



No laboreo en agrosistemas de secano en Aragón: Efectos a largo plazo en el almacenamiento de carbono orgánico y en la estructura del suelo.

Tesis
doctoral
2015

No laboreo en agrosistemas de secano en Aragón: Efectos a largo plazo en el almacenamiento de carbono orgánico y en la estructura del suelo.



Tesis doctoral

Nuria Blanco Moure

- Foto de portada: Muestra de la capa superficial de un suelo natural en la localidad de Artieda (Zaragoza).
- Foto de contraportada: Agregado de un suelo agrícola de Peñaflor (Zaragoza) tras su estallido por inmersión en agua.

TESIS DOCTORAL

No laboreo en agrosistemas de secano en Aragón: Efectos a largo plazo en el almacenamiento de carbono orgánico y en la estructura del suelo.



Universidad
Zaragoza



CSIC

CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

Nuria Blanco Moure
Zaragoza, junio de 2015

El presente trabajo de investigación se ha realizado gracias a una Ayuda Predoctoral de Formación de Personal Investigador (FPI), del Ministerio de Ciencia e Innovación, asociada al Proyecto de Investigación AGL2007-66320-C02-02.



M. Victoria López Sánchez, Científica Titular del Consejo Superior de Investigaciones Científicas (CSIC)

CERTIFICA

Que el trabajo descrito en la presente memoria, titulado: **“No laboreo en agrosistemas de secano en Aragón: Efectos a largo plazo en el almacenamiento de carbono orgánico y en la estructura del suelo”**, ha sido realizado bajo su dirección por Dña. Nuria Blanco Moure en la Estación Experimental de Aula Dei, CSIC, y reúne todos los requisitos necesarios para su aprobación como Tesis Doctoral.

Zaragoza, junio de dos mil quince

Dra. M. Victoria López Sánchez

*A Juan y Julieta, la tierra en la
que habitó.*

Tras semanas intentando encontrar la frase perfecta con la que empezar este apartado de agradecimientos descubrí que lo que más me apetecía era empezarlo con sinceridad así que quisiera expresar mi más sincero agradecimiento a todos aquellos que habéis hecho esta tesis posible. En primer lugar y muy especialmente a mi directora de tesis la Dra. María Victoria López Sánchez por su apoyo y su ayuda pero sobre todo por su afecto. Este agradecimiento quiero hacerlo extensible también a todos los miembros de mi grupo de investigación: David, Ricardo, Pepa, Ana y Carol porque aunque somos pequeños, somos valientes y hacemos buena ciencia. I would like to thank also Dr. Sacha Mooney and all the wonderful staff of School of Biosciences at the University of Nottingham for hosting and helping me with the determination of the architecture of the aggregates in the CT-scan. A todas las personas que trabajan y colaboran en hacer ciencia en mi país ya sean fijos o temporales, becarios, precarios, científicos titulares, informáticos, bibliotecarios, personal de mantenimiento y servicios, administrativos burocráticos e incluso a los Ministeriales por trabajar duro con pocos recursos, a menudo poco valorados y aun así hacerlo posible.

En el tiempo que llevo trabajando en ciencia he tenido la ocasión de disfrutar la calidad humana y profesional de las personas que conforman nuestra pequeña comunidad científica en el campus de Aula Dei. A todos quiero deciros que me siento muy orgullosa de decir que he realizado la tesis en la Estación. Muchas gracias especialmente al Departamento de Suelo y Agua por su cercanía física y emocional y al laboratorio de la Dra. María Herrero Romero por ser una segunda familia para mí y los míos. Al Dr. Javier Machín Gayarre por su ayuda con la clasificación de los suelos y su hospitalidad en Sos del rey Católico. Muchas gracias también al personal de apoyo a la investigación, biblioteca, informática, administración, mantenimiento, servicios, y a la casa de labor por alimentar nuestro cuerpo y nuestro conocimiento. A mis compañeros de alegrías y neuras varias: los becarios de la FFAD porque durante al menos un rato cada día he sentido que no había en el mundo gente que me entendiese más. No os voy a nombrar porque en el año que yo entré éramos legión. Sospecho que en estos últimos años somos una especie en extinción a merced de los vaivenes de la política científica.

A la gente de la Universidad de Zaragoza, especialmente a la Escuela Politécnica de Huesca, la Escuela de Doctorado y Pilar León del Departamento de Ciencias Agrarias y del Medio Natural por facilitarnos tanto los trámites en esta tesis

de final transoceánico. Al profesor Luis Alberto Angurel Lambán por su ayuda con la en la determinación de las propiedades mecánicas de los agregados. Vaya también mi agradecimiento a la gran familia docente española ya sean maestros, enseñanzas medias y universitarias porque sois la base de los científicos del futuro y porque estoy firmemente convencida que la educación es el motor de cambio a una sociedad más justa y mejor.

Quiero dar gracias asimismo a los amigos que me han acompañado a lo largo de mi vida y que, pacientemente, me han escuchado hablar de la tesis desde su principio. A la gente de Aragón que me ha dado tan buenos ratos "charrando" y tan buenas tardes de escalada. Ruth y Carlos, Antonio, Elodie, Jorge, Costanza, Erica, Migue, Laura, Jose y nuestro pequeño Dani al que nunca tengo tiempo de achuchar como se merece. A mis amigos de Vigo que en la distancia no pierden una ocasión para hacerme sonreir. Manuel, Jani, Rober, María José, Aitor, Flora e os meniños Brais, Héctor e Mariña que son o mellor de todos nos concentrados en frasquiños pequeños. I would like to thank also our new friends in Boston who encourage me to never give up. Donna and Jonh, Becky and Jonh, Faye, thanks for offer us a nest in the middle of the woods to settle our little family. Ashley, Chrissy, Margarida, Caitlin, Jessica and Ellie thanks for being so supportive and so optimistic. You are a great team!!

Ós amiguetes de Viladerrei por facerme sentir parte do pobo dende o principio. A miña familia de Viladerrei polo seu apoio, polo seu afecto, polos pequenos ratos e as grandes comidas familiares. A Bernardino e Maruja, Julio, Pablo, Susana e as nenas Carla, Marta e Iria que valen máis que todo o ouro do mundo.

A Conchi, Julio, Marta y Elena que siempre están ahí cuando los llamo y a mi familia de Toubes por los buenos recuerdos y los veranos eternos. A mis tíos Árita y Antonio por tener siempre abiertas las puertas de su casa y su corazón.

A mi familia a quien les debo la persona que soy en la vida. Gracias papá por ese sentido de la honestidad tan grande que tienes porque eso nos ha hecho personas comprometidas con la realidad. Gracias mamá por tu capacidad de entrega y la generosidad con la que afrontas tus relaciones en la vida. Gracias Miriam porque desde que puedo recordar siempre has estado de mi lado.

Y, finalmente a las dos personas más importantes en mi vida. A Juan, mi pareja y la persona a la que más admiro en el mundo. Porque si tres cosas hay que hacer en la vida, a tu lado ya he hecho dos y para plantar el árbol siempre nos quedará Toubes. Y a la pequeña Julieta que llegó y lo cambió todo.

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Lista de símbolos y abreviaturas

<i>a</i>	Rotura o pérdida inicial de agregados de suelo por humectación rápida (%)
C	Carbono
CaCO_3	Carbonato cálcico (g kg^{-1})
CC	Sistema de cultivo anual
CF	Sistema de cultivo de “año y vez”
Ch	Labor primaria con arado chisel
CL	Sistema de rotación cereal-leguminosa
cPOM	Materia orgánica particulada gruesa
cPOM-C	Carbono de la materia orgánica particulada gruesa (g C kg^{-1} suelo)
CT	Laboreo convencional
<i>d</i>	Diámetro medio de agregados de suelo (mm)
d-Min	Fracción órgano-mineral fácilmente dispersable
d-Min-C	Carbono de la fracción órgano-mineral fácilmente dispersable (g C kg^{-1} suelo)
<i>E</i>	Energía de rotura por compresión de agregados de suelo (J kg^{-1})
EC	Conductividad eléctrica (dS m^{-1})
fPOM	Materia orgánica particulada fina
fPOM-C	Carbono de la materia orgánica particulada fina (g C kg^{-1} suelo)
LC	Laboreo de conservación
LSD	Diferencia mínima significativa
MAP	Precipitación media anual (mm)
Min	Fracción órgano-mineral
Min-C	Carbono de la fracción órgano-mineral ($\text{g C fracción g}^{-1}$ SOC, Mg ha ⁻¹ , g C kg^{-1} suelo)
MP	Labor primaria con arado de vertedera

NAT	Suelo natural
NT	No laboreo o siembra directa
OC	Carbono orgánico (%, g kg ⁻¹)
OM	Materia orgánica
Peñaflor CC	Sistema de cultivo anual en Peñaflor
Peñaflor CF	Sistema de cultivo de “año y vez” en Peñaflor
POM	Materia orgánica particulada
POM-C	Carbono de la materia orgánica particulada (g C fracción g ⁻¹ SOC, Mg ha ⁻¹ , g C kg ⁻¹ suelo)
RT	Laboreo reducido
Sk	Rotura o pérdida de agregados de suelo por estallido durante humectación rápida (%)
SOC	Carbono orgánico del suelo (Mg ha ⁻¹ , g kg ⁻¹)
SOM	Materia orgánica del suelo
SR	Índice de estratificación
T ₆₀	Rotura o pérdida de agregados de suelo tras 60 minutos de agitación en agua (%)
TS	Resistencia a la rotura por compresión de agregados de suelo (kPa)
WAS	Estabilidad de agregados en húmedo (%)
μagg-Min	Fracción órgano-mineral ocluida en el interior de microagregados estables en agua
μagg-Min-C	Carbono de la fracción órgano-mineral ocluida en el interior de microagregados estables en agua (g C kg ⁻¹ suelo)

Resumen

La determinación del impacto del manejo agrícola sobre la calidad del suelo es esencial para evaluar la sostenibilidad de los sistemas agrícolas. Esto adquiere especial importancia en regiones semiáridas, como la Mediterránea, donde los suelos se caracterizan por bajos contenidos en C orgánico (OC) y por ser muy susceptibles a la degradación. En estos ambientes, los sistemas de laboreo de conservación pueden contribuir de forma sostenible a mantener la capacidad del suelo para la producción agrícola. En Aragón, al igual que en el resto de España, el interés de los agricultores por el no laboreo (NT) ha ido aumentando en los últimos años. Sin embargo, es escasa la información disponible sobre la respuesta del suelo a largo plazo en los escenarios reales en los que el agricultor utiliza el NT. El objetivo principal de esta Tesis Doctoral ha sido evaluar la capacidad de los sistemas agrícolas basados en NT para almacenar y estabilizar OC y mejorar el estado físico del suelo en diferentes zonas de cereal de secano en Aragón. En una primera etapa, un estudio de localización y caracterización de campos comerciales de NT mostró la diversidad de prácticas de manejo que el agricultor realiza en sus campos (diferente manejo de residuos de cosecha, de sistemas de cultivo y rotaciones, de aplicación de purines, etc.), reflejando la realidad de la agricultura de conservación en la región. Con el objetivo de profundizar en el objetivo general del trabajo de Tesis, se realizó una segunda selección de seis sitios de estudio, localizados en diferentes zonas agroclimáticas de la región, en los que se compararon pares de suelos adyacentes bajo NT y laboreo convencional (CT), y un tercer suelo inalterado con vegetación natural (NAT). Los resultados mostraron que el contenido de OC en los primeros 20 cm de suelo fue, como media, un 20% superior bajo NT que bajo CT. Las mayores ganancias se obtuvieron en los campos de NT de mayor duración y/o manejados con prácticas que llevaban un mayor aporte de biomasa al suelo. Sin embargo, esta ganancia se redujo o se invirtió a mayor profundidad de tal forma que, considerando el horizonte de 0-40 cm, el potencial del NT para almacenar OC fue similar o sólo ligeramente superior al del CT. El fraccionamiento físico de la materia orgánica del suelo mostró que la mayor parte del OC se encontró en la fracción órgano-mineral (80%) y,

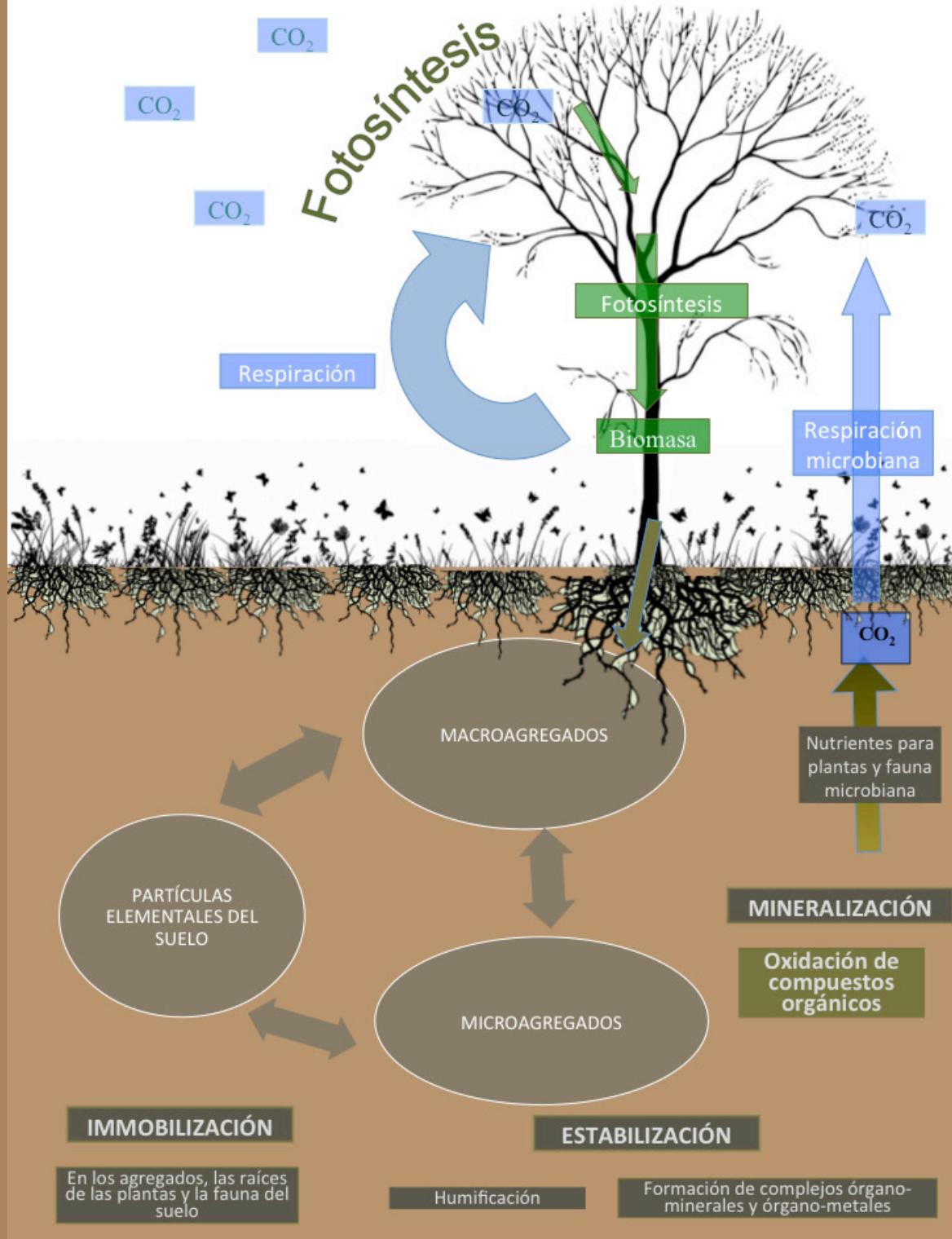
más concretamente, en la fracción órgano-mineral fácilmente dispersable (fuera de los microagregados estables en agua). Sin embargo, el manejo del suelo sólo afectó de forma significativa y consistente a las dos fracciones de materia orgánica particulada analizadas, la gruesa y la fina (>250 y $250-53 \mu\text{m}$, respectivamente), cuyas concentraciones disminuyeron al aumentar el grado de alteración del suelo. El contenido de arcilla del suelo influyó positivamente en la acumulación del C de la fracción órgano-mineral fácilmente dispersable y del OC total. Se encontraron también estrechas relaciones entre el C de la fracción órgano-mineral ocluida dentro de microagregados estables en agua y el peso de los microagregados. La materia orgánica particulada fina se mostró como un indicador sensible de los cambios producidos en el suelo por efecto del laboreo, con mayores concentraciones en NT que en CT e índices de estratificación siempre mayores que 2 bajo NT. Los mayores contenidos de OC en la superficie del suelo bajo NT se tradujeron en mejoras en el estado físico del suelo como lo demuestran los menores valores de resistencia a la rotura por compresión y de energía de rotura de agregados de suelo así como los moderados aumentos de estabilidad estructural en agua. Un análisis detallado de los datos mostró que la compleja relación encontrada entre la resistencia a la compresión y el OC se debe a una interacción positiva entre OC y arcilla lo que explica la alta resistencia encontrada en aquellos suelos donde coinciden los valores más elevados de OC y de arcilla. En comparación con los suelos naturales, los suelos agrícolas del área de estudio presentaron una baja estabilidad estructural en agua. En estos suelos, el estallido de los agregados (*slaking*) es el principal proceso de desagregación de la superficie del suelo por efecto del agua y está negativamente afectado por el contenido en OC. A pesar de las reducidas diferencias entre NT y CT en cuanto al almacenamiento de OC en la capa arable, el NT puede plantearse como una alternativa de manejo de los suelos de secano en Aragón para mejorar la calidad estructural del suelo y disminuir su susceptibilidad a procesos de degradación.

