterior	1.03 ± 0.35 c	< 0.0001
		Transitional	0.79 ± 0.29 b	
		Interior	0.34 ± 0.13 a	
	Mulch	Exterior	2.77 ± 0.66 a	> 0.05
		Transitional	2.73 ± 0.72 a	
		Interior	2.76 ± 0.73 a	
Wheat	Conventional tillage	Exterior	0.96 ± 0.38 c	< 0.0001
		Transitional	0.71 ± 0.28 b	
		Interior	0.43 ± 0.19 a	
	Mulch	Exterior	2.28 ± 0.54 a	> 0.05
		Transitional	2.24 ± 0.60 a	
		Interior	2.28 ± 0.71 a	

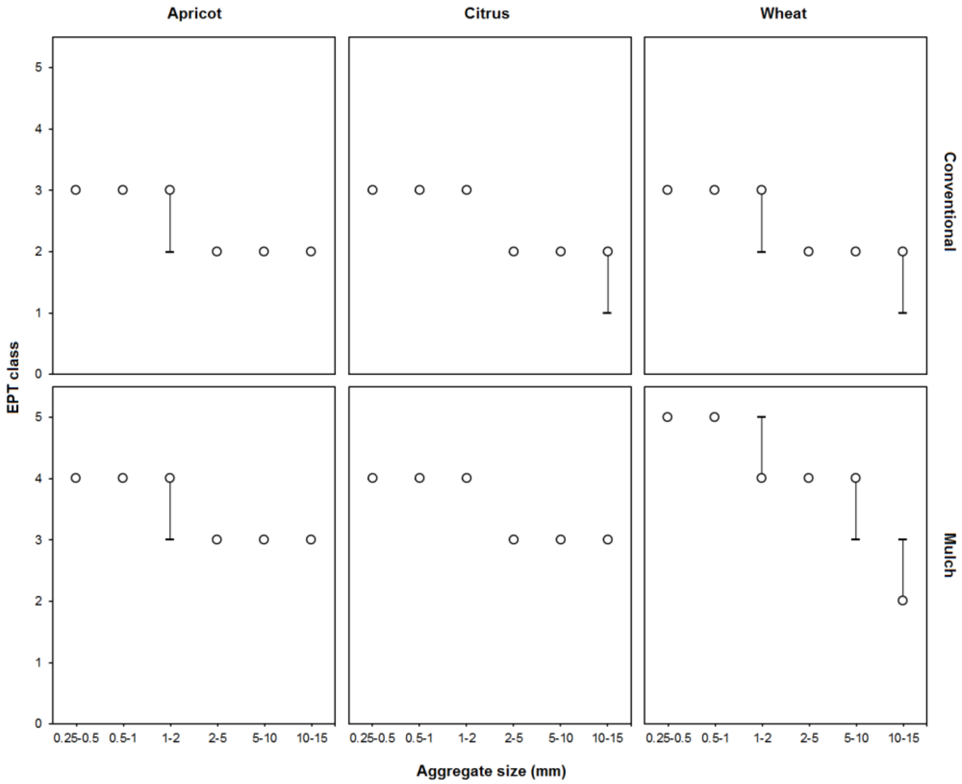


Figure 6. Intensity of WR (median EPT class) from each size fraction for soils under each crop (columns) and treatment (rows). Vertical bars show the range of variation.

significant, it only implies a jump between wettable and wettable to slightly water-repellent classes and has not any hydrological meaning.

4.3.5 SLAKING STABILITY AND RELATION WITH WATER REPELLENCY AND ORGANIC C CONTENT

Median values of stability to slaking determined in aggregates (~10 mm) from soil samples under different crops and treatments are shown in Table 12. Stability to slaking varied between crops and treatments. Median slaking values varied

Table 11. Results of the Kruskal-Wallis (KW, p) and Mood's median test (Median test, p) for intensity of soil WR (EPT) of soil samples from each crop and treatment for different aggregate layers (1: exterior; 2: transitional; 3: interior). N = 30 for each case.

Crop	Treatment	Layer	EPT	EPT range	KW, p	Median test, p
Apricot	Conventional tillage	Exterior	2	(1, 3)	> 0.05	> 0.05
		Transitional	2	(1, 3)		
		Interior	2	(1, 3)		
	Mulch	Exterior	2	(1, 4)	0.0095	> 0.05
		Transitional	3	(1, 4)		
		Interior	3	(2, 4)		
Citrus	Conventional tillage	Exterior	2	(1, 3)	> 0.05	> 0.05
		Transitional	2	(1, 3)		
		Interior	2	(1, 3)		
	Mulch	Exterior	2.5	(1, 4)	> 0.05	> 0.05
		Transitional	3	(1, 4)		
		Interior	3	(2, 4)		
Wheat	Conventional tillage	Exterior	2.5	(1, 3)	0.0410	0.0100
		Transitional	2	(1, 3)		
		Interior	2	(1, 3)		
	Mulch	Exterior	3	(1, 4)	> 0.05	> 0.05
		Transitional	2	(1, 4)		
		Interior	3	(2, 4)		

Table 12. Median vales and ranges (between parentheses) of slaking classes determined in aggregates from soil samples under each crop and treatment. Differences between medians from aggregates under different treatments were significant for all crops (Wilcoxon p-value = 0.0000).

Crop	Treatment	N	Slaking
Apricot	Conventional tillage	30	3 (2, 4)
	Mulch	30	4 (3, 6)
Citrus	Conventional tillage	30	3 (2, 4)
	Mulch	30	4 (4, 6)
Wheat	Conventional tillage	30	4 (3, 5)
	Mulch	30	5 (4, 6)
All cases		180	4 (2, 6)

between 3 (apricot and citrus) and 4 (wheat) in conventionally tilled soils and between 4 (apricot and citrus) and 5 (wheat) in mulched soils. In all cases, stability to slaking in mulched soils was 1 unit greater than in conventionally tilled soils.

Table 13. R-Spearman coefficients for slaking/EPT, slaking/OC and EPT/OC. N is 180 (all cases) and 30 (groups). (*) P-value ≤ 0.0.5.

Crop	Treatment	Slaking/EPT	Slaking/OC	EPT/OC
Apricot	Conventional tillage	0.7111 *	0.0913	0.2272
	Mulch	0.9387 *	0.2526	0.1908
Citrus	Conventional tillage	0.8686 *	-0.0901	-0.0117
	Mulch	0.9949 *	0.0558	0.0456
Wheat	Conventional tillage	0.0089	0.2142	-0.1995
	Mulch	0.9919 *	-0.0323	-0.0320
All cases		0.8699 *	0.5245 *	0.4317 *

Table 13 shows the R-Spearman coefficients for slaking/EPT, slaking/OC content and EPT/OC content. When all cases are considered together, stability to slaking was significantly correlated with EPT (R-Spearman = 0.8699). Significant positive correlations were found between stability to slaking and EPT in all cases, except for aggregates under wheat and conventional tillage. No significant correlations were found between stability to slaking and OC content or WR and OC content in aggregates under different crops and treatments, except when all cases were considered together (0.5245 and 0.4317, respectively).

4.4 DISCUSSION

4.4.1 DISTRIBUTION OF ORGANIC C BY AGGREGATE SIZE

Although soil OC content in the fine earth (< 2 mm) did not vary among crops, no-tilling and mulching treatments contributed to increase it largely (approximately by 3.4, on average) versus conventional tilling, as shown by previous research (Jordán et al., 2010). In contrast, the OC content of size fractions varied significantly among soils under apricot, citrus and wheat crops, independently of other factors. Generally, OC content was higher in the finer aggregates (0.25-0.5 and 0.5-1 mm), what is in agreement with previous research (Bisdom et al., 1993; Covaleda et al., 2011). Urbanek et al. (2007) observed that aggregates released by fragmenting following the plane of weakness show higher organic matter content with decreasing aggregate size. They explained this partly because of sampling disturbance. In our experiment, undisturbed soil aggregates were carefully handled and selected by size individually, not sieved in order to avoid disturbance as much as possible. Although the C content generally decreased with increasing aggregate size, this trend was much more intense in mulched soils. This is in contrast with results reported by Urbanek et al. (2007), who found that OC did not increased with decreasing aggregate size under conservation tillage. They observed that differences in treatment of samples may be the cause of different results, as a large amount of OC weakly associated to macroaggregates may be easily removed during mechanical disturbance (Urbanek et al., 2007). In addition, low organic matter inputs and high mineralization rates in conventionally tilled soils may lead to low OC concentrations independently of the size of aggregates and negligible differences.