Abstract

The determination of the impact of agricultural management on soil quality is essential to evaluate the sustainability of agricultural systems. This acquires special importance in semiarid regions, such as the Mediterranean, where soils are characterized by low organic carbon (OC) contents and by being highly susceptible to degradation. In these environments, conservation tillage systems can contribute to maintain, in a sustainable way, the soil capacity for agricultural production. In Aragon, as in the rest of Spain, the interest of farmers in no tillage (NT) has increased in recent years. However, there is little available information on the long-term response of soil in the actual scenarios in which the farmer uses this practice. The main objective of this PhD Thesis has been to assess the capacity of NT-based cropping systems to accumulate and stabilize OC and improve the physical condition of the soil in different cereal production areas of Aragon. In a first step, a study of localization and characterization of commercial fields of NT showed the diversity of management practices used by farmers in their fields (different crop residue management, cropping system and rotation, manure application, etc.), reflecting the reality of the conservation agriculture in Aragon. In order to deepen the overall goal of the thesis, a second selection of six study sites was made where pairs of adjacent soils under NT and conventional tillage (CT) were compared. In all sites, a nearby undisturbed soil under native vegetation (NAT) was included. The results showed that the OC content in the first 20 cm of soil was, on average, 20% higher under NT than under CT. The highest contents were obtained in the NT fields of longer duration and/or managed with practices that enhance the return of more crop biomass to the soil. However, this gain was reduced or inverted in the deeper soil layers so that, taking into account the whole soil profile (0-40 cm), the potential of NT to store OC was similar or only slightly higher than that of CT. Physical fractionation of soil organic matter showed that the mineral-associated organic matter and, more specifically, the easily dispersable mineral-associated fraction (outside water-stable microaggregates), constituted the main part of total soil OC. Only the two labile fractions isolated, the coarse and fine particulate organic matter (>250 and $250-53 \mu\text{m}$, respectively),

Abstract

were significantly and consistently affected by soil management and their concentrations decreased as soil disturbance increased. Soil clay content was a positive influencing factor for the easily dispersible mineral-associated fraction and for total soil OC. Strong relationships were also found between the OC of the mineral-associated organic matter fraction occluded within water-stable microaggregates and the mass of the microaggregates. The fine particulate organic matter has been shown to be a sensitive indicator of tillage-induced changes in soil, with higher concentrations in NT than in CT and stratification ratios always higher than 2 under NT. The higher OC contents at the soil surface under NT led to an improvement in the soil physical condition as evidenced by the lower values of tensile strength and rupture energy of soil aggregates as well as by the moderate increase in water aggregate stability. A detailed analysis of the tensile strength data showed the existence of a positive interaction between OC and clay which explains the high resistance found in those soils where match the highest values of OC and clay. Compared to natural soils, agricultural soils in the study area presented low structural stability in water. In these soils, slaking is the dominant disaggregation process by water and is negatively affected by soil OC. Regardless of the similar potential of NT and CT to storage OC in the 0-40 cm soil layer, NT can be considered as a sustainable alternative in rainfed cereal areas of Aragon to improve the structural quality of soils and reduce their susceptibility to degradation



Capítulo 1

Introducción

- Dinámica del carbono orgánico en el suelo.

1. 1. El uso agrícola del suelo.

La agricultura ha sido la actividad humana que mayor incidencia ha tenido sobre el suelo a lo largo de la historia y especialmente durante la segunda mitad del siglo XX con la intensificación de las prácticas agrícolas. Los avances en el manejo del suelo, como fueron el desarrollo de maquinaria agrícola, la aparición de productos agroquímicos, la mejora genética vegetal, etc., permitieron un espectacular desarrollo de la producción agrícola pero a expensas de un elevado coste económico y medioambiental (Martín de Santa Olalla, 2001). La deforestación, el sobrepastoreo, las prácticas agrícolas inadecuadas (laboreo excesivo, eliminación de la cubierta de residuos vegetales, etc.) han conducido en muchas ocasiones a la degradación del suelo con consecuencias particularmente graves en zonas áridas y semiáridas ya de por sí frágiles y con poca capacidad de recuperación. Según estimaciones realizadas en diferentes regiones del mundo, las tasas de erosión asociadas a las prácticas agrícolas convencionales son 1-2 órdenes de magnitud mayores que las tasas de erosión en suelos con vegetación nativa y que las tasas de erosión geológica a largo plazo (Montgomery, 2007). En el continente europeo, se estima que alrededor del 16% del área cultivada es vulnerable a la desertificación (Holland, 2004). Este porcentaje podría ser incluso mayor en la región Mediterránea donde las especiales condiciones climáticas se unen a un histórico e intenso manejo agrícola, generando un escenario propicio para el avance de la desertificación.

La evolución de los sistemas de laboreo ha ido estrechamente ligada a la disponibilidad de herramientas adecuadas para conseguir tres fines básicos: el control de malas hierbas, la descompactación del suelo y la preparación de un adecuado lecho de siembra. Aunque la aparición del arado vertedera supuso un gran avance en este sentido, se ha comprobado que el excesivo laboreo provoca un deterioro de la estructura del suelo, desencadenando o acelerando procesos de degradación como son la erosión y la compactación del suelo y ocasionando, finalmente, una pérdida de productividad agrícola (Hobbs et al., 2008; Lal, 2009). Las grandes pérdidas agrícolas causadas por las tormentas de polvo (*dust storms*) durante los años 30 en las llanuras centrales de EEUU son sólo una muestra de la catástrofe económica y ambiental que prácticas agrícolas inadecuadas pueden provocar en ecosistemas

sensibles. Este acontecimiento supuso un antes y un después en la política de conservación del suelo y control de la erosión, y en el planteamiento de técnicas agrícolas alternativas al laboreo tradicional. A partir de este momento, la búsqueda de nuevos sistemas de producción agrícola se ha encaminado a la reconciliación de dos grandes necesidades, garantizar la seguridad alimentaria y preservar la calidad de los recursos naturales.

1.2. El laboreo de conservación como alternativa.

El debate sobre la sostenibilidad de los modelos productivos agrícolas iniciado a mediados del siglo pasado continúa en la actualidad. En el escenario actual, con los precios del gasóleo a la alza y el interés creciente de diferentes sectores de la sociedad por la conservación de los recursos naturales y la biodiversidad, los sistemas de laboreo de conservación (LC) han ido ganando adeptos y se han consolidado como sistemas de manejo interesantes para reducir los costes económicos y ambientales frente a los sistemas de producción tradicionales (Lal, 2007, 2009). Dentro del término LC se incluye una amplia diversidad de prácticas de manejo del suelo que van desde un laboreo mínimo o reducido hasta la siembra directa o no laboreo [*no tillage* (NT)], todas ellas encaminadas a reducir el número e intensidad de las labores y a mantener tras la siembra la superficie del suelo cubierta con restos vegetales del cultivo anterior. También se habla de *agricultura de conservación* para definir una serie de técnicas que tienen como objetivo fundamental conservar, mejorar y hacer un uso más eficiente de los recursos naturales, mediante un manejo integrado del suelo, el agua, los agentes biológicos y los inputs externos, garantizando, al mismo tiempo, una producción a un alto nivel y con buena rentabilidad económica (FAO, 2001). En la actualidad, este término general se ha concretado en tres principios interrelacionados: 1) mínima alteración del suelo, a través de NT y siembra directa, 2) cobertura permanente del suelo y 3) rotación de cultivos (Kassam et al., 2012; FAO, 2014).

Estudios llevados a cabo durante las tres últimas décadas en diferentes regiones del mundo han demostrado la idoneidad del LC, y en especial del NT, para incrementar los niveles de carbono orgánico en la superficie del suelo y mejorar sus condiciones

físicas, químicas y biológicas con respecto a sistemas de laboreo convencional (West y Post, 2002; Govaerts et al., 2009) (Fig. 1.1). Pero de estos estudios también se deduce que la tasa y magnitud del cambio depende de una serie de factores como son clima y suelo, y de prácticas agrícolas como son rotación de cultivos, manejo de residuos de cultivo y aporte de materia orgánica al suelo.

Los beneficios económicos y medioambientales derivados de la adopción del LC y, especialmente del NT, han favorecido su extensión en países como EEUU, Argentina, Brasil, Australia o Canadá. Según datos de la FAO (FAO, 2013), en los últimos 11 años el NT se ha extendido por todo el mundo a una ritmo de alrededor de 7 millones ha al año, pasando de ocupar 45 millones ha en 1999 a 125 millones ha en 2011 (Friedrich et al., 2012). Sin embargo, en Europa la tasa de adopción ha sido bastante más lenta, contribuyendo con tan sólo un 1% al total mundial. Según datos oficiales del MAGRAMA (2013), se estima que en España 571.508 ha de superficie de cultivo anual se encuentra actualmente bajo NT y que un 19% de la misma se localiza en Aragón. Este porcentaje relativamente alto indica el creciente interés de los agricultores de la región por este sistema de manejo alternativo.

1.3. El laboreo de conservación en Aragón.

1.3.1. Características y limitaciones de los agrosistemas de secano.

El uso de la tierra en Aragón (47.683 km²) se distribuye de la siguiente manera: 37% dedicada a cultivo, 7% a prados y pastizales, 31% a bosques y 25% a otros usos, incluyendo las tierras marginales (Gobierno de Aragón, 2014). Del total de la superficie ocupada por la agricultura de secano (1,32 millones de ha), 744.156 ha corresponden a cultivos herbáceos (73% con trigo y cebada). Aproximadamente la mitad de la superficie de secano se sitúa en el centro de Aragón y, más concretamente, en áreas con una precipitación media anual <400 mm en las que el sistema tradicional de cultivo es la rotación cereal-barbecho (*año y vez*) con un largo periodo de barbecho de 16-18 meses. En los secanos situados más al norte (secanos subhúmedos de la zona subpirenaica y secanos húmedos del Pirineo), las condiciones climáticas son menos severas lo que permite un sistema de cultivo continuo de cereal o de rotación



Fig. 1.1. Aspecto del suelo en diferentes campos agrícolas del secano aragonés bajo laboreo tradicional (a, b, c) y no laboreo (d, e, f) en diferentes momentos de la campaña agrícola: inmediatamente tras la siembra (a,d); tras 4 meses con el cultivo ya establecido (b,e); y durante el periodo de barbecho en campos de año y vez (c,f).

de cultivos.

En los secanos áridos y semiáridos de la región, la escasa precipitación y su irregular distribución a lo largo del año constituyen los principales factores limitantes de la producción agrícola, cuyas consecuencias son bajos e inestables rendimientos (McAneney y Arrué, 1993; Austin et al., 1998). Esta limitación en la producción de biomasa se traduce, a su vez, en los bajos contenidos de materia orgánica de los suelos de secano. El centro de Aragón es, de hecho, una de las regiones más secas de la península Ibérica y una de las áreas semiáridas situadas más al norte de Europa. A ello hay que añadir que, a diferencia de otras regiones semiáridas de clima mediterráneo, el régimen de lluvias en el centro de Aragón se caracteriza por la ausencia de una estación de lluvias bien definida y por la alta probabilidad de que en cualquier mes del año la lluvia recibida sea extremadamente baja (<10 mm) o nula (McAneney y Arrué, 1993). Además, el *Cierzo*, viento frío y seco de dirección ONO, es habitual a lo largo de todo el año y no son raras rachas de 30 m s^{-1} (Biel y García de Pedraza, 1962). En cuanto a los suelos, éstos son principalmente alcalinos ($\text{pH} > 8$), con un alto contenido en carbonato cálcico ($>30\%$), bajo contenido en materia orgánica ($<2\%$) y una textura dominante entre franca y franco arenosa (Montañés et al., 1991).

En el sistema de cultivo de *año y vez* el manejo tradicional del suelo consiste en un pase con arado de vertedera, como labor primaria, seguido por varios pases de cultivador, como labores secundarias, durante el periodo de barbecho. Como consecuencia, los suelos en barbecho generalmente están desnudos y pulverizados por múltiples labores y, por tanto, muy expuestos a procesos de degradación (López et al., 2001). La labor profunda del suelo con aperos verticales, tipo subsolador, también son prácticas de manejo convencionales en los secanos menos áridos de Aragón. Sin embargo, en estos últimos años el laboreo tradicional está experimentando una progresiva regresión en la región como consecuencia, especialmente, del aumento de los costes de combustible y otros insumos, propiciándose con ello el interés por prácticas de manejo alternativas (López et al., 2001; Vallés, 2009).

En definitiva, las particulares condiciones de clima y suelo, junto a prácticas agrícolas inadecuadas hacen de Aragón y, especialmente del centro de Aragón, una

región propensa a procesos de degradación (López et al., 2001; García-Ruiz, 2010). Es en este contexto donde el LC se plantea como una alternativa de manejo con la que sería posible conciliar productividad agrícola y calidad medioambiental.

1.3.2. Antecedentes y prioridades de investigación.

Desde finales de los años 80 se han llevado a cabo diferentes trabajos de investigación sobre la idoneidad del LC como alternativa de manejo para el cultivo de cereal de secano en Aragón. En estos trabajos han sido estudiados diversos aspectos: desarrollo y rendimiento del cultivo, balance hídrico y propiedades físicas e hidráulicas del suelo, erosión eólica y, más recientemente, almacenamiento de carbono orgánico en el suelo y emisiones de CO₂ a la atmósfera. En la mayor parte de estos estudios se han comparado dos sistemas de LC (NT y laboreo reducido con chisel, [*reduced tillage (RT)*]) con el sistema tradicional de laboreo con vertedera [*convencional tillage (CT)*] en diferentes zonas cerealistas de secano en Aragón.

Desde el punto de vista de la respuesta del cultivo, los resultados indican que, en general, la producción de cereal no se vio afectada de forma sustancial por el sistema de laboreo utilizado. Sin embargo, en el caso del NT y en los secanos más áridos, esta respuesta sólo se manifestó a medio plazo (tras 8-10 años) ya que, a corto plazo (tras 2 años bajo NT), el crecimiento y rendimiento del cultivo fueron menores que bajo CT y RT (López y Arrué, 1997; Pérez-Marco, 1998; Moret et al., 2007). Asimismo, un análisis de los datos de rendimiento de cebada obtenidos en ensayos de laboreo establecidos por el Centro de Transferencia Agroalimentaria (Gobierno de Aragón) en dos diferentes zonas de Aragón, indicaba que tras 6 y 12 años, el rendimiento en grano fue un 5-6% superior bajo NL que bajo CT (Pérez-Berges, 2007).

En el sistema de cultivo *año y vez*, la eficiencia del barbecho en el almacenamiento del agua de lluvia ha sido evaluada y comparada bajo diferentes tratamientos de laboreo (López et al., 1996; Moret et al., 2006, 2007). En general, ni la cantidad de agua almacenada en el suelo ni la eficiencia del barbecho estuvieron afectadas significativamente por el tratamiento de laboreo y se cuestionaba la utilidad del barbecho en el secano aragonés debido a los bajos valores de eficiencia encontrados

(11% como media).

En cuanto a las propiedades físicas del suelo, en los secanos menos áridos de Aragón (secanos subhúmedos), los suelos ya mostraron tras 2 años bajo NT una mayor macroporosidad (bioporos) que bajo CT y RT como consecuencia de una mayor actividad biológica (López y Arrué, 1996). Por el contrario, los valores de resistencia del suelo a la penetración en la capa arable (0-40 cm) fueron muy elevados tras la siembra en NT (López et al., 1996). Incluso, tras 8-10 años, el suelo no labrado seguía más compactado que los suelos con laboreo y la conductividad hidráulica era significativamente menor debido a un menor número de poros de transmisión de agua por unidad de superficie (Moret y Arrué, 2007). El tratamiento de RT presentó un comportamiento muy similar a CT. Estudios más recientes sobre el estado de agregación del suelo indican que, en un suelo franco, el mayor contenido en carbono orgánico y mayor biomasa microbiana bajo NT conducen a un mayor diámetro medio de agregados y mayor estabilidad en húmedo en comparación con CT y RT (Álvaro-Fuentes et al., 2008a).