4.4.2 DISTRIBUTION OF ORGANIC C BY AGGREGATE REGION

The intra-aggregate distribution of OC varied in conventionally tilled soils, decreasing from the exterior to the interior layer. Contradictory results have been reported in previous research. Amelung and Zech (1996), Fan et al. (2013), Santos et al. (1997) and Urbanek et al. (2007) did not found gradients in the distribution of OC among the exterior and the interior regions of aggregates, but other authors have found conflicting results. Park and Smucker (2005), for example, found significant differences between the exterior and interior regions of aggregates from conventionally tilled silt loam soils, but not in other similar cases they studied. Ellerbrock and Gerke (2004) observed that, in arable soils, organic matter content in the exterior layer of aggregates was greater than in the interior with differences increasing with depth. Although bacteria and fungi cannot penetrate the interior layers of aggregates, leading to retarded mineralization of organic substances (Jasinska et al., 2006) in this region, Amelung and Zech (1996) suggested that continuous tillage contributes to losses of OC physically protected in the interior of aggregates and that preferential loss from aggregate surfaces is caused generally by accelerated decay. Our results suggest that higher OC concentration in the exterior layer of aggregates may be due to recent residue inputs or leachates from the surface and high mineralization rates in cultivated soils should help to make differences decrease in the medium- or long- term. This is in agreement with Ellerbrock and Gerke (2004) who described that new organic inputs are incorporated preferably in the exterior layer.

Our results also show that the intra-aggregate distribution of OC from mulched does not vary significantly. In native soils, where organic matter inputs are generally higher, researchers have reported increased OC concentration in the interior layer of forest soils (Fan et al., 2013; Jasinska et al., 2006) or homogenous OC concentrations in different regions of aggregates from forest soils (Park and Smucker, 2005) and prairie soils (Amelung and Zech, 1996). These results are similar to those observed in no-tilled soils by Park and Smucker (2005). Our findings suggest that higher inputs of organic residues result in higher OC content but not always in a heterogeneous intra-aggregate distribution.

4.4.3 RELATION BETWEEN WATER REPELLENCY AND TREATMENT

The intensity of WR did not vary significantly among size fractions of soils under apricot, citrus and wheat crops, independently of other factors. Although variation of soil WR has been reported in soils under natural vegetation (Jordán et al., 2008; Jordán et al., 2009; Martínez-Zavala and Jordán-López, 2009; Mataix-Solera et al., 2007; Schnabel et al., 2013; Zavala et al., 2014), the occurrence of WR is not common in tilled soils (Doerr et al., 2006; Woche et al., 2005). Our findings show that the intensity of soil WR increased from conventionally tilled to untilled mulched soil. This is in agreement with previous research, which has shown that conservative practices contribute to enhanced WR in cultivated soils (Blanco-Canqui and Lal, 2009; García-Moreno et al., 2013; González-Peñaloza et al., 2012; Simon et al., 2009).

4.4.4 DISTRIBUTION OF WATER REPELLENCY BY AGGREGATE SIZE

Higher OC concentration in finer aggregates conditioned the distribution of WR. This is in agreement with previous research in forest soils (Doerr et al., 1996; Jordán et al., 2011b; Jordán et al., 2014; Mataix-Solera and Doerr, 2004; Mataix-Solera et al., 2014). In conventionally tilled soils, where differences in OC content among aggregates with different size where small, the intensity of WR only increased from wettable (coarser aggregates) to slight (finer aggregates). In contrast, it varied between moderate/strong (finer aggregates) and slight/wettable (coarser aggregates) in mulched soils. Greater differences observed in aggregates with different size from mulched soils are in agreement with differences in the distribution of OC.

4.4.5 DISTRIBUTION OF WATER REPELLENCY BY AGGREGATE REGION

Although many authors have found correlations between OC content and persistence or intensity of WR in soils (Mataix-Solera and Doerr, 2004; Mataix-Solera et al., 2014), small or non-significant differences were observed in the intensity of WR from aggregate regions. According to Bisdom et al. (1993), WR is closely related with organic matter content. They observed that organic hydrophobic structures causing WR are relatively intact plant residues (remnants of roots, leaves and stems) and transformed organic matter coating mineral particles and aggregates or present in the soil matrix as interstitial materials. Significant differences were only found in mulched soils under citrus and conventionally tilled soils under apricot. Nevertheless, in both cases, these differences did not mean a qualitative jump between classes of WR (which were only from wettable to slightly water-repellent at best). Consequently, it can be assumed that mulching increased soil WR, but did not condition the distribution of hydrophobicity at the intra-aggregate level. In contrast to Urbanek et al. (2007), in our case, differences in chemical characteristics of organic matter, if existing, are not responsible of the intra-aggregate distribution of WR.

4.4.6 SLAKING STABILITY

Soil WR enhances aggregate stability to slaking. In contact with water, air bubbles entrapped in soil pores and differential swelling may cause tensions and destruction of aggregates (Chan and Mullins, 1994). Consequently, retarded wetting caused by WR may enhance aggregate stability to slaking. High positive significant correlations were observed between slaking stability and the intensity of WR in most cases. In contrast, poor (only when all cases were computed together) or non-significant correlations were found between slaking stability and OC. Although soil WR was generally correlated with slaking stability (only conventionally tilled soils under wheat showed no correlation), greater Spearman's correlation coefficients were observed in mulched soils. The intensity of WR seems to be the main responsible of slaking stability, as differences in OC content between conventionally tilled (1.35-1.55%) and mulched soils (4.60-5.25%) cannot explain differences in slaking. This is in agreement with previous results reported by different authors (Benito et al., 2003; Chenu et al., 2000; Granged et al., 2011b; Hallett et al., 2001b; Piccolo and Mbagwu, 1999; Zavala et al., 2010). According to Mataix-Solera et al. (2011), a direct consequence of retarded water entry in water-repellent aggregates is the enhanced aggregate stability, as the energy release rate and build-up of air pressure in pores is reduced.

4.4.7 GENERAL IMPLICATIONS OF RESULTS

Evidence of more intense WR on the surface of smaller aggregates is in contrast with the results observed by Peng et al. (2003), who found a trend of increased repellency with increasing aggregate size in severely degraded soils, apparently due to the eluviation of organic compounds and greater microbial activity in macropores. Our results show an opposite trend in agricultural soils, with more intense WR in finer aggregates (mostly below 2 mm), and this trend is even more pronounced in mulched soils, with higher organic matter inputs. This is in agreement with increased organic matter concentration in finer aggregates, as observed in conventinally tilled and mulched soils. Hydrophobic microbial exudates are produced mainly in the surface of macroaggregates in contact with macopores. Consequently, it may be suggested that hydrophobic compounds are leached from coarser to finer aggregates, where biological activity is reduced. In contrast to soils where WR concentrates in the surface of macroaggregates and water infiltration is more efficient, more intense WR in the surface of finer aggregates may limit infiltration rates. Inhibited infiltration caused by water-repellent fine aggregates may contribute to increased runoff rates, what has been previously observed at high organic matter input rates (González-Peñaloza et al., 2012; Jordán et al., 2010). Consequently, more research is required to determine the effect of WR incudec by low or moderate mulching rates in runoff generation, water dynamics and possible implications for nutrient transport or water retention in the root zone.

Our results show that subcritical to moderate WR and increased OC concentration contribute to stability of aggregates in mulched soils. On one hand, WR contributes to decreased slaking stress by reducing the energy release rate caused by entrapped air bubbles during wetting, and, on the other hand, organic substances increase bonding strength between mineral soil particles. Several authors (Czarnes et al., 2000; Hallet et al., 2001a; Mataix-Solera and Doerr, 2004; Mataix-Solera et al., 2011; Piccolo and Mbagwu, 1999) have highlighted the combined role of organic cementing substances and hydrophobic compounds in increasing the stability of soil aggregates. This is especially relevant for agricultural soils, as increased aggregate stability leads to infiltration through macropores, so reducing erosion risk and surface sealing, as shown by Peng et al. (2003).

5 MULCH APPLICATION IN FRUIT ORCHARDS INCREASES THE PERSISTENCE OF SOIL WATER REPELLENCY DURING A 15-YEARS PERIOD

5.1 INTRODUCTION

Water repellency is a property of soils that reduces the infiltration of water into the soil (Doerr et al., 2000). Delayed water infiltration has important hydrological and geomorphologic consequences (Doerr et al., 2000). Soil water repellency (SWR) may be linked to soil microorganisms, vegetation, soil organic matter (OM) content and composition, soil water content, wildfires, and other soil characteristics as acidity, texture, structure, clay mineralogy and others (Doerr et al., 2000). According to Blanco-Canqui (2011) this property is increasingly being recognized as an influential soil attribute under different scenarios of land use and management. Although SWR has been reported and studied by many researchers worldwide (DeBano, 2000a; Doerr et al., 2000), agricultural soils are usually considered wettable (Wallis and Horne, 1992). In contrast to this general statement, many studies have found that soil management practices can induce water repellency in cultivated soils (Blanco-Canqui, 2011; Blanco-Canqui and Lal, 2009).

Many plant species from non-cropped soils have been strongly associated with SWR, as perennial trees with a significant concentration of resins, waxes or aromatic oils, as eucalyptus, pines and other vegetation types (Mataix-Solera and Doerr, 2004; Hubbert et al., 2006; Lewis et al., 2006; Granged et al., 2011c; Jordán et al., 2010; Zavala et al., 2009b). In contrast, there are a short number of studies about the occurrence and impacts of water repellency in cultivated soils (Blanco-Canqui; 2011). Negative and positive impacts of water repellency on soil and crop production have been reviewed by Blanco-Canqui (2011), who cited negative impacts including increased runoff and soil erosion (Doerr et al., 2000; Shakesby et al., 2000), preferential flow, lateral flow or interflow, reduced water infiltration (Witter, et al., 1991), reduced nutrient availability and yields (Abadi Ghadim, 2000; Harper et al., 2000; McKissock et al., 1998), and accelerated leaching of agrochemicals (Ritsema et al., 1997; Dekker and Ritsema, 2000; Täumer et al., 2006). In case of slight SWR, positive impacts include reduced soil erodibility, crusting (Terry and Shakesby, 1993; Shakesby et al., 2000), improved decomposition rates of organic matter, improved structure (Eynard et al., 2004; Mataix-Solera and Doerr, 2004; Eynard et al., 2004; Arcenegui et al., 2008; Mataix-Solera et al., 2011), and carbon sequestration (Bachmann et al., 2008; Blanco-Canqui and Lal, 2009).

Soil management practices in cropped areas may influence the occurrence and distribution of SWR (Wallach et al. 2005; Urbanek et al., 2007). In particular, the impact of no-till and mulching practices on SWR has not been well studied. Increased SWR in no-tilled soils has been observed, for example, by Blanco-Canqui and Lal (2009), Blanco-Canqui et al. (2009), Chan (1992), González-Peñaloza et al. (2012), Hallet et al. (2001a), Pikul et al. (2009), Simon et al. (2009) and Roper et al. (2013). In contrast, other authors have reported limited or no influence of no-till practices in SWR (Eynard et al., 2004). Blanco-Canqui and Lal (2009) reported SWR as a common phenomenon in soils after long-term conservative practices. Both Blanco-Canqui and Lal (2009) and González-Peñaloza et al. (2012) have highlighted the significance of different degrees of subcritical SWR to the hydrological response of cultivated soils under conservative practices.

To what extent conservative practices as mulching and no tilling impact soil hydrological processes? What is the impact after medium- or long-term conservative management? These are important questions that need to be assessed. Conventional tillage is considered to trigger erosion risk in sloping Mediterranean soils. In contrast, management practices, as addition of crop or plant residues and reduced or no tillage, are considered strategies for reducing soil erosion risk in sensible areas. But the impact of SWR has been only recently studied in crop soils under conservative practices (Blanco-Canqui, 2011; Blanco-Canqui and Lal, 2009). The study of the impacts of even subcritical water repellency from soils under conservative types of management has been proposed recently to fill a gap in current research. Intensive research on SWR in no-till mulched soils after a significant period of time is necessary to study the impacts of conservative farming in SWR. The objectives of this research are 1) to study the development of SWR in mulched no-tilled soils from southern Spain during a period of 15 years, 2) to study the relationship between SWR and soil organic matter (OM) content and 3) to study the impact of SWR on the hydrological response of mulched no-tilled soils.

5.2 MATERIAL AND METHODS

5.2.1 STUDY AREA AND EXPERIMENTAL DESIGN

Experimental work was carried out in calcareous soils from the province of Sevilla (southern Spain; Figure 7). Soils included in this study are developed from calcareous sandstone, and are classified as Luvic Calcisols and Calcic Luvisols (WRB, 2006). Climate is Mediterranean type, with warm dry summers and moderately wet cool winters. According to data from the nearby weather station Las Cabezas (25 masl; 37° 1’ N, 5° 53’ W), mean temperature is 17.6 °C, with monthly mean temperature ranging between 9.8 (January) and 26.0 °C (August). Annual mean rainfall 449.4 mm, with mean monthly rainfall ranging between 0.9 (July and August) and 79.3 mm (November).

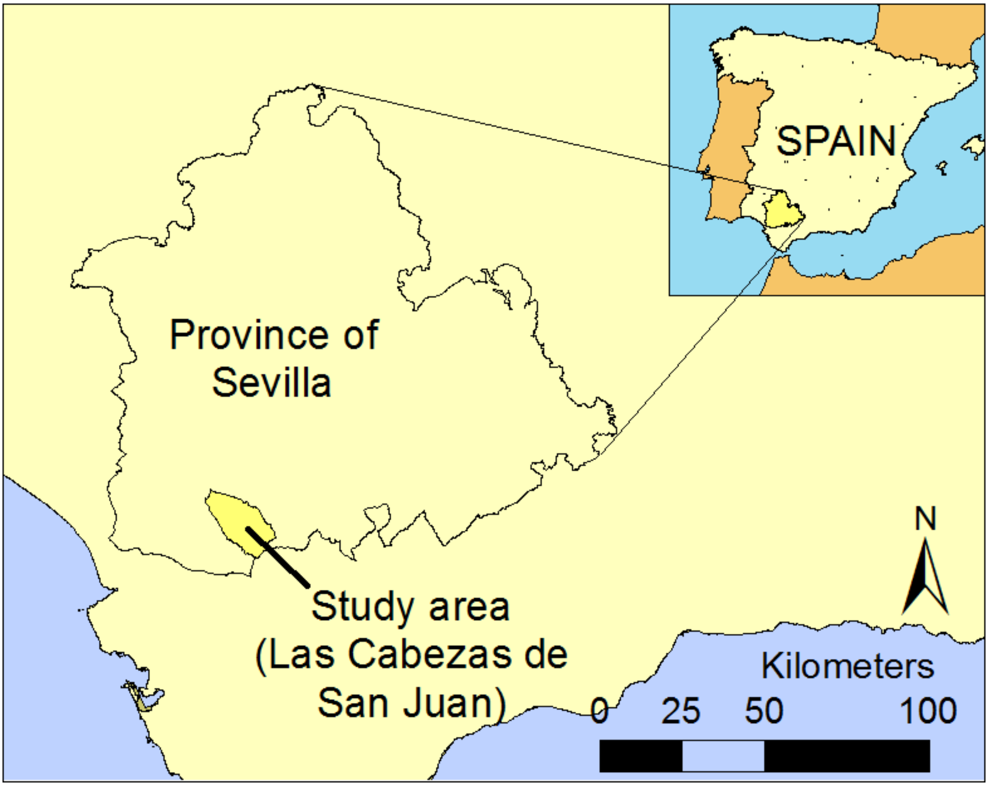


Figure 7. Study area.