En el centro de Aragón, donde el *Cierzo* es frecuente a lo largo de todo el año, los campos en barbecho son altamente susceptibles a la pérdida de suelo por erosión eólica debido a la insuficiente cubierta de residuos vegetales en la superficie del suelo y las múltiples operaciones de laboreo realizadas por el agricultor (López et al., 2001). Por este motivo, se han realizado en esta región varios estudios sobre el papel que juega el LC en el control y prevención de las pérdidas de suelo por erosión eólica. Los trabajos de López et al. (1998), Sterk et al. (1999) y Gomes et al. (2003) demostraron que tanto la saltación como el flujo vertical de aerosoles llegan a reducirse hasta niveles mínimos si la labor con vertedera es sustituida por una labor de chisel como labor primaria durante el barbecho. La menor susceptibilidad del suelo bajo RT se explica por una menor fracción erosionable (como media, un 10% inferior), mayor porcentaje de suelo cubierto por restos vegetales del cultivo anterior y por grandes agregados (30% más de cobertura) (López et al., 1998, 2000). Con estos trabajos se confirma la importancia de los residuos vegetales para el control de los procesos de degradación del suelo.

En los suelos de los secanos áridos y semiáridos de Aragón, donde la producción

de biomasa es baja, el mantenimiento de una adecuada cubierta de residuos en la superficie del suelo sólo es posible con sistemas de LC y, en especial, con NT. López et al. (2003, 2005) señalaron que la falta de operaciones de laboreo hacen del NT la mejor estrategia de manejo durante el largo periodo de barbecho ya que, al final del mismo, un 10-15% de la superficie del suelo todavía se mantenía cubierta con restos del cultivo de cebada. Por el contrario, en los tratamientos con laboreo, la labor de vertedera incorporaba al suelo prácticamente la totalidad de los residuos (90-100%) y el chisel lo hacía en un 50-70%.

Los trabajos más recientes sobre comparación de sistemas de laboreo han cuantificado las emisiones de CO₂ del suelo a la atmósfera (Álvaro-Fuentes et al., 2007, 2008b). Los resultados obtenidos mostraban cómo el flujo de CO₂ era altamente dependiente de las condiciones climáticas lo que explicaba que se encontraran más diferencias entre campañas agrícolas que entre tratamientos de laboreo. A pesar de que el efecto del laboreo no fue muy significativo, las menores tasas de emisión de CO₂ correspondieron siempre al tratamiento de NT (Álvaro-Fuentes et al., 2008b). Es interesante destacar que, mientras los flujos de CO₂ registrados el día anterior a las labores fueron bajos y similares en todos los tratamientos de laboreo comparados, inmediatamente después de las labores se produjo un aumento significativo de las emisiones de CO₂ en los tratamientos con laboreo, especialmente bajo CT (Álvaro-Fuentes et al., 2007). Estos mayores flujos con CT se explican por la mayor tasa de descomposición de la materia orgánica del suelo debido al efecto de la labor en la rotura de agregados, la aireación del suelo y la incorporación al suelo de los residuos de cosecha (Álvaro-Fuentes et al., 2009). En este sentido, los trabajos de Álvaro-Fuentes et al. (2008a,b,c, 2009) en el secano aragonés, demostraron que el contenido de carbono orgánico de la superficie del suelo puede incrementarse de forma significativa con la adopción de sistemas de NT y la intensificación del sistema de cultivo (eliminación del periodo de barbecho).

Los resultados obtenidos en los estudios anteriores indican que el LC puede plantearse como una alternativa de manejo sostenible para el secano aragonés. Pero de estos resultados también se deduce que la magnitud de la respuesta del suelo y del cultivo depende enormemente de las condiciones de clima y suelo, y del

tiempo transcurrido desde la adopción del LC. Por tanto, para llegar a conclusiones fiables sobre la idoneidad de estos sistemas alternativos es necesario evaluar su potencial bajo diferentes condiciones agroclimáticas y disponer de datos de larga duración. También hay que señalar que los trabajos anteriores se han llevado a cabo en parcelas experimentales establecidas y mantenidas por grupos de investigación. Aunque importantes para la investigación, las condiciones controladas en las parcelas experimentales pueden diferir de las prácticas reales llevadas a cabo por los agricultores en sus campos. Por ello, debemos ser cautos al extrapolar los resultados provenientes de pequeñas parcelas a la escala de grandes campos agrícolas (Blanco-Canqui y Lal, 2008; Christopher et al., 2009). Esta misma idea se infiere de las conclusiones alcanzadas en el proyecto europeo *Knowledge Assessment and Sharing on Sustainable Agriculture*, KASSA (Arrué et al., 2007), donde se destaca la necesidad de trasladar los estudios realizados en las parcelas de ensayo a los escenarios reales en los que se desarrollan los sistemas de LC y sobre los que existe cierto grado de desconocimiento. Este desconocimiento también se constata en Aragón. Así, una encuesta elaborada por el Centro de Transferencia Agroalimentaria del Gobierno de Aragón (CTA-DGA) y la Asociación de Agricultura de Conservación de Aragón (AGRACON) señala una percepción muy positiva de las ventajas del LC por parte de los agricultores que la utilizan (Vallés, 2009). Sin embargo, esta misma encuesta destaca la falta de conocimiento sobre los suelos en los que se están aplicando estas técnicas.

1.4. Carbono orgánico del suelo y agricultura.

El suelo es el mayor reservorio de carbono de la biosfera. A nivel mundial, los suelos almacenan tres veces más carbono, en forma de materia orgánica [*organic matter* (OM)], que la atmósfera y la biomasa vegetal (Fischlin et al., 2007). Aunque hoy en día sabemos que este gran reservorio es sensible a los cambios climáticos y a la actividad humana, nuestro conocimiento sobre cómo y en qué escala de tiempo se producirá la respuesta a dichos cambios es aún limitado (Schmidt et al., 2011). La abundante literatura científica que hay al respecto refleja la gran importancia que tiene el carbono orgánico del suelo [*soil organic carbon* (SOC)] no sólo por su

potencial como sumidero de C atmosférico (reducción de CO₂ atmosférico), sino también por ser esencial para la sostenibilidad del suelo, de especial relevancia en el caso de sistemas agrícolas.

El contenido de SOC es considerado, de hecho, un indicador clave de la calidad del suelo y del sistema agrícola en su totalidad ya que está relacionado con numerosas propiedades y procesos responsables de la productividad agrícola y la integridad medioambiental. Incluso en regiones semiáridas, donde la capacidad del suelo para la producción agrícola es más limitada, el SOC puede ejercer una gran influencia sobre la calidad del suelo favoreciendo la estabilidad estructural, la porosidad, la capacidad de agua disponible, la capacidad de intercambio catiónico, e incrementando, finalmente, la producción y los beneficios económicos del agricultor (Carter, 2002; Haynes, 2005; Ogle y Paustian, 2005).

Desgraciadamente, la agricultura mecanizada e intensiva desarrollada durante el siglo XX ha causado una disminución de SOC a nivel mundial con serias implicaciones agrícolas y medioambientales. Según estudios de larga duración, la agricultura convencional ha reducido aproximadamente a la mitad el contenido de SOC durante los primeros 20-40 años tras la puesta en cultivo de un suelo natural (Johnston, 1973; Matson et al., 1997). En el caso de Europa, de acuerdo con la *Estrategia Temática para la Protección del Suelo* (Comisión Europea, 2006), entre los ocho procesos de degradación del suelo identificados, destaca la disminución de SOC. Entre las causas, se señalan, además de factores climáticos, actividades humanas insostenibles. De hecho, alrededor de un 45% de los suelos europeos tienen un bajo o muy bajo contenido en carbono orgánico [*organic carbon (OC)*], <20 g kg⁻¹ (Agencia Europea de Medio Ambiente, 2010). Estas cifras son aún más preocupantes en la región Mediterránea ya que se estima que alrededor de un 74% de su superficie presenta un horizonte superficial de suelo (0-30 cm) con un contenido en OC <20 g kg⁻¹ (Van-Camp et al., 2004). Ante esta situación, la Comisión Europea señala la necesidad de adoptar prácticas de manejo sostenibles, como las técnicas de LC, ya que pueden contribuir de forma eficaz a la solución de los problemas agromedioambientales que están incidiendo gravemente en extensas zonas agrícolas.

europeas (Jones et al., 2012).

La utilización de sistemas de LC, y en especial NT, podría invertir este evidente declive en SOC, tal y como señalan estudios realizados en las últimas décadas en diferentes regiones del mundo (revisados por West y Post, 2002; Govaerts et al., 2009). Sin embargo, de estos estudios también se concluye que la respuesta al cambio en el manejo del suelo puede ser variable y no sólo por la multitud de factores que pueden influir (clima, suelo, prácticas agrícolas, etc.) sino también por la propia complejidad de la OM, como vamos a ver a continuación.

1.4.1. Fracciones de materia orgánica del suelo.

Se ha dicho de la materia orgánica del suelo [*soil organic matter* (SOM)] que es “el componente más complejo y menos conocido de los suelos” (Magdoff y Weil, 2004). Esta complejidad se debe a que la SOM es una mezcla heterogénea de sustancias orgánicas de diversa composición química y diferente tasa de descomposición. Con el objetivo de dilucidar su compleja composición y comprender su dinámica y mecanismos de estabilización en el suelo, la comunidad científica ha realizado un considerable esfuerzo desarrollando técnicas que permiten separar fracciones o pools de SOM con características y dinámicas diferentes. Una detallada relación de las principales técnicas utilizadas se puede encontrar en el trabajo de revisión realizado por Wander (2004).

Una vez que se ha comprendido que la persistencia de la OM en el suelo depende no sólo de su calidad o naturaleza sino también de su localización dentro de la matriz del suelo, se han desarrollado nuevos métodos de fraccionamiento dirigidos a la separación y cuantificación de pools de SOM activos (lábiles) vs. resistentes (recalcitrantes). Los métodos de fraccionamiento físico, basados en la separación por tamaño y/o densidad, están siendo muy útiles en la investigación de la dinámica del OC al tener en cuenta la complejidad estructural y funcional de la SOM, a diferencia de los clásicos métodos de fraccionamiento químico (Christensen, 2001; Wander, 2004).

Basándose en un procedimiento de fraccionamiento físico, Cambardella y Elliot (1992) separaron la fracción de SOM unida a las partículas menores de 53 µm de

la fracción de mayor tamaño que definieron como materia orgánica particulada [*particulate organic matter (POM)*]. La POM está compuesta principalmente por fragmentos finos de restos vegetales y otros residuos orgánicos (hifas, hongos, secreciones mucilaginosas) en diferentes estados de descomposición. Esta fracción constituye una fuente de energía para los microorganismos y es un importante agente de formación de macroagregados. Al constituir un reservorio de carbono lábil y, por tanto, de fácil descomposición, la POM es sensible a cambios en el manejo del suelo (Cambardella y Elliot, 1992; Wander, 2004). Por el contrario, la fracción órganomineral [*mineral-associated organic matter (Min)*], más transformada, corresponde a la SOM estabilizada a través de su unión con partículas minerales (arcillas y limos). Debido a su elevada persistencia en el suelo y su alta contribución al SOC total, esta fracción resulta de particular interés en el contexto del ciclo global del carbono (Schmidt et al., 2011; Feng et al., 2013).

La identificación de fracciones de SOM sensibles a cambios en el manejo del suelo resulta de gran interés a la hora de evaluar la idoneidad de los sistemas de LC. De hecho, el contenido total de SOM no es siempre el mejor indicador de calidad del suelo, especialmente en regiones semiáridas, donde las altas temperaturas y los bajos contenidos de humedad del suelo son factores limitantes para la acumulación de SOM (Chan et al., 2003; Moreno et al., 2006; Melero et al., 2012). Ya que bajo estas condiciones cambios significativos en el SOM asociados al LC sólo pueden esperarse a largo plazo, resulta de especial interés identificar indicadores más sensibles y tempranos. Éste parece ser el caso de la POM ya que son diversos los estudios en los que se señala un incremento de esta fracción tras la adopción del NT (Six et al., 1999, 2000a; Dou y Hons, 2006; Virtó et al., 2007; Álvaro-Fuentes et al., 2008c; Martín-Lammerding, 2013). Sin embargo, su efectividad como indicador parece depender de varios factores como son la textura del suelo, la cantidad y calidad de los residuos vegetales aportados y el historial de manejo (Domínguez et al., 2009; Martín-Lammerding, 2013). La respuesta de la fracción Min es, por el contrario, mucho más variable (Álvaro-Fuentes et al., 2008c; Jagadamma y Lal, 2010; Bhattacharyya et al., 2012) y la causa parece ser compleja ya que implica, además de a muchos factores influyentes (tales como textura y mineralogía), a la

naturaleza inherente de esta fracción y a los diferentes mecanismos de estabilización (recalcitrancia bioquímica y asociaciones órgano-minerales) (Six et al., 2000b; Chenu et al., 2006; Moni et al., 2010; Kleber et al., 2011). En este sentido hay que señalar que, si bien en estos últimos años se ha avanzado mucho en la caracterización de las diferentes fracciones de SOM, todavía es necesaria más investigación para alcanzar un mayor conocimiento sobre la contribución específica de cada fracción a la calidad y funcionamiento del suelo (Schmidt et al., 2011; Stockmann et al., 2013).

1.4.2. Mecanismos de estabilización de la materia orgánica del suelo.

El contenido de SOC es el resultado del balance entre los aportes (entradas) y las pérdidas (salidas) de OM. En los ecosistemas naturales la OM se incorpora al suelo a través del aporte continuo de biomasa vegetal (áerea y subterránea) y de rizodeposiciones, y se pierde principalmente por mineralización aunque, en determinadas situaciones, las pérdidas por lixiviación y erosión también pueden llegar a ser importantes (Sollins et al., 1996). Mientras que en estos sistemas las condiciones ambientales y, más en concreto, las climáticas (precipitación y temperatura), son los factores que más afectan a los flujos de OC, en el caso de suelos de cultivo, el manejo agrícola parece ejercer una influencia decisiva en el balance final de carbono (Magdoff y Weil, 2004). Salvo en las situaciones en las que se aplica OM externa (estiércol, purín, compost, etc.), el principal aporte de OC a un suelo agrícola proviene de los restos de cosecha. En estos suelos la entrada de OC suele ser menor que en suelos naturales y no se debe, generalmente, a una menor productividad primaria neta sino a la retirada por parte del agricultor de mucha de la biomasa vegetal producida. Asimismo, las prácticas agrícolas tradicionales, y más concretamente el laboreo intensivo del suelo, favorecen la pérdida de SOM y explican, en conjunto, la sustancial disminución del contenido de SOC que conlleva la puesta en cultivo de un suelo natural (Magdoff y Weil, 2004).

El laboreo afecta a la dinámica de la SOM a través de tres mecanismos principales: incorporación de residuos de cosecha al interior del suelo, cambio en las condiciones microclimáticas del suelo y alteración periódica de la estructura del suelo por laboreo (Balesdent et al., 2000). Los tres mecanismos favorecen la

mineralización de la SOM y el tipo, frecuencia e intensidad de la labor determinan la tasa y magnitud de la mineralización. El modelo conceptual propuesto por Six et al. (1998) contempla el efecto perturbador del laboreo en la dinámica de la SOM a través del ciclo de formación y destrucción de agregados de suelo (Fig. 1.2). Este modelo nos permite comparar la situación de un suelo labrado (CT) con otro no labrado (NT) y comprender por qué el laboreo estimula y acelera la descomposición de la SOM. La rotura física de macroagregados de suelo por efecto de la labor expone la OM de su interior a la acción de los microorganismos e inhibe la formación y estabilización de microagregados dentro de macroagregados (Six et al., 1998). La menor tasa de renovación o *turnover* de los macroagregados bajo NT favorece la protección y estabilidad de la SOM aunque el grado con el que esto ocurre es variable. Según datos recogidos en diversos trabajos de revisión, esta variabilidad responde no sólo a diferencias en las condiciones climáticas y edáficas, sino también al tiempo transcurrido desde la adopción del NT y al historial de manejo previo (Balesdent et al., 2000; West y Post, 2002; Franzluebbers, 2004). Por tanto, para poder llegar a comprender correctamente la dinámica de la SOM, son necesarios estudios de larga duración en los que la comparación entre sistemas de laboreo se realice bajo una amplia diversidad de condiciones de clima y suelo.

Como hemos señalado anteriormente, la respuesta de la SOM a cambios en el manejo del suelo también depende de la fracción de OM y de su localización dentro de la matriz del suelo. En este sentido, existe un creciente interés por comprender y caracterizar los procesos mediante los cuales la OM persiste en el suelo. Básicamente son tres los mecanismos de estabilización propuestos (Sollins et al., 1996; Six et al., 2002; von Lützow et al., 2006) (Fig. 1.3): (1) estabilización física mediante la protección de la OM en el interior de los agregados frente al ataque de microorganismos y enzimas; (2) estabilización química por la unión química o fisicoquímica de la OM a las partículas minerales del suelo (arcillas y limos) formando complejos órgano-minerales; y (3) estabilización bioquímica debida a la naturaleza recalcitrante de compuestos orgánicos ya sea por su propia composición molecular o resultado de la transformación metabólica durante la descomposición de la SOM. Sin embargo, debido a la alta complejidad tanto de estos procesos en sí

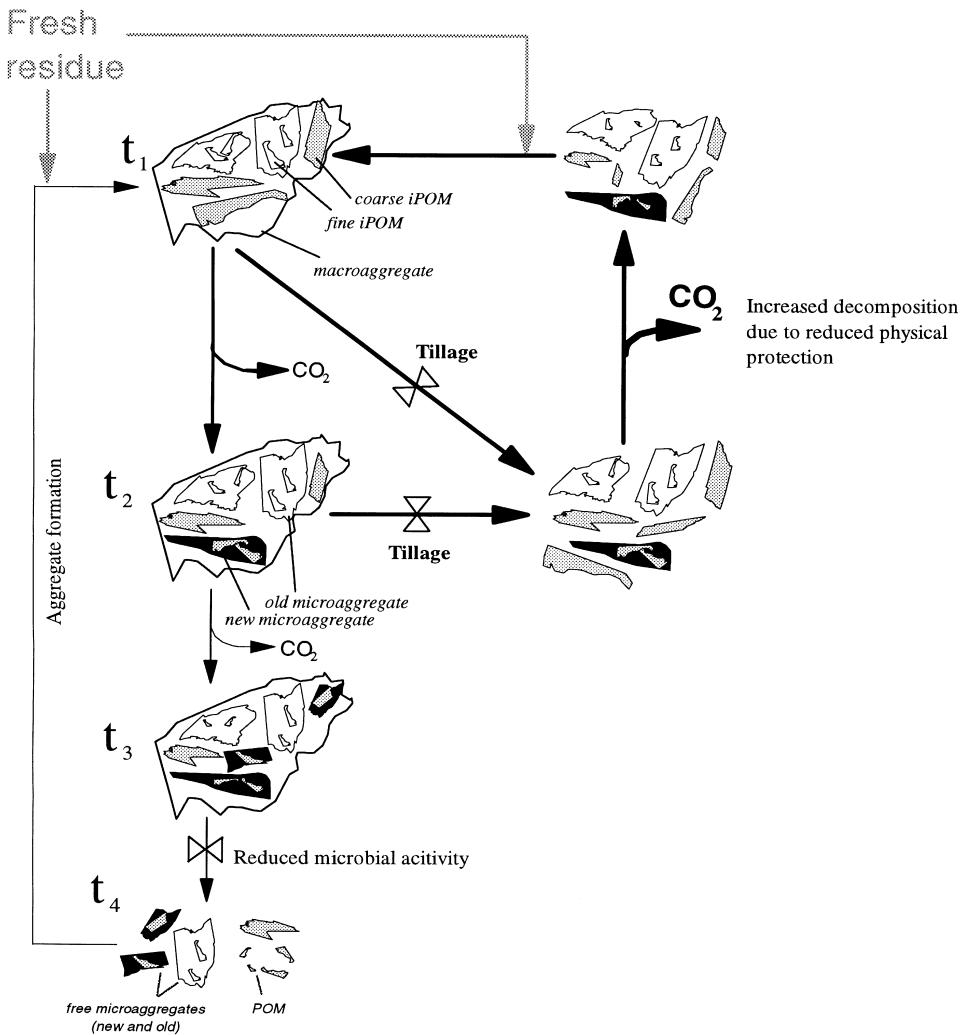


Fig. 1.2. Modelo conceptual del “ciclo de vida” de un macroagregado de suelo y de la formación de microagregados en el que se muestra la dinámica de almacenamiento y mineralización de la materia orgánica del suelo. Fuente: Six et al. (2000a).

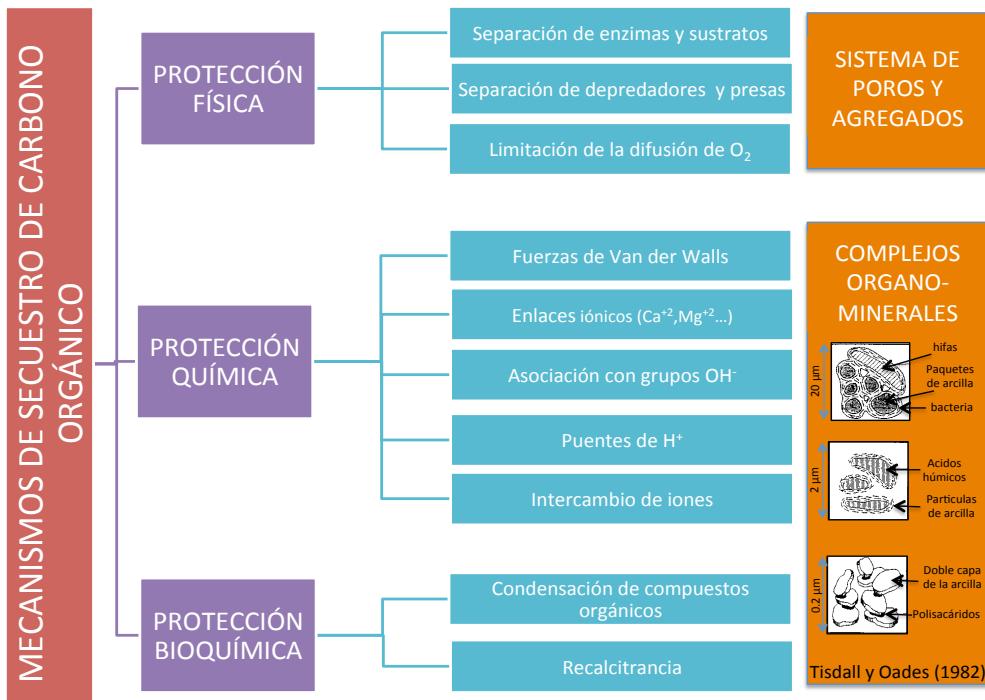


Fig. 1.3. Principales procesos implicados en la protección de la materia orgánica en el suelo.
Fuente: Elaboración propia.

como de sus interacciones, aún no se ha logrado comprender totalmente la dinámica de estabilización de la SOM ni sus mecanismos de regulación (Schmidt et al., 2011; O'Brien y Jastrow, 2013).

Debido a la alta persistencia de la OM estabilizada en los complejos organo-minerales y sus implicaciones en el mantenimiento a largo plazo de la calidad y productividad del suelo, el número de estudios sobre la fracción Min de la SOM ha aumentado considerablemente (Clemente y Simpson, 2013; Feng et al., 2013; Jindaluang et al., 2013; Lopez-Sangil y Rovira, 2013; O'Brien y Jastrow, 2013, entre otros). Hoy en día sabemos que la formación de complejos organo-minerales está controlada en gran medida por la textura del suelo y, especialmente, por el contenido en arcilla y su mineralogía (Chenu et al., 2006; Sollins et al., 2006). Sin embargo, las uniones implicadas en las formaciones organo-minerales son de muy diverso

tipo y fuerza (puentes de hidrógeno, puentes con cationes polivalentes, interacciones electrostáticas e hidrofóbicas, fuerzas de van der Waals, etc.) (Fig. 1.3) lo que, junto a sus posibles interacciones, complican su identificación y caracterización (Plante et al., 2006; Lopez-Sangil y Rovira, 2013). Por otro lado, la superficie de las arcillas tienen un número limitado de sitios de unión que pueden saturarse a concentraciones altas de OC (Six et al., 2002).

En definitiva, de los estudios anteriores podemos concluir que los procesos y mecanismos de estabilización de la SOM son complejos y que nuestro conocimiento sobre los mismos es aún limitado. Por ello, es necesaria más investigación que permita la comprensión de la heterogeneidad del suelo a pequeña escala y que ayude a predecir la respuesta de los diferentes pools de SOM a cambios en el uso y manejo del suelo.

1.5. Estructura del suelo y laboreo.

Una adecuada estructura del suelo es un requisito esencial para el uso sostenible del suelo ya que de ello depende la mayoría de los procesos físicos, químicos y biológicos que ocurren en su interior. En los suelos agrícolas, las prácticas de manejo, en general, y el laboreo, en particular, pueden influir enormemente en los procesos de formación y estabilización de la estructura del suelo (Kay y Angers, 2000). Junto al tráfico de maquinaria agrícola, el laboreo constituye una importante fuerza externa que, de forma directa e inmediata, altera la estructura del suelo, rompiendo los agregados y liberando la SOM protegida en su interior. De hecho, el laboreo intensivo y continuado que ha acompañado a la agricultura durante el siglo XX, además de causar pérdidas importantes de SOM, ha provocado o acelerado otros procesos de degradación, como la erosión y la compactación del suelo, que no son más que manifestaciones del deterioro de la estructura del suelo (Montgomery, 2008; Lal, 2009). En Europa, estos procesos de degradación siguen siendo preocupantes, especialmente en la región Mediterránea, donde la erosión y la pérdida de SOM parecen seguir aumentando debido a prácticas de manejo inadecuadas (Jones et al., 2012).

El desarrollo de la estructura del suelo está estrechamente relacionado con la

dinámica del SOM y, por tanto, cualquier tratamiento que favorezca la acumulación de OC, también incrementará la estabilidad estructural del suelo. De la misma manera, una buena estructura del suelo asegurará la protección de OC en el interior de agregados estables y, con ello, su acumulación y persistencia en el suelo (Carter y Stewart, 1996; Carter, 2002). El modelo conceptual de Six et al. (2000a), representado en la Figura 1.2, muestra esta positiva interrelación entre estructura y SOM; también de este esquema se deduce que el efecto combinado de ausencia de laboreo y presencia de residuos de cultivo, como ocurre en un sistema de NT, puede favorecer la formación y estabilidad de agregados de mayor tamaño y, con ello, una mayor protección de OM que en un sistema de CT (Kay y Angers, 2000). La importancia que tiene la OM en el mantenimiento de la estructura del suelo se refleja en los intentos realizados por llegar a establecer valores umbrales o críticos de contenido de OC por debajo de los cuales se produce un deterioro significativo de la estructura del suelo. A pesar de que en la literatura podemos encontrar muchos ejemplos de relaciones positivas entre SOM y propiedades de la estructura del suelo, son pocos los estudios en los que se establecen niveles críticos de SOM. Según estos trabajos, los valores críticos de SOC se encontrarían en un rango de entre 12 y 35 g kg⁻¹ (Kemper y Koch, 1966; Greenland et al., 1975; Carter, 1992; Le Bissonnais y Arrouays, 1997; Boix-Fayos et al., 2001). Aún sabiendo que estos valores no son universales sino específicos para cada suelo y que no siempre se encuentran relaciones significativas entre SOM y propiedades de la estructura del suelo (Loveland y Web, 2003), la obtención de estos datos sigue siendo un objetivo de investigación debido a su utilidad a la hora de evaluar la calidad del suelo y la sostenibilidad de los sistemas agrícolas (Krull et al., 2004; Murphy, 2014).

1.5.1. Propiedades de los agregados de suelo.

Apesar de la importancia de la estructura del suelo, su evaluación y caracterización siguen suponiendo hoy en día un cierto reto ya que no existe una única propiedad ni un único método aceptado universalmente que nos permita su caracterización (Díaz-Zorita et al., 2002; Dexter, 2002). En realidad, el término “estructura del suelo” expresa un concepto cualitativo y no totalmente objetivo y es por ello que han sido

muy diferentes las aproximaciones que se han utilizado para su caracterización (Kay y Angers, 2000; Díaz-Zorita et al., 2002). En cualquier caso, el mantenimiento de una adecuada estructura depende de la presencia de agregados de suelo estables, siendo, por tanto, un requisito necesario para un uso sostenible del suelo. Diferentes estudios han subrayado la necesidad de profundizar en el estudio de las propiedades de los agregados de suelo y caracterizar su dinámica de formación y destrucción para una mejor comprensión de los procesos involucrados en la estabilidad estructural del suelo (Horn, 1990; Blanco-Canqui et al., 2005). El interés de este tipo de estudios se justifica por la influencia que tienen las características de los agregados, por ejemplo, en la emergencia y desarrollo radicular del cultivo (De Freitas et al., 1996), en la capacidad de aireación y retención de agua del suelo (Watts y Dexter, 1997) y en la estabilización y almacenamiento de OC en el suelo (Denef et al., 2004; Six et al., 2004).

Se han propuesto varios modelos de agregación basados en la dinámica del OC (Emerson, 1959; Greenland, 1965a,b; Tisdall y Oades, 1982; Dexter, 1988; Kay, 1990, Six et al., 1999). Tal y como se muestra en la Tabla 1.1, la mayor parte de estos modelos coinciden en que los suelos consisten en agregados de diferente tamaño unidos entre sí por compuestos orgánicos e inorgánicos. Estos agregados dentro del suelo constituyen un sistema dinámico en el que las unidades se crean y se destruyen constantemente. En la mayoría de los suelos el proceso de formación de la estructura se rige por un cierto orden jerárquico de agregación. Esta ordenación o disposición de partículas y agregados de suelo se realiza a tres niveles principales de agregación (Fig. 1.4 y Tabla 1.1) (Tisdall y Oades, 1982): (1) nivel arcilla o microestructuras ($<53 \mu\text{m}$ de diámetro); (2) nivel microagregado ($53\text{-}250 \mu\text{m}$); y (3) nivel macroagregado ($>250 \mu\text{m}$).

Modernas revisiones del modelo jerárquico de agregación han demostrado que la formación de los microagregados estables se produce en el interior de macroagregados del suelo que han sido estabilizados por compuestos orgánicos temporales o transitorios (Oades, 1984; Golchin et al., 1994a,b; Six et al., 1999; Jastrow, 1996). El modelo implica que los macroagregados suelen almacenar mayor cantidad de SOC que los microagregados (Angers y Carter, 1996; Jastrow y Miller,

Tabla 1.1. Modelos de formación de agregados de suelo en secuencia cronológica. Fuente: Adaptado de Blanco-Canqui y Lal (2004, p. 491).

Autores	Mecanismos de agregación
Emmersen (1959)	Las agregados de suelo están formados por dominios de cristales de arcillas y cuarzo estabilizadas por la OM. La cantidad de OC almacenado en los agregados es directamente proporcional a la superficie específica de los minerales de arcilla.
Edwards y Bremmer (1967)	Teoría de los microagregados. La formación de los macroagregados se produce por la unión de la OM, iones polivalentes y arcillas sin carga. El tamaño máximo de los microagregados estables es 250 μm lo cual excluye a la arena de la formación de agregados. Los macroagregados se producen como resultado de la unión de los microagregados y la OM estaría físicamente protegida en el interior de los microagregados.
Greenland (1965a,b)	Los agregados se forman y estabilizan por polisacáridos derivados de la acción microbiana sobre los residuos vegetales frescos, pero su efectividad depende de las características intrínsecas del suelo.
Tisdall y Oades (1982)	Teoría jerárquica de agregación. A cada nivel de agregación le corresponde un agente aglutinante característico (partículas minerales libres y microagregados tamaño limo ($<20 \mu\text{m}$)-persistentes, microagregados ($20\text{--}250 \mu\text{m}$)-temporales, macroagregados-transitorios). Tras la degradación de los macroagregados se liberan microagregados estables.
Oades (1984)	Raíces y hongos estabilizan los macroagregados y en su interior se forman los microagregados estables. La degradación de los macroagregados libera los microagregados estables.
Elliott y Coleman (1988)	Teoría jerárquica de poros. Establece 4 categorías jerárquicas de poros: (1) macroporos; (2) poros entre macroagregados; (3) entre microagregados dentro de macroagregados; y (4) dentro de microagregados. Estos poros constituyen limitaciones para el movimiento de la fauna del suelo. Las condiciones anaeróbicas del interior de los macroagregados favorecen la formación de los microagregados.
Dexter (1988)	Principio de exclusión de la red de poros. Establece que los agregados de un nivel inferior (macroagregados) son más densos y están más cohesionados que los agregados de niveles superiores (microagregados) ya que en los niveles inferiores se excluyen los grandes poros que existen a nivel macroagregado.
Shipitalo y Protz (1989)	Confirman la teoría de Oades de formación de los microagregados a partir de macroagregados en agregados formados por las heces de las lombrices de tierra.
Kay (1990)	La dimensión de los compuestos que actúan como nexo de unión dentro de los agregados es proporcional a las superficies que tienen que unir.
Oades y Waters (1991)	Confirmaron la teoría jerárquica de agregados sólo para suelos en los que la OM es el principal agente aglutinante.
Golchin et al. (1994a,b)	Vincula la formación de agregados a la degradación de la OM. Los microbios de la rizosfera consumen OM fresca produciendo POM (de origen vegetal) y compuestos microbianos. La POM se convierte en el centro de los microagregados estables.
Six et al. (1999)	Teoría de agregación y secuestro de carbono en campos agrícolas. La puesta en marcha de un cultivo acelera la tasa de renovación de los macroagregados de suelo lo que provoca la pérdida de parte de la POM intramacroagregado. El uso agrícola también inhibe la formación de microagregados en el interior de los macroagregados y el secuestro de SOC a largo plazo. Los macroagregados se estabilizan por residuos vegetales frescos, raíces y POM interagregado.