For this research, soils from fruit orchards (peach, *Prunus persica* and *P. persica* var. *nectarina* and apricot, *P. armeniaca*) were selected under different management types: conventional tillage (CT), no-tilling and low mulching rate (1-4 Mg ha^{-1} year^{-1} wheat straw residues on untilled soil; MR1), no-tilling and moderate mulching rate (5-8 Mg ha^{-1} year^{-1}; MR2), and no-tilling and high mulching rate (9-12 Mg ha^{-1} year^{-1}; MR3). Periods under each type of management ranged from 1 to 15 years. At each area under the same type of management and time of treatment, four experimental plots (2 × 2 m^2) randomly distributed in inter-rill areas with slope 8-12% were selected. The total number of plots was 240 (4 types of management × 15 periods of treatment × 4 plots). Herbicides (glyphosate) were eventually applied in order to control weeds.

5.2.2 SOIL SAMPLING AND ANALYSIS

For OM content analysis, four soil samples (0-1 cm) were collected at the vertices of each 2 × 2 m^2 experimental plot and transported in plastic bags to the laboratory for soil analysis. Soil samples were dried at laboratory room temperature (25 ^{o}C) to a constant weight and sieved (2 mm) to eliminate coarse soil particles. Soil OM content was determined by the Walkley-Black method (Walkley and Black, 1934). The average content of the four samples was considered as representative for each plot.

Soil water repellency determinations and rainfall simulations were carried out *in situ* under field conditions by 25 July - 28 August 2012 after a period of at least 30 days without rainfall. Persistence of SWR was analysed by the water drop penetration time (WDPT) test (Wessel, 1988). At each case, 5 drops of distilled water were placed on the soil surface and time for complete infiltration was recorded. The average time considered representative for each case. When present, plant residues were gently brushed off or removed by hand. Water drops were applied with an automatic micropipette onto the surface of each sample from a height of approximately 5 mm to avoid excess kinetic energy affecting sand-droplet interaction (Doerr, 1998). According to Bisdom et al. (1993), soil plots were classified as wettable (WDPT ≤ 5 s) or slightly water repellent (5-60 s).

5.2.3 RAINFALL SIMULATION

Two from the four soil plots on each site were selected for rainfall simulation experiments (30 plots for each one of the four treatments considered, totaling 120 plots). Simulated rainfall allows controlling rainfall amount, intensity and duration, so that they are suitable, and is useful for studying soil response to storms of certain characteristics (Meyer, 1994). Data cannot be easily extrapolated, but can be used for comparative purposes. Rainfall simulations were carried out after soil sampling in the center of each experimental plot. Simulations were performed using a rainfall simulator described by Lasanta et al. (2000). The structure is supported by metal legs, covered with a wind protector and leveled when placed on a sloping surface. A nozzle (3.5 m high) is connected through a rubber pipe to a mobile automatic pump. The water from the nozzle falls onto a circular area of 1963.5 cm^2 that is rounded by a steel ring (50 cm in diameter). The ring was carefully tapped into the soil following the slope to prevent leakage and direct the runoff flow to the outlet of the plot. Before the experiments, rainfall intensity was measured by five rain gauges (10 cm in diameter) distributed uniformly over the plot. The mean rainfall intensity for the experiments was 49.1 ± 2.1 mm h^{-1} and the duration of the simulations was 60 minutes. This rainfall intensity may be considered representative in the study area, as the recurrence period for storms 50 mm h^{-1} during 60 minutes is 2 years, according to data from the nearby weather station Lebrija-5-895 (Lebrija, Sevilla; 36° 15' N, 5° 7' W).

Deionized water was used because the chemical composition of the water may influence the soil response (Agassi et al., 1994). A gutter installed on the downstream side of the plot conducted the runoff to a sample collection box. For each rainfall simulation, time to ponding (Tp), time to runoff (Tp), and runoff rate were determined. Time to ponding was recorded when 40% of the surface showed ponds on flat or concave microsurfaces. It is assumed that runoff starts when ponding exceeds a critical value. According to Cerdà (2001), ponding can be identified as a shine on the soil surface where the top few millimeters of the soil are saturated before runoff starts. All visual determinations were carried out by the same person at all plots. The volume of runoff was determined every 2 minutes for volumetric determinations.

5.2.4 DATA ANALYSIS

Data analysis included correlations, regressions and analysis of variance. Assumption of normality of data was assessed using the Kolmogorov-Smirnov test ($p \geq 0.05$). Since most variables were not normally distributed, alternative non-parametric Kruskal-Wallis test was used for analyzing significant differences among treatments. When Kruskal-Wallis null hypothesis was rejected, pos-hoc pair wise comparisons were performed to investigate differences between means (Bonferroni test). All computations were performed using Statgraphics Centurion version 16 (StatPoint Technologies, 1982-2011).

5.3 RESULTS AND DISCUSSION

5.3.1 SOIL WATER REPELLENCY UNDER DIFFERENT MULCHING RATES

Data in Table 14 clearly demonstrate the influence of different mulching rates in SWR from fruit orchards in the study area. WDPT (Table 15) varied between 0 and 1 s (CT), 1 and 7 s (MR1), 1 and 16 s (MR2) and 1 and 20 s (MR3). SWR assessment, performed after a period of at least 30 days without rainfall, were not affected by soil moisture content. Soils under CT did not show significant changes in SWR for

Table 14. Mean ± standard deviation of water drop penetration time (WDPT, s) and organic matter contents (%) for different management practices and number of years. CT: conventional tillage; MR1: 1-4 Mg ha^{-1} year^{-1} wheat straw application; MR2: 5-8 Mg ha^{-1} year^{-1}; MR3: 9-12 Mg ha^{-1} year^{-1}. N = 4 for each treatment and number of years.

	WDPT (s)				Organic matter content (%)			
Number of years	CT	MR1	MR2	MR3	CT	MR1	MR2	MR3
1	1 ± 1	1 ± 1	2 ± 1	1 ± 1	1.7 ± 0.2	2.0	1.8 ± 0.4	1.8 ± 0.2
2	0 ± 1	1 ± 1	2 ± 1	3 ± 1	1.9 ± 0.3	2.0 ± 0.3	2.0 ± 0.3	2.0 ± 0.4
3	1 ± 1	2 ± 1	3 ± 1	4 ± 1	1.7 ± 0.2	2.2 ± 0.2	2.2 ± 0.3	2.2 ± 0.5
4	1 ± 1	2 ± 1	4 ± 1	5 ± 1	1.6 ± 0.1	2.3 ± 0.3	2.4 ± 0.4	2.3 ± 0.5
5	0 ± 1	2 ± 1	5 ± 1	7 ± 1	1.6 ± 0.1	2.5 ± 0.4	2.6 ± 0.5	2.6 ± 0.5
6	1 ± 1	3 ± 1	5 ± 1	8 ± 1	1.5 ± 0.2	2.6 ± 0.5	2.9 ± 0.6	3.0 ± 0.5
7	1 ± 1	3 ± 1	6 ± 1	9 ± 1	1.6 ± 0.4	2.6 ± 0.5	3.1 ± 0.5	3.2 ± 0.7
8	1 ± 0	3 ± 1	7 ± 1	10 ± 1	1.5 ± 0.2	2.7 ± 0.6	3.4 ± 0.4	3.6 ± 1.0
9	1 ± 0	3 ± 1	7 ± 1	10 ± 1	1.5 ± 0.3	2.8 ± 0.5	3.6 ± 0.3	3.8 ± 0.9
10	1 ± 1	4 ± 1	8 ± 1	12 ± 1	1.6 ± 0.4	2.9 ± 0.5	4.0 ± 0.4	4.6 ± 1.2
11	0 ± 1	4 ± 1	9 ± 1	14 ± 2	1.6 ± 0.5	2.9 ± 0.4	4.4 ± 0.2	5.0 ± 1.2
12	0 ± 1	4 ± 1	10 ± 1	15 ± 2	1.6 ± 0.5	3.1 ± 0.5	4.7 ± 0.3	5.6 ± 1.4
13	1 ± 1	5 ± 1	11 ± 2	16 ± 2	1.4 ± 0.2	3.2 ± 0.6	5.1 ± 0.4	6.2 ± 1.4
14	1 ± 1	5 ± 2	12 ± 2	18 ± 1	1.4 ± 0.2	3.4 ± 0.7	5.7 ± 0.7	6.7 ± 1.8
15	0 ± 1	5 ± 1	13 ± 2	18 ± 2	1.5 ± 0.4	3.7 ± 0.7	6.1 ± 0.4	7.2 ± 1.7
All data	0 ± 0	3 ± 1	6 ± 3	9 ± 5	1.6 ± 0.3	2.7 ± 0.6	3.6 ± 1.4	4.0 ± 2.0