1998; Puget et al., 1995; Alvaro-Fuentes et al., 2008a), pero este almacenamiento se desarrolla a corto plazo (Franzluebbers y Arshad, 1997; Sainju et al., 2003). Los microagregados, por el contrario, almacenan y promueven el secuestro de SOC a largo plazo (Monreal y Kodama, 1997).

Bajo las premisas del modelo jerárquico de agregación y el principio de exclusión de poros (Tabla 1.1) se deduce que la estabilidad de los diferentes niveles de agregación depende de los niveles inferiores. Según este planteamiento, la investigación con agregados de suelo permitirá conocer la susceptibilidad del suelo a la degradación debida a procesos que afectan a su estructura primaria. Con la caracterización de propiedades como la resistencia a la compresión y la estabilidad en húmedo de agregados de suelo se determina la capacidad del suelo para mantener la distribución y tamaño de sus agregados tras someterlo a diferentes estreses (abrasión, dispersión, compactación, etc.), ya sean producidos por la acción del clima (lluvia, viento) o por fuerzas mecánicas externas (laboreo) (Angers y Carter, 1996). Por ello y, como veremos a continuación, son propiedades que pueden resultar muy útiles a la

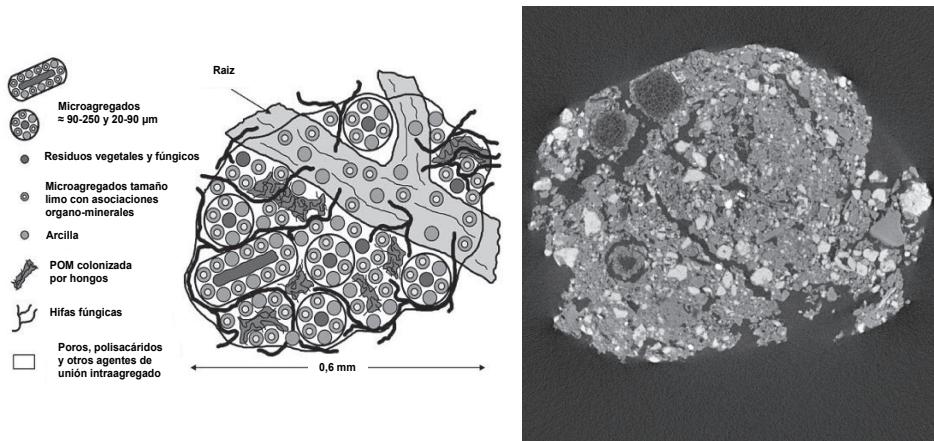


Fig. 1.4. Diagrama conceptual de la teoría jerárquica de agregación mostrando los microagregados de suelo en el interior de un macroagregado. Fuente: Modificado de Jastrow y Miller (1998, p. 209).

hora de evaluar la idoneidad de un determinado sistema de manejo bajo condiciones específicas de clima y suelo.

1.5.1.1. Resistencia a la compresión.

La resistencia del suelo a la rotura por compresión [*tensile strength* (TS)] es una propiedad dinámica que mide la fuerza de las uniones inter e intra-agregado y es, por tanto, un indicador del grado de agregación del suelo (Horn y Dexter, 1989) y de su estabilidad estructural (Watts y Dexter, 1998). A pesar de que es una de las propiedades mecánicas más útiles por ser muy sensible al tipo de suelo y al manejo (Watts y Dexter, 1998; Blanco-Canqui et al., 2005), su determinación no es muy habitual en los estudios sobre LC.

La mayor parte de los trabajos que evalúan la TS se han centrado en la comparación de suelos agrícolas frente a suelos de pastos y praderas (Watts y Dexter, 1998; Munkholm y Kay, 2002). De estos trabajos se concluye, por ejemplo, que el laboreo y, en general, el manejo agrícola del suelo conduce a un aumento de TS y que esto se puede traducir, al mismo tiempo, en una mayor resistencia de estos suelos a ser de nuevo labrados o, lo que es lo mismo, en un mayor esfuerzo de preparación de la cama de siembra (Munkholm y Kay, 2002; Blanco-Canqui et al., 2005). Sin embargo, la respuesta al LC puede diferir de la encontrada con sistemas de laboreo tradicional debido a la reducción del número e intensidad de las labores y a la mayor actividad biológica del suelo (Butt et al., 1999). Además, la respuesta puede depender de otra serie de factores como la textura o el contenido de SOC. Por ejemplo, Benjamin y Cruse (1987), comparando un sistema de laboreo con subsolador con otro de NT en dos suelos de diferente textura, encuentran diferencias significativas en los valores de TS en el suelo franco-arcilloso pero no en el franco-limoso.

En cuanto al contenido de SOC, la literatura muestra discrepancias en su relación con la TS y que éstas pueden ser debidas a diferencias en las condiciones de suelo y manejo (Beare et al., 1994; Imhoff et al., 2002). Imhoff et al. (2002) encuentran que el efecto del OC depende de la textura del suelo ya que, mientras que en suelos arcillosos el aumento de carbono conduce a un incremento de los valores de resistencia, en suelos con menor contenido en limo más arcilla (suelos frances)

los reduce. El contenido de agua en el suelo también parece afectar en gran medida a los valores de TS (Causarano, 1993; Munkholm y Kay, 2002) y esto se debe a que la fuerza de unión entre la OM y las partículas minerales del suelo disminuye al aumentar la humedad del suelo (Causarano, 1993). Esta característica adquiere mayor relevancia en suelos agrícolas ya que la determinación de TS puede ser muy útil para identificar el periodo más idóneo para la preparación de la cama de siembra (Munkholm y Kay, 2002).

De los resultados obtenidos en todos estos estudios se puede concluir que son muchas y complejas las interrelaciones entre las propiedades de los agregados de suelo que afectan a la TS. Por este motivo, es mucha la investigación que podría llevarse a cabo y que ayudaría a evaluar de forma precisa los cambios producidos en el suelo por efecto del manejo y, en concreto, por la adopción de sistemas de LC.

1.5.1.2 Estabilidad estructural en húmedo.

Debido a su relación con muchos procesos de carácter agrícola y medioambiental (movimiento y almacenamiento de agua en el suelo, susceptibilidad del suelo a la erosión hídrica, etc.), la estabilidad estructural de suelo en agua es una propiedad tradicionalmente empleada para la cuantificación de los cambios en la estructura del suelo asociados a la actividad agrícola (Amézketa, 1999; Grönsten y Børresen, 2009).

El procedimiento más comúnmente utilizado para la determinación de esta propiedad es el método de tamizado en húmedo propuesto por Kemper y Koch (1966) y mejorado posteriormente por Kemper y Rosenau (1986). Con este método, se cuantifica la rotura total de agregados de suelo causada por su inmersión y agitación en agua. Aun siendo el método más utilizado y habiéndose demostrado como idóneo en los estudios sobre manejo de suelo y también sobre comparación de sistemas de laboreo (Rhton, 2000; Mrabet et al., 2001; Eynard et al., 2005; Álvaro-Fuentes et al., 2008a), este método no discrimina entre los diferentes procesos de desestabilización implicados: explosión/estallido (*slaking*) e hincharimiento de los agregados (*swelling*), dispersión de las arcillas y rotura mecánica por abrasión. Esta limitación resulta de vital importancia a la hora de identificar las propiedades

y mecanismos responsables de la formación y estabilización de agregados. Así, en aquellos suelos en los que el contenido de OM es el principal responsable de la agregación del suelo, el método de Kemper y Rosenau (1986), evaluando todos los procesos de desestabilización en conjunto, resulta adecuado ya que la resistencia de los agregados al estallido (el proceso de desestabilización más importante) parece ser función de la SOM (Chenu et al., 2000). Sin embargo, cuando la SOM juega un papel limitado como agente cementante y son otras las propiedades responsables (arcillas, CO_3Ca , etc.), se hace necesaria la separación de los diferentes mecanismos de desestabilización para poder discriminar suelos. Para ello, se han planteado diferentes métodos y aproximaciones (Amézketa, 1999; Nimmo y Perkins, 2002) pero que, en cierta manera, han contribuido a incrementar el número de procedimientos de determinación y, con ello, a la falta de métodos estandarizados. Todo ello complica la comparación de datos obtenidos en diferentes laboratorios y dificulta el establecimiento, con fines predictivos, de adecuadas relaciones entre estabilidad y otras propiedades del suelo. Por este motivo, es de gran interés profundizar en el estudio de los diferentes procesos de desestructuración del suelo en agua y llegar a establecer un método fiable de caracterización que permita una aplicación directa en la evaluación del suelo en cuanto a su calidad, respuesta al manejo agrícola y susceptibilidad a procesos de degradación.

1.6. Objetivos, planteamiento y estructura del trabajo.

El objetivo general de esta Tesis Doctoral es evaluar la capacidad de sistemas agrícolas basados en no laboreo (NT) para almacenar carbono orgánico y mejorar el estado físico del suelo en zonas de cereal de secano en Aragón. Esta evaluación se ha llevado a cabo utilizando campos de agricultores en los que se practica laboreo de conservación, dando el salto desde una investigación a nivel de parcela experimental a escenarios reales representativos del secano aragonés. Para la consecución de este objetivo general, se han abordado tres objetivos específicos que se detallan a continuación.

Objetivo 1. Caracterización general de los escenarios reales de NT en Aragón.

Con este objetivo, que se desarrolla en profundidad en el *Capítulo 2* del presente trabajo, se ha establecido el marco de manejo y tipología de suelos sobre los que se está aplicando el NT en diferentes zonas agroclimáticas de producción de cereal de secano en Aragón. Para ello, se han llevado a cabo dos tareas principales. Una primera tarea ha consistido en la **localización de campos de agricultores en los que se lleve practicando NT de forma continuada durante al menos 5 años**. El punto de partida ha sido un listado de aproximadamente 400 agricultores proveniente de una encuesta regional llevada a cabo en 1998 y actualizada en 2007 por el Centro de Técnicas Agrarias del Gobierno de Aragón (CTA-DGA). Para el desarrollo de esta tarea se ha contado con la ayuda del CTA y de la Asociación de Agricultura de Conservación de Aragón (AGRACON). La información obtenida, a partir de 22 campos finalmente seleccionados, ha permitido conocer la diversidad de prácticas de manejo que acompañan a los sistemas de NT y aproximarnos a la realidad de la agricultura de conservación en Aragón.

Una segunda tarea ha consistido en la **determinación del contenido de carbono orgánico y de propiedades generales de la superficie del suelo bajo NT**. Con el propósito de realizar una primera evaluación de los sistemas de NT, también se seleccionaron campos adyacentes manejados con laboreo convencional (CT) con

objeto de comparación. Por tanto, en esta primera parte del trabajo de Tesis, un total de 22 pares de suelos de NT y CT han sido caracterizados y comparados.

A partir de la información obtenida en este primer objetivo, se ha llevado a cabo una segunda selección de campos con los que profundizar en el objetivo general de la Tesis a través de la consecución de los objetivos 2 y 3. El trabajo se ha centrado finalmente en 6 sitios de estudio, situados en diferentes zonas agroclimáticas de Aragón, y en cada uno de ellos se ha contado con el par de suelos bajo NT y CT y con un suelo próximo inalterado con vegetación natural (NAT) incluido como control. En la elección de estos campos se ha tenido en cuenta, además de su representatividad, que el NT se estuviera practicando un número elevado de años y que, en cada sitio, los tres campos fueran contiguos para asegurar condiciones topográficas y edáficas lo más similares posible.

Objetivo 2. Evaluación del potencial del NT para almacenar y estabilizar carbono orgánico en el suelo.

Este objetivo se ha concretado en los dos siguientes subobjetivos:

2.1. Determinación del efecto del NT en el contenido de C orgánico y su distribución en diferentes fracciones de la materia orgánica del suelo.

A partir del fraccionamiento físico de la materia orgánica, se han aislado y cuantificado diferentes fracciones o *pools* de materia orgánica de los suelos de NT y CT y del suelo NAT de cada sitio de ensayo. Con este subobjetivo, además de analizar la influencia del laboreo y uso del suelo en la fracción lábil y recalcitrante del C orgánico del suelo (materia orgánica particulada y fracción órgano-mineral), se ha pretendido identificar fracciones que puedan servir como indicadores sensibles a cambios en el manejo del suelo (*Capítulo 3*).

2.2. Estudio de la influencia de la textura del suelo en el almacenamiento y estabilización del C orgánico.

Para la consecución de este subobjetivo, se han establecido relaciones entre la

textura del suelo (arcilla y/o limo) y el contenido de C orgánico de las fracciones de materia orgánica aisladas. Tal y como se detalla en el *Capítulo 4*, en esta etapa se ha realizado una separación más completa de estas fracciones con el fin de disponer de mayor información especialmente sobre la fracción organo-mineral. De esta manera, se ha pretendido identificar aquellas fracciones más estrechamente relacionadas con el contenido en arcilla y limo y evaluar su papel en la protección y preservación de C orgánico en suelos agrícolas y suelos naturales. Otras propiedades generales del suelo, como contenido en CO_3Ca y yesos, pH, etc., también han sido consideradas en las relaciones anteriores.

Objetivo 3. Evaluación de los efectos del NT en propiedades de la estructura del suelo.

Con el estudio de propiedades de la estructura del suelo, además de evaluar el estado físico del suelo tras un uso continuado y prolongado del NT, se han querido identificar los principales factores influyentes en dichas propiedades, prestando especial atención al C orgánico del suelo. Para ello, se han abordado los dos siguientes subobjetivos:

3.1. Caracterización de la resistencia a la compresión y la estabilidad estructural en húmedo de agregados de suelo bajo NT.

El efecto del laboreo y uso del suelo en la resistencia del suelo a la rotura por compresión ha sido evaluado a partir de la caracterización de agregados individuales de diferentes tamaños provenientes de los suelos bajo NT y CT y del suelo NAT de los seis sitios de estudio (*Capítulo 5*). Como se detalla en el *Capítulo 6*, la caracterización de la estabilidad estructural en húmedo ha llevado implícitas, además, la identificación y cuantificación de los diferentes procesos implicados en la desestabilización de agregados de suelo en agua (estallido, hinchamiento, dispersión de arcillas y abrasión).

3.2. Identificación de propiedades de suelo responsables de los cambios en la estabilidad estructural del suelo asociados al manejo agrícola.

Con el propósito de explicar la variabilidad encontrada en la respuesta de

las propiedades de la estructura del suelo a cambios en el uso y manejo del suelo, se han establecido relaciones entre dichas propiedades y otras básicas de suelo entre las que se ha prestado especial atención al contenido en C orgánico. En el **Capítulo 5** se muestran los resultados relativos a la resistencia a la rotura por compresión y en el **Capítulo 6** los correspondientes a los procesos de desestabilización del suelo en agua.

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Capítulo 2

No tillage in rainfed Aragon (NE Spain): Effect on organic carbon in the soil surface horizon.

Soil & Tillage Research (2012) 118, 61-65

► Paisajes del secano aragonés.

2.1. Abstract

Conservation tillage has been encouraged as a management alternative to preserve soil and water resources in semiarid Aragon (NE Spain). In fact, its adoption by farmers, and especially of no tillage (NT) systems, has increased in recent years. However, little information concerning the soils on which these techniques are applied is available for this region. The objective of this study was to assess the potential of NT to increase organic carbon content in the soil surface (0-20 cm) in rainfed Aragon. To this aim, 22 pairs of adjacent farm fields under NT and conventional tillage (CT) were compared in different cereal production areas. The fields were under continuous NT between 5 and 19 years but half were over 10 years. Soil organic carbon (SOC) in NT ranged from 7.06 to 18.53 g kg⁻¹ (0-20 cm depth) and was higher than 12 g kg⁻¹ in nearly 30% of the fields. These contents represented between 8% less (only one case) and 55% more SOC under NT than under CT with an average gain of 20% in favour of NT. The highest SOC contents were found in the NT fields of longer duration (>10 years) and/or managed with practices that enhance the return of more crop biomass to the soil (complete residue return, cropping intensification and manure application). The identification of the current management practices used by farmers has allowed us to know the diversity of the NT-based cropping systems and the reality of the conservation agriculture in our region. Overall, results from this on-farm study indicate that NT can be recommended as a viable alternative to CT to increase organic carbon at the soil surface in cereal production areas of Aragon.

2.2. Introduction

Soil organic carbon (SOC) is a key indicator of soil quality, and also of the entire agricultural system, as it is related to many properties and processes responsible for agricultural productivity and environmental integrity. Even in semiarid regions, where the capacity of soil for agricultural production is limited, the SOC can exert a great influence on soil quality, leading to better physical and chemical soil conditions and increasing, finally, production and economic benefits for the farmer (Carter, 2002; Haynes, 2005; Ogle and Paustian, 2005).

Intensive and continued tillage practices during the 20th century have caused a worldwide decline in SOC with serious environmental and agricultural implications. In the case of Europe, according to the recently adopted Thematic Strategy for Soil Protection (European Commission, 2006), decrease of SOC, together with soil erosion and compaction, are the main soil degradation processes identified. Besides climatic reasons, unsustainable practices of human activities are the most relevant driving forces. This EU communication highlights the need to adopt sustainable management practices, such as conservation tillage, since they can contribute effectively to the solution of agro-environmental problems, of particular interest for the threatened Mediterranean region.

Studies conducted over the past 25 years in different regions of the world have demonstrated the suitability of the conservation tillage, and especially of no tillage (NT), to increase SOC and improve soil quality compared to conventional tillage (CT) systems (West and Post, 2002; Govaerts et al., 2009). These studies also show that the rate and magnitude of change depend on a number of factors such as climate and soil, and interactions with other agricultural practices. At present, it is estimated that NT is practiced on about 117 million ha world wide but only 1.15 million ha are in Europe (Derpsch and Friedrich, 2010). In Spain, according to the Spanish Conservation Agriculture Association (AEAC/SV, 2008), 650,000 ha of agricultural land are under NT. This figure reflects that the rate of adoption of NT is still small in Spain and this despite the fact that the long-term research shows positive results for conservation tillage (Moreno et al., 2010).

Due to particular soil and climate conditions and inappropriate agricultural

practices, Aragon (NE Spain) is a region prone to land degradation by wind and water erosion (López et al., 2001; López-Vicente et al., 2008). For this reason, the adoption of conservation tillage practices has been encouraged as an alternative to preserve soil and water in this region. In fact, according to previous results on soil and crop response to conservation tillage in cereal production areas of Aragon (López et al., 2005; Moret et al., 2007; Álvaro-Fuentes et al., 2008, 2009), NT could be regarded as a viable management alternative. Furthermore, a recent survey conducted by the Department of Agriculture and Food of the Government of Aragon (Vallés, 2009) found a very positive perception of the advantages of conservation tillage by farmers and an increasing adoption in the last years, especially of NT. However, this report also highlights the lack of knowledge about the soils on which these techniques are applied.

The little available information on SOC in agrosystems in Aragon has been collected from small research plots and from single soil types (Álvaro-Fuentes et al., 2009). However, farming practices applied by farmers in their NT fields can be very diverse and differ from those in experimental plots (Blanco-Canqui and Lal., 2008). For these reasons, direct measurements of SOC under on-farm conditions across a range of soils, microclimate and agronomic practices are necessary to get a broad knowledge of the potential of NT in the region. In order to remedy this lack of information, the objective of this study was to assess the potential of NT to increase SOC in the surface layer by comparing adjacent farm fields of NT and CT across different rainfed cereal areas of Aragon. Likewise, this work allowed us to identify current soil and crop residue management practices used by farmers in the region.

2.3. Material and methods

A total of 22 pairs of NT and CT farmer fields were selected from rainfed cereal areas of the provinces of Zaragoza (10 pairs), Huesca (11) and Teruel (1) in Aragon (NE Spain, Fig. 2.1). The fields are located in areas receiving from 400 to 700 mm of mean annual precipitation. Particularly, 32% of them are located between isohyets 400 and 500 mm, 50% between 500 and 600 mm and, finally, 18% above 600 mm. The precipitation exceeds 700 mm per year only in one field (741 mm)

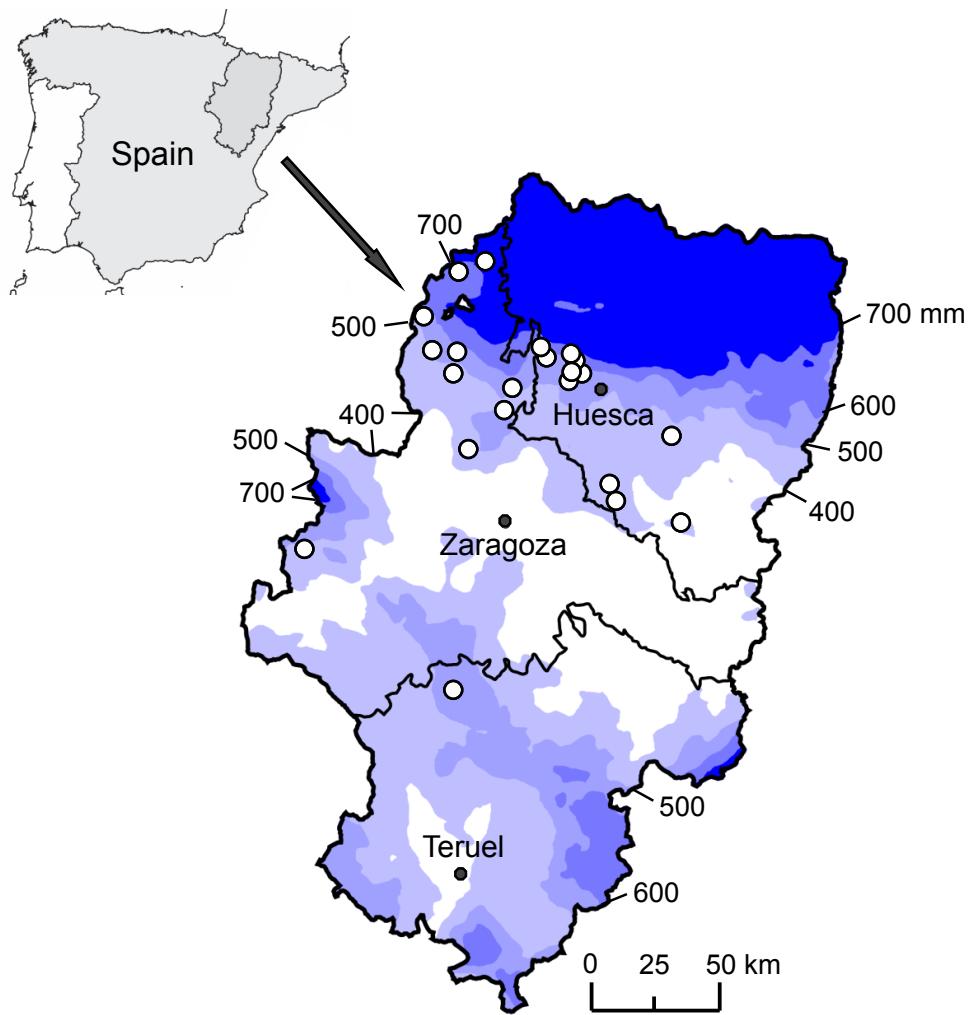


Fig. 2.1. Location of the study sites and average annual rainfall isohyets (mm).

All soils were medium-textured soils, varying from sandy loam to silty clay loam (Fig. 2.2). Sand content ranged from 50 to 550 g kg⁻¹ (0-20 cm soil depth), silt from 280 to 620 g kg⁻¹ and clay from 140 to 370 g kg⁻¹. The CaCO₃ content varied between 60 and 540 g kg⁻¹ but was higher than 200 g kg⁻¹ in 80% of the fields.

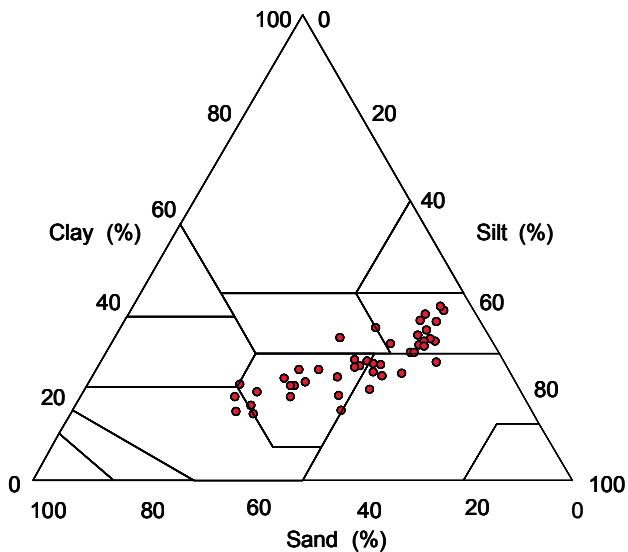


Fig. 2.2. Soil texture class triangle showing the percentages of sand (2000-50 µm), silt (50-2 µm) and clay (<2 µm) of the study soils in the depth of 0-20 cm.

Two main criteria were considered in the selection of the fields: number of years of continuous NT and proximity of the two fields, NT and CT, in each site. The duration of NT varied between 5 and 19 years but in half of the fields was greater than 10 years. Both fields were contiguous, thus ensuring that soil type and slope were as similar as possible. With regards to cropping system, in some sites it was not the same under NT than under CT. Thus, in NT the usual cropping system followed by farmers is the continuous cereal cropping (wheat or barley). In some of these fields (7 of 22) a legume was introduced in rotation with cereal with a varying frequency depending on the site. In the CT fields, legume crop was more unusual (3 of the 22 fields) and, in contrast to NT, in the areas of lower rainfall the traditional

farming system is the cereal-fallow rotation (one crop in 2 years).

Three main tillage implements were identified in the study area as primary tillage tools used by farmers in the CT fields: mouldboard plough, chisel and subsoiler. Although the mouldboard plough has been the most traditional implement in the region (López et al., 2001), its use has been reduced in these last years. In fact, in 16 of the 22 fields characterized in the present study the soil was tilled with chisel. However, only in three cases soil management can be considered as reduced tillage since the rest soil surface was pulverized by excessive chiselling and soil cover by crop residues was low. In 30% of the CT fields, farmers alternate the use of chisel plough with mouldboard plough or subsoiler.

Soil sampling (0-5 and 5-20 cm depths) was made in three different zones within each field where two soil samples were collected and mixed to make a composite sample. A total of 264 soil samples were taken (22 sites x 2 fields x 2 depths x 3 replicates). Once in the laboratory, the soil was air-dried and ground to pass a 2 mm sieve. Soil organic carbon (SOC) and CaCO_3 contents were determined by dry combustion with a LECO analyser (*RC-612* model, LECO Corp., St. Joseph, MI). Soil particle size distribution was obtained by laser diffraction analysis (*Coulter LS230* laser grain-sizer, Coulter Corp., Miami, FL). Six undisturbed soil samples were also taken per depth and field (2 in each of the 3 sampling zones per field) to determine the dry bulk density by the core method.

Within each study site, statistical comparisons between NT and CT were made using one-way ANOVA. As in each of the sites, the two fields were contiguous and sited on similar landscape position and same soil, the three sampling locations (i.e. sampling zones within each field) were used as pseudoreplicates (Christopher et al., 2009). The least significant difference (LSD) test was used to compare treatment means ($P<0.05$).

2.4. Results and discussion

2.4.1. Soil organic carbon under no tillage

Soil organic carbon content in the 0-20 cm depth ranged from 7.06 to 18.53 g kg^{-1} and was higher than 12 g kg^{-1} in nearly 30% of the NT fields (Fig. 2.3). This value of

12 g kg^{-1} is considered a minimum needed for an optimal agricultural use in Western Europe (Bullock, 1997). It is to expect that from this threshold value, increases in SOC will lead to improved soil quality and increased agricultural productivity. In any case, all studied soils had SOC contents lower than 20 g kg^{-1} , in agreement with the levels of SOC estimated for this region in the Map of Topsoil Organic Carbon in Europe (Jones et al., 2005). These contents are comparatively lower than those of other European regions but correspond well to the figures estimated for Southern Europe where a 74% of the land has a surface soil horizon (0-30 cm) with less than 20 g kg^{-1} of organic carbon (Van-Camp et al., 2004). The stratification ratios of SOC (0-5/5-20 cm in depth; Fig. 2.3) did not reach the threshold value of 2 (Franzluebbers, 2002) possibly due to the continuity of the two considered depths (Moreno et al., 2006). Even so, the highest SOC contents were always found in the surface layer (0-5 cm) with about an average of 40% more carbon stored than at 5-20 cm. This higher concentration in surface layers has been well documented for agricultural soils under NT (West and Post, 2002) and it is due to the crop residue retention on the soil surface and the absence of soil disturbance by tillage.

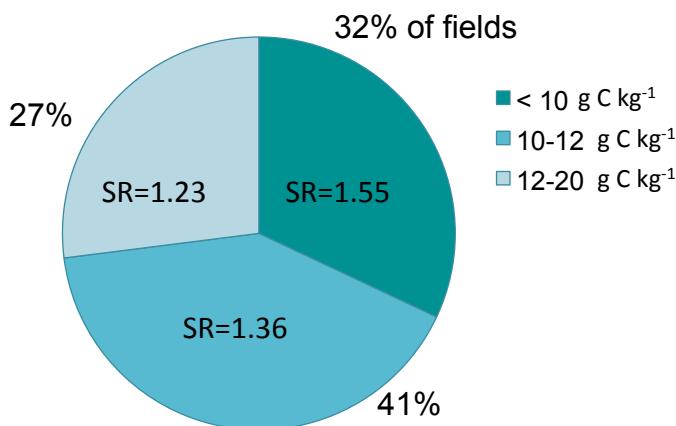


Fig. 2.3. Distribution of no tillage fields according to soil organic carbon content at 0-20 cm depth. The stratification ratio (SR) is the organic carbon content at 0-5 cm depth divided by that at 5-20 cm depth.

The number of years with NT seems to be a factor responsible for the differences among fields. In fact, a 50% and 40% of the variability found in SOC was explained by the number of consecutive years under NT for depths of 0-5 and 0-20 cm, respectively (Fig. 2.4). This suggests that the benefits associated with the adoption of NT will increase with time as observed in other regions of the world (West and Post, 2002; Angers and Eriksen-Hamel, 2008). As explained below, the data point not included in the regression corresponded to a field from which crop residues are removed by the farmer.

Several studies have demonstrated that accompanying agricultural practices to NT, such as crop rotation, crop residue retention or application of manure, can also enhance the SOC storage (Halvorson et al., 2002; Heenan et al., 2004; Dalal et al., 2011). In our study conditions, the manure application also appears to play a beneficial role in soils under NT. For example, in Fig. 2.5A we compare two fields after 13 years of no-till, managed by the same farmer and located in the same agroclimatic zone (mean annual precipitation of 430 mm). The only two differences are that in one of the fields the farmer applies animal manure and in the other does not. The second difference is that, although the two soils are medium textured, the soil without manure has a silt plus clay content greater than the soil with manure (silty clay loam vs. loam texture). As Fig. 2.5A shows, the SOC content in 0-20 cm depth was 50% higher in the soil with manure even though its texture makes it less suitable for carbon storage than the other soil.

Likewise, results indicate that an adequate management of crop residues is essential for successful NT in rainfed Aragon. In the areas with higher rainfall and hence higher production, farmers remove the straw from the field to prevent later problems with seeding. In some cases, as occurs in the study field with more years under NT (19 years; see Fig. 2.4), soil cover by residues retained in the field was low (<30%) and, strictly speaking, this would not be a conservation tillage system. In Fig. 2.5B the SOC in this field is compared with that one of a similar field from a nearby area of slightly less rainfall (676 vs. 741 mm) and where crop residues are always chopped and left on the soil surface. We estimate that, despite the different duration of NT (10 vs. 19 years), the removal of crop residues from the field led to a reduction of 20% of the SOC at 0-20 cm depth.

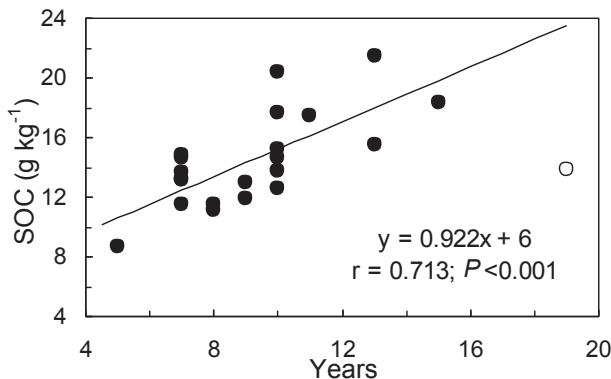


Fig. 2.4. Relationship between the duration of continuous no tillage management and the soil surface organic carbon, SOC (0-5 cm depth). The point represented by a white circle was not included in the regression analysis (see comments in the text).