all periods of treatment, with WDPTs ranging between 0 and 1 s in all cases. On average, WDPT from mulched soils was 3 ± 1 s (MR1), 6 ± 3 s (MR2) and 9 ± 5 s (MR3). Independently of the period of time under treatment, the proportion of wettable samples was 100.0% in soils under CT, but decreased between 93.3% (MR1) and 25.0% (MR3) in mulched soils. Differences between WDPT from soils under CT and MR1 are significant, but, together, 116 from 120 soil plots were considered wettable (60 samples under CT and 56 samples under MR1). Respectively, 60 and 75% of soil plots under MR2 and MR3 were considered slightly water repellent (Table 15).

The results of the Kruskal-Wallis test (KW, p) for SWR (WDPT) from different years of treatment and mulching rates are shown in Table 15. No significant differences

Table 15. Statistical analyses of soil water repellency data (mean WDPT ± standard deviation, s) under different treatments. N: number of data; CV: coefficient of variation; KS, p: Kolmogorov-Smirnov p-value. KW, p: Kruskal-Wallis p-value. Values

Treatment	N	WDPT (s)	CV (%)	Minimum	Maximum	Range	Proportion of wettable samples (%)	KS, p	KW, p
CT	60	0 ± 0 a	97.5	0	1	1	100.0	< 0.05	> 0.05
MR1	60	3 ± 1 b	47.8	1	7	6	93.3	0.0918	0.0000
MR2	60	6 ± 3 c	51.6	1	16	15	40.0	0.5881	0.0000
MR3	60	9 ± 5 d	54.2	1	20	19	25.0	0.5575	0.0000
All treatments	240	5 ± 5	95.5	0	20	20	64.6	< 0.05	0.0000
KS, p		0.0000							

Table 16. Regression analysis of WDPT versus number of years, OM content versus number of years and WDPT versus OM content under different treatments. Non-significant regression equations are not shown.

Variables	Treatment	Intercept	Slope	r	r^2	p-value
Number of years/WDPT	MR1	0.9143	0.2732	0.8038	0.6461	0.0000
	MR2	0.6857	0.7706	0.9508	0.9040	0.0000
	MR3	0.2405	1.2116	0.9812	0.9628	0.0000
	All treatments	0.5946	0.5632	0.5004	0.2504	0.0000
Number of years/OM	MR1	1.7295	-0.0197	-0.3085	0.0952	0.0000
	MR2	1.8429	0.1078	0.7410	0.5491	0.0000
	MR3	0.8288	0.3922	0.8690	0.7552	0.0000
	All treatments	1.3954	0.1952	0.5465	0.2987	0.0000
OM/WDPT	MR1	0.0545	1.1259	0.4817	0.2320	0.0001
	MR2	-1.4464	2.3153	0.9005	0.8109	0.0000
	MR3	0.2803	2.4335	0.8895	0.7912	0.0000
	All treatments	-3.2286	2.8169	0.8938	0.7989	0.0000

were found for SWR after different periods of time under CT (with water drops infiltrating almost instantaneously). Significant differences were found for water repellency from soils under different mulching rates after different number of years. No water-repellent samples were observed in any case for mulching periods of treatment shorter than 4 years, but WDPT increased slightly with the number of years of treatment. WDPT increased progressively with time in mulched soils between 1 ± 1 and 5 ± 2 s (MR1), 2 ± 1 and 13 ± 2 s (MR2) and 1 ± 1 and 18 ± 2 s (MR3) (Table 14).

Small but significant SWR was observed in mulched soils just one or two years after beginning treatments, reaching subcritical SWR (Blanco-Canqui and Lal, 2009; González-Peñaloza et al., 2012). On average, WDPT reached the 5 s threshold after 13 years (MR1), 5 years (MR2) or 4 years (MR3).

Regressions between WDPT and number of years under different treatments are shown in Table 16. No significant regression was observed for WDPT and number of years under CT. The correlation coefficient is moderately strong for MR1 treatment (r = 0.8038) and strong for MR2 and MR3 (r = 0.9508 and 0.9812, respectively). The slope of regression equations increases progressively from MR1 (0.2732) to MR3 (1.2116), showing that persistence of SWR increases with time at different speed depending on mulching rate, as shown in Table 14.

Soil water repellency has been found to be present in many types of vegetated areas, but it is less common in tilled soils (Doerr et al., 2006; Woche et al., 2005). In contrast, conservative practices as mulching or no tilling have been found to enhance SWR. Enhanced SWR has been reported by Simon et al. (2009) in mulched soils compared with conventionally tilled soils after 6-16 years. Several authors have found similar impacts in SWR after the addition of plant residues and organic manure to soils (Blanco-Canqui et al., 2007; Blanco-Canqui and Lal, 2009; González-Peñaloza et al., 2012). Blanco-Canqui and Lal (2009) suggested that microbial activity in soils with annual application of organic matter and animal manure may induce or improve SWR.

Subcritical SWR has been observed under different mulching rates during the first years of treatment (MR2 and MR3) and through all experimental period (MR1). Subcritical SWR has been reported by Eynard et al. (2004) in no-tilled soils under laboratory conditions and González-Peñaloza et al. (2012), who have suggested that small differences between SWR from cropped soils under conservative practices may be important for surface runoff generation at plot or farm scale, as well as for soil aggregate stability or for the development of preferential flow paths

Table 17. Statistical analyses of organic matter content (mean OM ± standard deviation, %) under different treatments. N: number of data; CV: coefficient of variation; KS, p: Kolmogorov-Smirnov p-value. KW, p: Kruskal-Wallis p-value. Values followed by the same letter within the same column do not show significant differences.

Treatment	N	OM (%)	CV (%)	Range	Range	KS, p	KW, p
CT	60	1.6 ± 0.3 a	17.7	1.2-2.2	1	< 0.05	> 0.05
MR1	60	2.7 ± 0.6 b	23.4	1.84.6	2.8	0.4016	0.0007
MR2	60	3.6 ± 1.4 c	38.3	1.5-6.6	5.1	0.5660	0.0000
MR3	60	4.0 ± 2.0 c	49.6	1.6-9.4	7.8	0.2108	0.0000
All treatments	240	3 ± 1.5	52.3	1.2-9.4	8.2	< 0.05	0.0000
KS, p		0.0000					

in studied soils. This is in agreement with Blanco-Canqui (2011), who suggested that small delays in aggregate wetting may cause great changes in the soil hydrological response. According to a recent review by Blanco-Canqui (2011), slight water repellency improves soil aggregation, soil water distribution, nutrient storage, carbon sequestration and stabilizes the pore system; also, it reduces soil erodibility, aggregate slaking, crusting and rapid decomposition of organic materials.