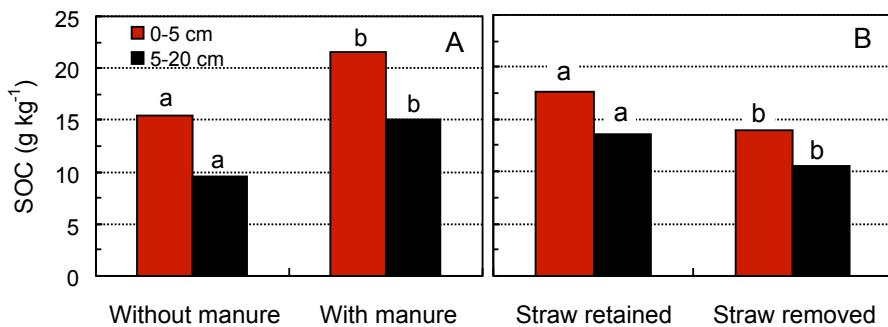


Fig. 2.5. Soil organic carbon (SOC) in four no tillage fields under similar soil and climate conditions (within each graph A and B) but with the following management differences: A) 13 years under no tillage with and without application of manure; B) 10 years leaving the cereal straw in the field and 19 years removing the straw. Within each graphic (A and B) and soil depth, columns with different letters are significantly different ($P < 0.05$).

2.4.2. No tillage versus conventional tillage

As previously indicated, the cropping system under NT and CT differed in some sites, especially in the driest ones (<500 mm of annual precipitation) where the traditional cereal-fallow rotation under CT is, generally, replaced with the continuous cereal cropping under NT. Therefore, following the remark made by Blanco-Canqui and Lal (2008) in their work on the potential of long-term NT to sequester SOC in the eastern United States, the present study shows data on the effect of NT- and CT-based cropping systems on SOC rather than those of tillage alone. The comparison of both systems was based on the calculation of the relative gain or loss of SOC under NT with respect to CT in each site (i.e.(NT-CT)/CT) and was expressed in Mg C ha⁻¹ to take into account the differences in soil bulk density between both tillage systems.

With the exception of only one case, the SOC under NT was always higher than under CT (ratio>0) (Fig. 2.6). These values represent between 1 and 55% more SOC with NT, averaging about 20%. The lowest differences (ratios close to 0) corresponded to the sites with the NT fields of shorter duration (5-7 years). As long-term studies show (West and Post, 2002; Christopher et al., 2009), increases in SOC with the adoption of NT is time-dependent and less than 10 years is usually not enough time to produce a marked accumulation of SOC with respect to a CT management. The ratio values of 0.10-0.20 (Fig. 2.6), which represent SOC increments between 10 and 20% in NT with respect to CT, generally corresponded to the sites where the straw is frequently or continuously removed from the NT fields. Also, they were obtained in cases where the CT system is actually a reduced tillage management (chiselling as primary tillage and crop residues retained in the field), an increasingly common practice in some areas of Aragon.

The highest differences in SOC between NT and CT (Fig. 2.6), i.e. ratios >2, generally reflect the use in the NT fields of improved practices such as total residue return, manure application or intensification of cropping system. For example, after 10 years of annual cereal cropping with NT the SOC in the 0-20 cm depth was increased in 55% with respect to that in the adjacent CT field under the traditional cereal-fallow rotation (Fig. 2.7). In other study site, a 25% more SOC was stored in the surface layer in a 13-yr NT field under a cereal-legume rotation than in the CT

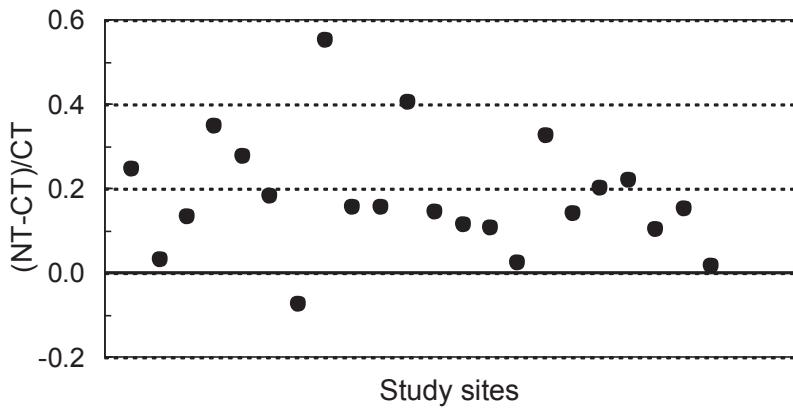


Fig. 2.6. Relative difference in soil organic carbon content (0-20 cm; Mg ha⁻¹) between no tillage (NT) and conventional tillage (CT) in 22 study sites from different cereal production areas of Aragon.

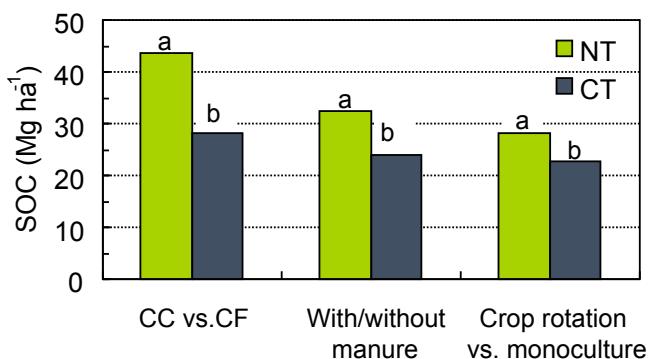


Fig. 2.7. Effect of no tillage- and conventional tillage-based cropping systems on soil organic carbon (SOC, 0-20 cm depth) at three different sites of cereal agriculture in Aragon. Columns with different letters within the same study site are significantly different ($P<0.05$). NT, no tillage; CT, conventional tillage; CC, continuous cropping; CF, cereal-fallow rotation.

field under a continuous cereal cropping (Fig. 2.7). Likewise, in another location, the combination of animal manure application and NT during 10 years led to an increase of 32% in SOC with respect to the contiguous CT field without manure addition (Fig. 2.7).

The above results are in agreement with those compiled in scientific literature reviews (e.g., Jarecki and Lal, 2003; Govaerts et al., 2009) and suggest that the use of these improved practices (complete residue return, cropping intensification and rotation, and manure application) may be strategies for increasing SOC in NT vs. CT soils. Also, similarly to the meta-analysis studies conducted by Alvarez (2005) and Angers and Eriksen-Hamel (2008) for a wide range of soils, climate and tillage practices, other site characteristics such as precipitation or soil texture do not seem to explain the differences in SOC under NT and CT among the study sites. Probably, a higher impact of the NT duration, cropping intensity or crop residues management, could be masking the effect of other influential factors.

The depth of soil sampling can greatly affect the conclusions about the SOC sequestration rates (Angers and Eriksen-Hamel, 2008; Blanco-Canqui and Lal, 2008; Christopher et al., 2009). In this sense, it is important to remember that the results obtained in the present study come from the superficial horizon of the soil (0-20 cm) and that the whole soil profile must be considered to reach conclusions about the potential of NT to sequester SOC vs. CT systems. However, this evident remark does not question the environmental benefits of NT derived from the higher accumulation of organic matter on the soil surface. Among them, an enhanced structural stability of soil and, therefore, a lower soil susceptibility to two main degradation processes that affect agricultural lands of semiarid Aragon, wind and water erosion (López et al., 2001; Álvaro-Fuentes et al., 2008).

2.5. Conclusions

Results from this on-farm study indicate that NT can be recommended as a viable alternative to CT to increase organic carbon at the soil surface (0-20 cm) in rainfed cereal areas of Aragon (NE Spain). On average, 20% more SOC was stored under NT than under CT. The highest SOC contents were found in the NT fields of

longer duration (>10 years) and/or managed with practices that enhance the return of more crop biomass to the soil (complete residue return, cropping intensification and manure application). The identification in this study of the current management practices used by farmers has allowed us to know the diversity of the NT-based cropping systems and to be aware of the reality of the conservation agriculture in Aragon. The increasing interest of farmers for NT could help to reduce the risk of soil degradation in the study area but further studies should consider the whole soil profile to correctly evaluate the potential of NT to sequester SOC.

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Capítulo 3

**Long-term no tillage effects on particulate
and mineral-associated soil organic matter
under rainfed Mediterranean conditions**

Soil Use and Management (2013) 29, 250-259

- Detalle del perfil de suelo bajo no laboreo en la localidad de Artieda (Zaragoza).

3.1. Abstract

Soil organic carbon (SOC) plays an essential role in the sustainability of natural and agricultural systems. The identification of sensitive SOC fractions can be crucial for an understanding of SOC dynamics and stabilization. The objective of this study was to assess the effect of long-term no tillage (NT) on SOC content and its distribution between particulate organic matter (POM) and mineral-associated organic matter (Min) fractions in five different cereal production areas of Aragon (north east Spain). The study was conducted under on-farm conditions where pairs of adjacent fields under NT and conventional tillage (CT) were compared. An undisturbed soil nearby under native vegetation (NAT) was included. The results indicate that SOC was significantly affected by tillage in the first 5 cm with the greatest concentrations found in NT (1.5-43% more than in CT). Below this depth (up to 40 cm), SOC under NT decreased (20-40%) to values similar or less than those under CT. However, the stratification ratio (SR) never reached the threshold value of 2. The POM-C fraction, disproportionate to its small contribution to total SOC (10-30%), was greatly affected by soil management. The pronounced stratification in this fraction ($SR > 2$ in NT) and its usefulness for differentiating the study sites in terms of response to NT make POM-C a good indicator of changes in soil management under the study conditions. Results from this on-farm study indicate that NT can be recommended as an alternative strategy to increase organic carbon at the soil surface in the cereal production areas of Aragon and in other analogous areas.

3.2. Introduction

Soil organic matter (SOM) plays an essential role in maintaining the necessary chemical, physical and biological conditions for sustainability and environmental integrity of ecosystems (Lal, 2004). Unfortunately, 20th century tillage practices have caused a worldwide decline in SOM with serious environmental and agricultural implications. According to the Thematic Strategy for Soil Protection (European Commission, 2006), the decrease of SOM is one of the main processes of soil degradation in Europe. Besides climatic reasons, human activities are the most relevant driving forces. The need to adopt sustainable management practices that can contribute to improving SOM, such as conservation tillage, is of particular relevance to the Mediterranean region where 74% of the land has a surface soil horizon (0-30 cm) with $<20 \text{ g kg}^{-1}$ of organic carbon (Van-Camp et al., 2004).

Many studies have shown the potential of conservation tillage, and especially of no tillage (NT), to increase SOM and improve soil quality (Govaerts et al., 2009) although the rate of adoption of these alternative systems has been relatively slow in Europe. No tillage is practised on about 117 million ha throughout the world but only 1.15 million ha is in Europe (Derpsch and Friedrich, 2010). For Spain, 650,000 ha of agricultural land is under NT. This indicates that NT adoption is still low in Spain. In Aragon (NE Spain), as described in Chapter 2 of this thesis, there is an increasing interest of farmers in NT systems but, at the same time, there is lack of knowledge about the soils on which these techniques are being applied. A greater adoption rate of NT could help to reduce the high risk of land degradation by wind and water erosion in this semiarid region of Aragon (López et al., 2001; García-Ruiz, 2010).

Total soil organic C (SOC) is not always the best indicator of changes in soil management, especially under semiarid climatic conditions where low soil moisture and high temperature are limiting factors for SOC accumulation (Chan et al., 2003; Moreno et al., 2006; Melero et al., 2012). Under these conditions significant changes in SOC are only to be expected after several years of NT adoption. The advance in SOM fractionation techniques has made possible the separation of the heterogeneous organic material into labile and recalcitrant pools defined not only on the basis of their composition and turnover rates but also in their response to soil management

(Cambardella and Elliot, 1992; Six et al., 2002a; Haynes, 2005). Thus, while labile SOC pools seem to be influenced by management practices, the recalcitrant SOC fractions may or may not be affected by the tillage system (Álvaro-Fuentes et al., 2008; Jagadamma and Lal, 2010). The reasons for this variable response seem to be complex and can involve not only many influential factors (such as soil texture and mineralogy), but also the inherent nature of the fraction and the different mechanisms of C stabilization (biochemical recalcitrance and organo-mineral associations) (Six et al., 2002b; Moni et al., 2010). Thus, research into the characterization of the different SOC fractions is needed to increase our understanding of the specific contribution of each fraction to soil function and quality.

The few available data on SOC fractions in agricultural soils of Aragon have been derived from small research plots and from single soil types (Álvaro-Fuentes et al., 2008). However, direct measurements under on-farm conditions across different soils, microclimates and agronomic practices are necessary since farming practices are very diverse and can differ from those in experimental plots. The objective of this study was to assess the effect of long-term NT on SOC content and its distribution between particulate organic matter-C (POM-C) and mineral-associated organic C (Min-C) fractions under rainfed Mediterranean conditions. With this aim, six fields of NT were compared with adjacent conventional tillage fields and with undisturbed soils under native vegetation in different cereal production areas of Aragon.

3.3. Materials and methods

3.3.1. Description of the study sites

Six long-term NT fields (9-21 years) were selected from the information obtained in the previous study, described in the Chapter 2, where 22 soils under NT were characterized across different rainfed cereal areas of Aragon to assess the potential of this practice to increase soil surface OC. The selected fields were representative of the different scenarios of NT in the region and were located in areas receiving a mean annual precipitation ranging from 350 to 740 mm (Table 3.1 and Fig. 3.1).

With the exception of the Peñaflor site, the study was conducted under on-farm conditions (fields of collaborating farmers) where pairs of adjacent fields under NT

Table 3.1.

Location and management characteristics of the studied sites (NT, no tillage; RT, reduced tillage; CT, conventional tillage; NAT, natural soil; CC, continuous cropping; CF, cereal-fallow rotation; CL, cereal-legume rotation; MP, mouldboard ploughing; Ch, chisel ploughing).

Site	Location	MAP ^a	Soil type ^b	Land use and management
Peñafiel CC	41° 44' 30" N 0° 46' 18" O (259 m elev.)	355	Hypocalcic Calcsol	19-yr NT-CC barley. 19-yr CT-CC (MP) barley. 19-yr RT-CC (Ch) barley. Maintenance of crop residues in the field. Straw chopped and spread in NT/RT (>30% of soil cover by crop residues) and incorporated into the soil in CT. NAT: Typical semiarid grassland.
Peñafiel CF	41° 44' 22" N 0° 46' 30" O (259 m elev.)	355	Hypocalcic Calcsol	20-yr NT-CF. 20-yr CT-CF (MP). 20-yr RT-CF (Ch). Maintenance of crop residues. Straw chopped and spread in NT/RT (>30% residue cover) and incorporated into the soil in CT. NAT: Typical semiarid grassland.
Lanaja	41° 43' 22" N 0° 21' 19" O (422 m elev.)	433	Hypocalcic Calcsol	10-yr NT-CL followed by 4-yr NT-CC barley with maintenance of crop residues (>30% residue cover). >14-yr CT-CF (MP) and straw removed. NAT: Frequently grazed area developed over an abandoned terrace (>40-yr) with sparse vegetation and patches of low shrubs.
Torres de Alcanadre	41° 57' 52" N 0° 05' 00" O (431 m elev.)	468	Calcaric Cambisol	9-yr NT-CC cereal with maintenance of crop residues (>30% residue cover). >9-yr CT-CC cereal (MP/Ch) and straw removed. NAT: Typical Mediterranean shrubland and <i>Pinus halepensis</i> . Soil surface covered with mosses and algae.
Undúes de Lerda	42° 33' 43" N 1° 07' 26" O (860 m elev.)	676	Haplic Calcsol	13-yr NT-CF. Maintenance of crop residues (>30% residue cover). >13-yr CT-CF (MP) and straw removed. NAT: Typical Mediterranean shrubland and <i>Pinus halepensis</i> .
Artieda	42° 35' 46" N 0° 59' 39" O (526 m elev.)	741	Hypocalcic Calcsol	19-yr NT-CC cereal followed by 2-yr NT-CL and straw removed (≈10-15% residue cover). >21-yr CT-CC cereal (MP/Ch) and straw removed. NAT: Typical Mediterranean shrubland.

^a Mean annual precipitation.

^b World Reference Base for Soil Resources, 2007.