5.3.2 SOIL WATER REPELLENCY AND SOIL ORGANIC MATTER CONTENT

Soil OM content for different treatments and years is shown in Table 14. Organic matter content from CT soils did not show significant variations between years (1.6 ± 0.3%, on average). In contrast, mulch application increased OM content from 2.0 ± 0.2 to 3.7 ± 0.7% (MR1), 1.8 ± 0.4 to 6.1% (MR2) and 1.8 ± 0.2 to 7.2 ± 1.7% (MR3). The results of the KW test for OM content after different years of treatment and different mulching rates are shown in Table 17.

Slight water repellency observed in mulched soils at the end of treatments may be attributed to the input of hydrophobic organic matter as a consequence of the addition of plant residues (Blanco-Canqui et al., 2007). As shown in Table 17, no significant temporal changes are observed in OM content from soils under CT, but significant changes are observed in OM content from mulched soils at MR1 (p = 0.0007), MR2 and MR3 (p = 0.0000).

Absence of changes in water repellency from not amended soils under CT is explained by the reduced organic matter inputs and high mineralization rates, as shown by previous research. González-Peñaloza et al. (2012) did not found changes in wettability from citrus-cropped soils in eastern Spain. In agricultural soils from the central Great Plains (USA), Blanco-Canqui et al. (2009) observed that soils under CT stay wettable, while conservative practices as no tilling or reduced tilling induced SWR in most cases. According to Urbanek et al. (2007), significant amounts of OM are lost during plowing, causing a decrease in SWR.

Positive correlations between SWR and OM content have been found by different authors (Chenu et al., 2000; Mataix-Solera and Doerr, 2004; Varela et al., 2005; Zavala et al., 2009b), but poor or no significant correlations have been reported by others (Harper et al., 2000; Scott, 2000; Doerr et al., 2005; Zavala et al., 2009a). Diversity of results is due to the presence of small quantities of hydrophobic substances causing significant water repellency (Doerr et al., 2000), so that soils under deep litter or mor-type humus may be expected to be the most water-repellent. In the case of no-tilled or mulched soils, González-Peñaloza et al. (2012) found significant correlations between SWR (logWDPT) and organic matter content in no-tilled soils (r = 0.9100) and no-tilled soils with organic manure addition (r = 0.9940).

Significant regressions were found for OM content and number of years for MR2 (r = 0.7410) and MR3 soils (r = 0.8690; Table 16). In the case of MR1, the correlation coefficient was near 0 (r = -0.3085), but mean OM content increased from 2.0 ± 0.2 to 3.7 ± 0.7%. MR2 and MR3 mulching rates induced a great input of OM in soil. Soil OM contents after addition of organic residues may vary according to mineralization rates (Haynes and Naidu, 1998).

The regression analyses between OM content and WDPT from soils under MR1 showed a positive but weak correlation coefficient (r = 0.4817). It may be suggested that at relatively low OM inputs (in comparison to MR2 and MR3), small differences in mineralization rates may cause variability in the composition of OM, inducing differences in SWR, as seen above. However, correlation coefficients for OM and WDPT under MR2 and MR3 treatments were stronger (r = 0.9005 and 0.8895, respectively). These results are in agreement with studies of other authors, who have reported that tillage contributes to significantly reduce SWR by removing the organic hydrophobic coatings of soil particles and aggregates (Buczko et al., 2006; González-Peñaloza, 2012; López-Garrido et al., 2012).

5.3.3 SOIL HYDROLOGICAL RESPONSE

Both Tp and Tr have been considered as indicators of soil wettability (Cerdà and Doerr, 2007). Different treatments studied in this research showed a range of wettability behaviours and hydrological responses. Tp is related to the suitability of soils for water infiltration without surface ponding, which is related to soil matrix flow and sorptivity (Imeson, 1983). On average, CT soils showed relatively short Tp, 166 ± 42 s (Table 18). Tp from MR1 soils sharply increased to 687 ± 426 s and MR2 and MR3 increased up to 298 ± 139 s, on average. On average, soils under MR1 showed the longest period of time for showing ponding evidence, although data varied in a wide range (145 - 1562 s) when all periods of treatment were considered together. Generally, Tp increased with time when all treatments were considered together (Table 6), showing a correlation coefficient near 0 ($r = 0.3242$), although all treatments did not contribute equally to this. Soils under CT, MR2 and MR3 did not show significant differences between Tp from soil plots after different number of years of treatment ($p < 0.05$). In contrast, Tp from soils under MR1 varied significantly with time ($p = 0.0000$), and the correlation coefficient between number of years under treatment and Tp for soils under MR1 is moderately strong ($r = 0.6243$).

On average, time required for runoff production since the beginning of rainfall simulation showed a similar behavior (Table 18). Tr data from all treatments ranged between 275 and 2056 s. The shortest mean Tr was recorded in soils under CT (377 ± 67 s). On average, the longest Tr was recorded in MR1 soils (1096 ± 529 s). Tr from MR2 and MR3 soils varied between 275 and 2056 s and did not show significant differences between both groups, but were on average (611 ± 273 s) longer than Tr from CT soils. Time to runoff from MR1 and MR2 soils showed significant differences between years ($p = 0.0180$ and 0.0410, respectively). In both cases, Tr increased with time and the correlation coefficient between number of years and Tr was moderate (Table 18). It is remarkable that higher mulching rates induced great differences in Tp and Tr in time. MR1 contributed to enhanced Tp and Tr, but no significant correlations were observed with the number of years of treatment.

Runoff rate from CT soils was 50.1 ± 7.9 s, on average. It decreased in MR1 soils (37.3 ± 5.2 s) to progressively increase with mulching rate, 46.6 ± 7.5 and 67.5 ± 6.1 s for MR2 and MR3 soils, respectively (Table 18). Correlation coefficients were strong in both cases ($r = 0.9478$ and 0.9354, respectively; Table 18).

Previous research has highlighted the strong impact of SWR on infiltration and runoff rates in forest soils (Cerdà et al., 1998; Doerr et al., 2003; Jordán et al., 2008;

Table 18. Statistical analyses of time to ponding (Tp, s), time to runoff (Tr, s) and runoff rate (%) under different treatments. N: number of data; SD: standard deviation; CV: coefficient of variation; KS, p: Kolmogorov-Smirnov p-value. KW, p: Kruskal-Wallis p-value. Values followed by the same letter within the same column do not show significant

	Treatment	N	Mean ± SD	CV (%)	Minimum	Maximum	Range	KS, p	KW, p
Tp	CT	30	166 ± 42 a	25.1	119	268	149	< 0.05	> 0.05
	MR1	30	687 ± 426 c	62.0	145	1562	1417	0.0249	0.0055
	MR2	30	285 ± 142 b	50.0	117	787	670	0.0480	> 0.05
	MR3	30	311 ± 136 b	43.8	137	637	500	< 0.05	> 0.05
	All treatments	120	362 ± 305	84.2	117	1562	1445	< 0.05	0.0207
	KS, p		0.0000						
Tr	CT	30	377 ± 67 a	17.8	305	522	217	0.0000	> 0.05
	MR1	30	1096 ± 529 c	48.3	328	2056	1728	< 0.05	0.0180
	MR2	30	562 ± 239 b	42.5	279	1354	1075	0.0215	0.0410
	MR3	30	660 ± 298 b	45.1	275	1235	960	< 0.05	> 0.05
	All treatments	120	673 ± 420	62.3	275	2056	1781	< 0.05	0.0347
	KS, p		0.0000						
Runoff rate	CT	30	50.1 ± 7.9 c	15.8	38.7	64.0	25.3	< 0.05	> 0.05
	MR1	30	37.3 ± 5.2 a	13.9	29.2	44.9	15.7	< 0.05	> 0.05
	MR2	30	46.6 ± 7.5 b	16.1	31.8	56.0	24.2	< 0.05	0.0219
	MR3	30	67.5 ± 6.1 d	9.0	54.5	77.4	22.9	< 0.05	0.0177
	All treatments	120	50.4 ± 12.9	25.6	29.2	77.4	48.2	< 0.05	> 0.05
	KS, p		0.0000						

Jordán et al., 2009). In burnt forested soils from Portugal, Ferreira et al. (2000) found that seasonal variations of hydrophobicity contributed to changes in overland flow, although this impact declined with time. In contrast, these authors found that ploughing destroyed SWR. Changes in Tp, Tr and infiltration and runoff rates may be also influenced by changes in soil aggregation and by the frequency and geometry of pores. Addition of plant residues to soil may increase porosity, increase the roughness and the interception of raindrops, delaying runoff generation and enhancing infiltration rates (De Gryze et al., 2006; Jordán et al., 2010). But several authors have found a major influence of SWR in the hydrological response of amended soils. In arable soils under a range of management practices, Hallet et al. (2001a) observed that the effect of soil management practice on its hydraulic transport properties appears to be affected more by subcritical water repellency than differences in the pore structure. Also, after the addition of maize residues, Cosentino et al. (2010) concluded that water sorptivity from soils is influenced by water repellency more strongly than by other physical soil properties, as improved structure or changes in the pore system.

The impact of subcritical SWR is not completely known. González-Peñaloza et al. (2012) suggested that no important effects were expected in the hydrological or erosional impact of subcritical SWR from citrus-cropped soils under conservative management practices in southern Spain. In our experiment, low mulching rates (MR1) increased Tp as a consequence of organic matter input and its impact in soil physical properties, as shown by Jordán et al. (2010) and Mulumba and Lal (2008). In contrast, higher mulching rates decreased Tp, as water infiltration rates through

Table 19. Regression analysis of time to ponding (Tp), time to runoff (Tr) and runoff rate versus number of years under different treatments. Non-significant regression equations are not shown.

Variables	Treatment	Intercept	Slope	r	r^2	p-value
Number of years/Tp	MR1	198.8480	61.0170	0.6243	0.3898	0.0000
	All treatments	179.4752	22.8469	0.3242	0.1051	0.0000
Number of years /Tr	MR1	478.9900	77.0679	0.6344	0.4025	0.0000
	MR2	322.9264	29.8384	0.5449	0.2969	0.0000
	All treatments	409.7614	32.9471	0.3398	0.1155	0.0000
Number of years /Runoff rate	MR2	33.5987	1.6205	0.9478	0.8983	0.0000
	MR1	57.1929	1.2871	0.9354	0.8750	0.0000

the soil surface were reduced by increased water repellency. As a consequence, time required for runoff generation showed a similar behaviour. Subcritical SWR observed in MR1 and MR2 soils might be related to reduced Tp and Tr. SWR seems to be the main cause of enhanced runoff rate in MR3 soils (compared to conventionally tilled soils). In contrast, decreased runoff rates from MR1 and MR2 soils may be mostly related to physical changes in the soil surface layer due to organic inputs. As shown by Martínez-Zavala and Jordán (2008), irregularity of the soil surface favours infiltration through macropores and inter-aggregate cracks. Mulching contributes to decrease runoff flow and enhance infiltration (Lal et al., 1980; Jordán et al., 2010; Puustinen et al., 2005). Under relatively low mulching rates, the effect of subcritical or slight SWR in runoff generation may be limited due to the most favorable effects of organic matter inputs.

6 CONCLUSIONS

The research carried out in this thesis constitutes an approach to the study of the baseline of water repellency in Mediteranean forest and agricultural soils and some of the related physical and chemical parameters. These results contribute to shed light on some aspects of water repellency not sufficiently studied, as its relation with conservative soil practices and its distribution at aggregate and intra-aggregate scales in cropped soils under different types of management. The results previously discussed allow obtaining the following conclusions:

NATURAL SOIL WATER REPELLENCY IN DIFFERENT TYPES OF MEDITERRANEAN WOODLANDS

Appreciable water repellency has been observed in soils from the province of Huelva (south-western Spain), with hydrophobicity increasing according to the following order: soils under holm oaks < eucalypts < pines. Water repellency from forest soils varied according to dominant plant species. Soils under holm oaks showed the greatest wettability, although soils ranged between wettable and strongly water repellent. The severity of water repellency increased progressively in soils under eucalypts and pines, the latter showing more than 90% water-repellent soil samples.

Severity of water repellency from soils under eucalypts and holm oaks increased with the presence of shrubs and herbaceous plants, but similar levels were not reached out of the tree-covered areas. Soils under oak forest were wettable or slightly water-repellent in these areas. In both cases, bare soils were mostly wettable. In contrast, soils pine forest showed a significant proportion of extremely water-repellent samples under the tree cover, and slight to strong water repellency in areas under the canopy of shrubs and herbaceous vegetation. In this case, bare soil samples were wettable to strongly water-repellent.

A negative correlation was observed between soil water repellency and the proportion of bare soil, but soils under different forest types showed different responses. Although wettable to strongly water-repellent soils were observed in bare areas under pines, bare soil areas were mostly wettable under eucalypts and holm oaks. Tree cover usually increased the occurrence and severity of water repellency, especially under pines and eucalypts. Soil acidity and the proportion of coarse particles (sand + silt) also contribute to enhanced soil water repellency. The negative correlation between water repellency class and the proportion of exchangeable K suggests that K deficiency for trees and shrubs restricts the input of hydrophobic substances in soil.

ORGANIC CARBON, WATER REPELLENCY AND SOIL STABILITY TO SLAKING UNDER DIFFERENT CROPS AND MANAGEMENTS

The organic C content varied in function of soil use, treatments and aggregate size. In general, mulching contributed to enhance soil water repellency in cropped soils under apricot, citrus and wheat. The organic C content varied between aggregates of different size, generally decreasing with increasing diameter. This trend was more intense in mulched than in conventionally tilled soils.

The distribution of organic C content in aggregates from mulched soils was homogeneous. Aggregates from conventionally tilled soils showed lower contents, but irregularly distributed, with larger concentrations in the exterior layer of aggregates. This gradient may be caused by recent organic matter inputs.

The intensity of water repellency (assessed by the ethanol test) increased with mulching and decreasing aggregate size. Higher intensities of water repellency found in finer aggregates may be caused by higher organic C concentrations, especially in mulched soils. Small or no differences were found among aggregate layers from soils under different uses and treatments. Although organic C content did not show any influence in aggregate stability to slaking, the intensity of water repellency contributed to enhanced stability, especially in mulched soils under all crops considered.

Further research is required to study the impact of these results on runoff generation, soil erosion risk and water dynamics and associated nutrient transport in soils showing subcritical to moderate water repellency. These issues are especially relevant for conservative management of agricultural soils. Future studies should also consider the effect of the redistribution of hydrophobic substances between and within micro-and macro-aggregates, as well as physical, chemical and biological processes involved.

MULCH APPLICATION IN FRUIT ORCHARDS INCREASES THE SEVERITY OF SOIL WATER REPELLENCY IN THE LONG-TERM

Results of this study show that mulching and no-tilling practices contribute to enhance soil water repellency. Addition of low quantities of straw residue to no-tilled soils (1-4 Mg ha^{-1} year^{-1}) induced subcritical soil water repellency, while moderate or high mulching rates (5-8 and 9-12 Mg ha^{-1} year^{-1}) induced slight soil water repellency after a few years of treatment.

Regression analyses show that soil water repellency is correlated with organic matter inputs, especially at higher mulching rates. Subcritical or slight soil water repellency showed significant impacts in time to ponding and time required for runoff initiation. Both variables increased with time under treatment at low (MR1) or moderate mulching rate (MR2). Time required for ponding and runoff generation was significantly enlarged especially in soils under relatively low mulching rates.

Beneficial impacts of organic matter input were evident in the delay of ponding and runoff initiation after low mulch rates, when compared to conventionally tilled soils. Increased water repellency after relatively moderate or high mulch rates reduced the positive impact of organic matter and contributed to accelerate ponding and runoff flow.

Runoff rates increased with time, but, on average, it decreased at low or moderate mulching rates respect to conventionally tilled soils as a consequence of positive changes caused by organic matter inputs in soil structure and surface heterogeneity. In contrast, high mulching rates contributed to trigger runoff flow.

More studies in long-term mulched no-tilled soils are necessary for a better knowledge of the implications of conservative soil management practices for the development of soil water repellency and consequences in the hydrological and erosional response of cropped soils. Studies at different scales are required for fully determine possible impacts of subcritical or slight soil water repellency.

7 CONCLUSIONES

La investigación llevada a cabo en esta tesis constituye una aproximación al estudio de la repelencia al agua tanto en suelos forestales mediterráneos como en suelos agrícolas, así como de algunos de los parámetros físicos y químicos relacionados. Estos resultados contribuyen a arrojar luz sobre algunos aspectos de la repelencia al agua no suficientemente estudiados, como su relación con las prácticas de conservación de suelos y su distribución a escalas que van desde el interior de los agregados hasta regionales. Los resultados obtenidos permiten obtener las siguientes conclusiones.

REPELENCIA AGUA EN SUELOS NATURALES BAJO DIFERENTES TIPOS DE BOSQUE MEDITERRÁNEO

Se ha realizado el estudio de la distribución de la repelencia al agua en los suelos de la provincia de Huelva (suroeste de España), observando un aumento de la hidrofobicidad de acuerdo con el siguiente orden: encinar<eucaliptal<pinar. La repelencia al agua de los suelos forestales estudiados varía según las especies vegetales dominantes. Aunque mostraron un rango amplio de grados de hidrofobicidad, en general, los suelos bajo encinar mostraron la mayor capacidad de humectación. La severidad de la repelencia al agua aumentó progresivamente en los suelos bajo eucaliptos y pinos. En este último caso, más de 90% de las muestras de suelo fueron clasificadas como repelentes al agua.

La severidad de la repelencia al agua de los suelos bajo eucaliptos y encinas aumentó con la presencia de arbustos y plantas herbáceas, pero disminuyó generalmente fuera de la cobertura arbórea. Los suelos bajo encinar mostraron carácter hidrofílico o ligera repelencia al agua. En ambos casos, los suelos desnudos se comportaron mayoritariamente como hidrofílicos. Por el contrario, los suelos bajo pinar mostraron una proporción significativa de muestras extremadamente repelente al agua bajo cobertura arbórea, y ligera a fuerte repelencia al agua en las zonas bajo el dosel de arbustos o vegetación herbácea. En este caso, las muestras de suelo desnudo mostraron carácter desde hidrofílico a fuertemente repelente al agua.

También se observó una correlación negativa entre el grado de repelencia al agua del suelo y la proporción de suelo desnudo, aunque los suelos bajo diferentes tipos de bosque mostraron diferentes respuestas. Aunque las áreas desnudas bajo pinar variaron entre hidrofílicas y fuertemente repelentes al agua, el suelo desnudo bajo encinar y eucaliptal era mayoritariamente hidrofílico. Por lo general, la cubierta arbórea contribuyó a aumentar la incidencia y la severidad de la repelencia al agua, especialmente bajo los pinos y eucaliptos. La acidez del suelo y la proporción de partículas gruesas (arena + limo) también contribuyeron a intensificar la repelencia al agua del suelo. La correlación negativa entre la clase repelencia al agua y la proporción de K^+ intercambiable sugiere que la deficiencia de K en especies leñosas disminuye el aporte de sustancias hidrofóbicas en el suelo.

REPELENCIA AL AGUA, CARBONO ORGÁNICO Y ESTABILIDAD ESTRUCTURAL DEL SUELO BAJO DIFERENTES TIPOS DE CULTIVO Y MANEJO

El contenido de C orgánico varía en función del uso del suelo, su manejo y el tamaño de los agregados. En general, el mulching contribuyó a incrementar la repelencia al agua del suelo en los suelos cultivados bajo albaricoque, cítricos y trigo. El contenido en C orgánico varió con el tamaño de los agregados, generalmente disminuyendo con el aumento de diámetro. Esta tendencia fue más intensa en suelos bajo mulching que en los suelos bajo laboreo convencional.

La distribución de contenido de C orgánico en agregados de suelo con mulching fue homogénea. En cambio, los agregados bajo laboreo convencional mostraron un menor contenido, pero con una distribución más irregular, con mayores concentraciones en la capa exterior de los agregados. No está clara la razón de esta distribución heterogénea, pero puede pensarse que está causado por aportes de materia orgánica recientes.

La intensidad de la repelencia al agua (determinada mediante el test del porcentaje de etanol) aumentó en los suelos bajo mulching y con la disminución de tamaño de los agregados. Los agregados más finos mostraron intensidades más altas de repelencia al agua, causadas por mayor contenido en C orgánico, especialmente en el caso de suelos bajo mulching. Se encontraron diferencias pequeñas o nulas entre capas de agregados de suelos bajo diferentes tipos de uso y manejo. Aunque el contenido de C orgánico no mostró ninguna influencia en la estabilidad de los agregados, la intensidad de la repelencia al agua contribuyó a una mayor estabilidad, especialmente en el caso de suelos bajo mulching, independientemente del cultivo.

Se requiere más investigación para estudiar el impacto de estos resultados en la generación de escorrentía, el riesgo de erosión del suelo y la dinámica del agua o el transporte de nutrientes asociados en suelos que muestran repelencia al agua entre subcrítica y moderada. Estos resultados son especialmente relevantes en el caso de las prácticas de conservación de suelos agrícolas. En el futuro debe abordarse también el efecto de la redistribución de las sustancias hidrofóbicas entre y dentro de los micro y macroagregados, así como sus características físicas, químicas y biológicas.

LA APLICACIÓN DE MULCH EN SUELOS CULTIVADOS INCREMENTA EL GRADO DE REPELENCIA AL A GUA A LARGO PLAZO

Los resultados de este estudio muestran que tanto el mulching como las prácticas de no laboreo contribuyen a mejorar la repelencia al agua del suelo. La adición de pequeñas cantidades de residuos de paja (1.4 Mg ha^{-1} año^{-1}) indujo un nivel subcrítico de repelencia al agua en el suelo, mientras que tasas mayores (5-8 y 9-12 Mg ha^{-1} año^{-1}) sólo ocasionaron la aparición de ligera repelencia al agua después de varios años de tratamiento.

Los análisis de regresión muestran que la repelencia al agua del suelo se correlaciona razonablemente bien con los aportes de materia orgánica, especialmente en el caso de las tasas más elevadas de mulching. La repelencia subcrítica o ligera mostró efectos significativos en el acortamiento del tiempo de encharcamiento y el tiempo requerido para la iniciación de escorrentía. Ambas variables se incrementaron con el tiempo bajo tasas bajas (MR1) o moderadas de mulching (MR2). En el caso de los suelos bajo M3, ambas variables se incrementaron significativamente

Son evidentes los impactos positivos del aporte de materia orgánica bajo tasas bajas de mulching en la reducción de la respuesta hidrológica, en comparación con los suelos bajo laboreo convencional. Sin embargo, a tasas moderadas o altas, el aumento de la repelencia al agua redujo el impacto positivo de la materia orgánica y contribuyó a acelerar el encharcamiento y la aparición de la escorrentía.

Las tasas de escorrentía aumentaron con el tiempo de tratamiento, pero, en promedio, fueron más bajas en suelos bajo tasas bajas o moderadas de mulch que bajo laboreo convencional, como consecuencia de la mejora de la estructura del suelo y el incremento de la rugosidad y heterogeneidad de la superficie. Por el contrario, las altas tasas de mulching favorecieron la formación acelerada de escorrentía.

Está clara la necesidad de más estudios a largo plazo para obtener un mejor conocimiento de las implicaciones de las prácticas de conservación de suelo en el desarrollo de la repelencia al agua, así como sus consecuencias en la respuesta hidrológica y erosiva de suelos cultivados. Futuros estudios deben considerar también diferentes escalas para determinar plenamente los posibles impactos de la repelencia al agua ligera o subcrítica.

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