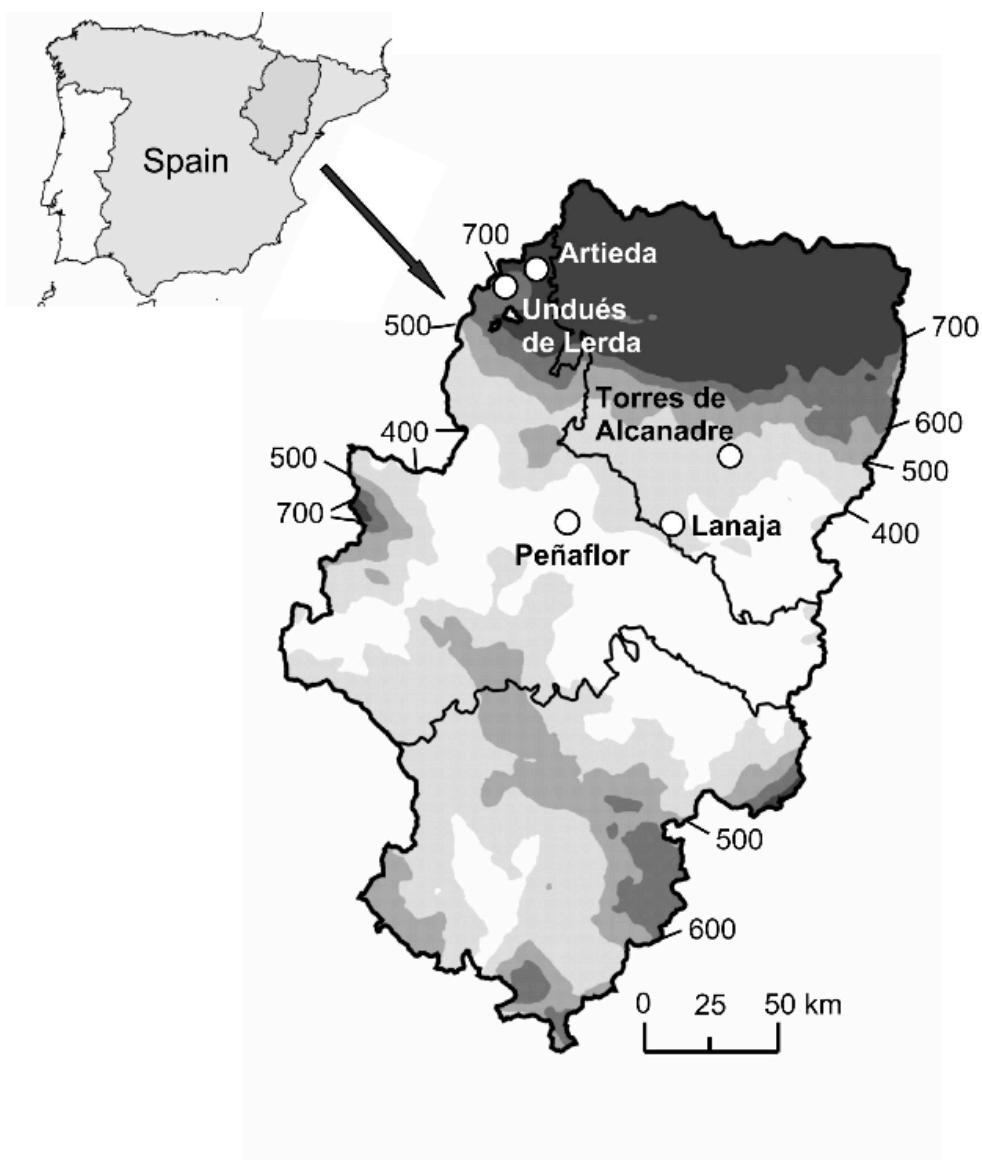


Fig. 3.1. Location of the study sites and average annual rainfall isohyets (mm).

and conventional tillage (CT) were compared. In Peñaflor, the study was carried out in research plots from a long-term tillage experiment at the dryland research farm of the Estación Experimental de Aula Dei (Consejo Superior de Investigaciones Científicas). In this case, three tillage treatments (NT, CT and reduced tillage, RT) were compared under the traditional cereal-fallow rotation (CF, one crop in 2 years) and under continuous cropping (CC) with barley. Within each cropping system a randomized complete block design with three replicates per tillage treatment was used. More details about the Peñaflor site can be found in López et al. (1996). In all sites, an undisturbed soil under native vegetation (NAT) and close to the NT and CT fields was included in the study for comparison purposes.

Information on location and soil management characteristics for each site are shown in Table 3.1. Briefly, in the CT system mouldboard plough was used as primary tillage tool as traditional implement in the region. However, in two of the sites, Torres de Alcanadre (hereafter, Torres) and Artieda, farmers alternate the use of chisel plough with mouldboard plough. NT soils were not tilled and weeds were controlled by herbicides. The RT treatment in the Peñaflor site consisted of chisel ploughing (non-inverting action) with partial incorporation of crop residues into the soil. With respect to crop residue management, the case of Artieda should be noted, the study site located in the area with the highest rainfall and hence highest production. As a common practice in this area, farmers remove the straw from the NT and CT fields to prevent later problems with seeding.

Cropping system was not the same under NT and CT in the Lanaja site (Table 3.1). This reflects the general trend observed in the driest areas of Aragon, where the traditional cereal fallow rotation under CT is generally replaced with the continuous cereal cropping under NT; even a legume can be introduced in rotation with cereal with a varying frequency depending on the site. Therefore, the results from the present study provide data on the effect of NT- and CT-based cropping systems on SOC rather than on tillage alone.

All soils were medium-textured soils, varying from sandy loam (the Torres site) to silty clay loam (Undués de Lerda), alkaline ($\text{pH} > 8$; CaCO_3 contents of 50–560 g kg^{-1}) and generally low OC contents ($< 20 \text{ g kg}^{-1}$ for agricultural soils) (Table

3.2). In each site, both NT and CT fields were contiguous and the NAT soil close to them, thus ensuring that soil type and topography were as similar as possible. The differences observed are attributed to the soil management itself. Even though the soil is the same (i.e., same parent material), the soil particle distribution within the profile will not be the same in the case of the ploughed soils with total soil inversion than in the non-tilled soils or in the case of the cultivated soils vs. the undisturbed soils. All fields were nearly level with the exception of those of the Torres site where a slight slope (3-4%) was present.

3.3.2. Soil sampling and analyses

Soil samples for OC analysis were collected at three depths (0-5, 5-20 and 20-40 cm) and from three different zones within each field (NT, CT and NAT) where two samples per depth were collected and mixed to form a composite sample. At the Peñaflor site, each of the composite samples came from each of the 3 tillage plots per treatment. Thus, a total of 27 composite samples were obtained from each site (36 in Peñaflor) (3 or 4 treatments x 3 depths x 3 replicates). Six undisturbed soil samples were also taken per depth and field (2 in each of the 3 sampling zones per field) to determine the dry bulk density by the core method. The study was over two growing seasons (2009-2010 and 2010-2011), with sampling done in similar periods. Thus, at the sites where there was continuous cropping, sampling was after planting during the fall period and at the fields under the cereal-fallow rotation during the early fallow phase after the cereal harvest in June. At each site all soil samples were collected on the same day.

In the laboratory, visible roots and organic debris were removed by hand and then air-dry soil (<2 mm) from each depth, field and site, was physically fractionated following the Cambardella and Elliot (1992) procedure. With this method using soil dispersion and sieving, particulate organic matter (POM, >53 µm) and mineral-associated organic matter (Min, <53 µm) were isolated.

The OC concentration in both SOM fractions was determined by dry combustion with a LECO analyser (RC-612 model). Total SOC content was calculated as the sum of the POM-C and Min-C contents and expressed on a mass per unit area basis

Table 3.2.
Selected properties of the studied soils in the 0-40 cm depth (CT, conventional tillage; RT, reduced tillage; NT, no tillage; NAT, natural soil). In Peñaflor, CC refers to the continuous cropping system and CF to the cereal-fallow rotation.

Site	Treatment	pH	EC (1:5) ^a	CaCO ₃	Gypsum	Organic carbon	Sand	Silt	Clay
		(H ₂ O, 1:2.5)	dS m ⁻¹	g kg ⁻¹	g kg ⁻¹	g kg ⁻¹	g kg ⁻¹	g kg ⁻¹	g kg ⁻¹
Peñaflor CC	CT	8.2	0.46	453	48	11.5	320	436	244
	RT	8.5	0.16	460	46	11.0	340	440	220
	NT	8.5	0.17	467	43	10.6	367	422	211
	NAT	8.3	0.79	560	44	11.2	492	351	157
Peñaflor CF	CT	8.4	0.18	471	46	10.6	333	433	234
	RT	8.4	0.16	482	46	10.2	316	445	239
	NT	8.4	0.18	485	47	10.5	318	445	237
	NAT	8.3	0.79	560	44	11.2	492	351	157
Lanaja	CT	8.3	0.31	439	34	10.0	117	600	283
	NT	8.4	0.23	405	34	10.9	125	608	266
	NAT	8.3	0.64	324	40	8.7	272	537	191
Torres de Alcanadre	CT	8.5	0.12	237	29	8.8	576	284	140
	NT	8.6	0.13	229	28	9.4	571	294	135
	NAT	8.5	0.14	245	29	11.5	619	264	118
Undués de Lerda	CT	8.3	0.13	56	66	14.7	106	531	363
	NT	8.3	0.13	89	65	14.5	115	533	352
	NAT	8.2	0.20	119	64	25.2	209	487	303
Artieda	CT	8.1	0.19	177	46	10.6	370	394	236
	NT	8.2	0.18	239	44	10.2	314	451	235
	NAT	8.2	0.15	84	65	16.4	308	416	276

^a EC, electrical conductivity

by multiplying the OC concentration value by the corresponding soil bulk density. Soil particle size was obtained by laser diffraction analysis (Coulter LS230), CaCO₃ content by dry combustion with the LECO analyser, and electrical conductivity (EC), pH and gypsum content by standard methods.

3.3.3. Statistical analyses

As the study was conducted under farm conditions, the NT, CT, and NAT treatments were not field replicated. However, in each of the sites, the fields were contiguous and sited on similar landscape positions and soil. Therefore, the three sampling locations within each field were used as pseudoreplicates and statistical comparisons among treatments were made using one-way ANOVA assuming a randomized experiment (Christopher et al., 2009). In the case of the Peñaflor site, the randomized complete block design with three replicates per tillage treatment was also applied and statistical results were compared with those obtained from the pseudoreplicate analysis. Treatments means were compared by the Duncan's multiple range test ($P<0.05$). When data showed non-normality, transformations were made and ANOVA conducted with the transformed data. Computations were performed using SPSS 19.0 statistical software.

3.4. Results and discussion

3.4.1. Tillage effects on total soil organic carbon

With the exception of the NAT soil of Undués and Artieda, total SOC contents in the 0-40 cm layer were $<20\text{ g kg}^{-1}$ (Fig. 3.2), in agreement with SOC as estimated for this region in the Map of Topsoil Organic Carbon in Europe (Jones et al., 2005). Although this range is less than for other European regions, it corresponds well to estimated data for Southern Europe where 74% of the land has a surface soil horizon (0-30 cm) with $<20\text{ g kg}^{-1}$ of organic C (Van-Camp et al., 2004).

At the most humid sites (Artieda and Undués), the greatest SOC contents were in the NAT soils and in the driest ones they were similar (1 and 7% more in NAT at Peñaflor CF and Peñaflor CC, respectively) or even less than those in the agricultural soils (nearly 20% less at Lanaja). These relatively small SOC contents of the NAT

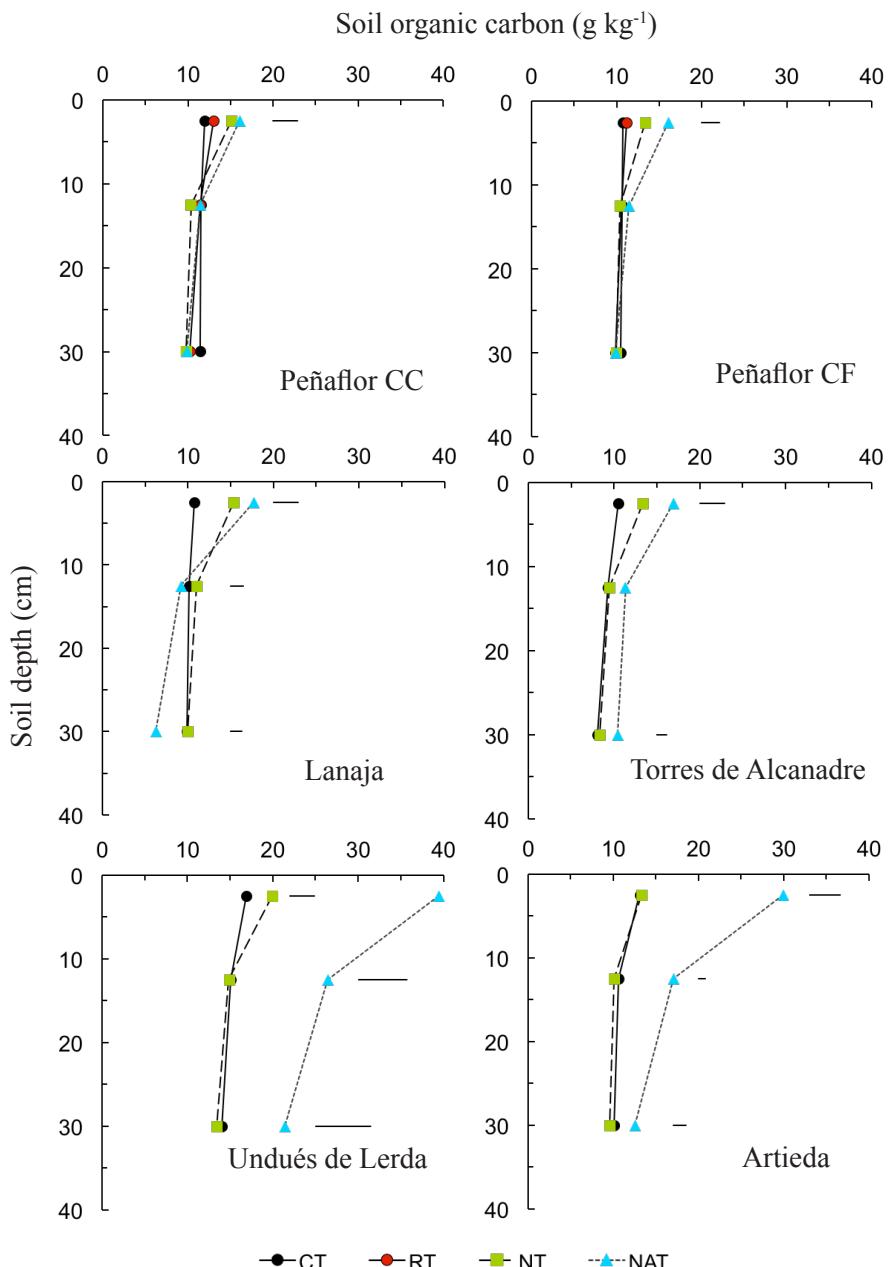


Fig. 3.2. Depth distribution of soil organic carbon concentration under different tillage and management systems (CT, conventional tillage; RT, reduced tillage; NT, no tillage; NAT, natural soil). In Peñaflor, CC refers to the continuous cropping system and CF to the cereal-fallow rotation. Horizontal bars indicate LSD ($P<0.05$) for comparisons at the same soil depth, where significant differences were found.

soils in the driest areas are because of these fields often being in the marginal lands and are not suitable for crop production due to limited depth or excessive stoniness. In the case of the Lanaja site, the lowest SOC concentration of the NAT field is because of their semi-natural conditions as it is in an abandoned agricultural terrace (>40 yr) that is frequently grazed by livestock (Table 3.1). From a comprehensive database on Spanish grassland and agricultural soils, Romanyà and Rovira (2011) also found greater differences in SOC concentration between grassland and arable areas as the climate became wetter.

For cultivated soils, SOC was significantly affected by tillage only in the first 5 cm of soil with the highest concentrations found generally in NT (Fig. 3.2). The magnitude of this increase with respect to CT varied considerably between sites, ranging from only 1.5% at Artieda to 43% at Lanaja. At the other sites, this increase varied between 18 and 28%. Below 5 cm depth, SOC concentrations under NT decreased considerably (22-38%) up to values similar to those under CT or slightly lower (Fig. 3.2). Thus, the greater SOC at the soil surface in NT was offset by the lower concentration at depth, so that the average SOC concentration in the 0-40 cm profile was not significantly different from that of CT. At Artieda, the lack of difference between tillage systems even in the top layer (Fig. 3.2) can be explained by the farmer's practice of removing crop residues from the NT field (Table 3.1); this negated the expected increase in SOC associated with conservation tillage. SOC contents under NT were nearly or > 12 g kg⁻¹ in the 0-20 cm depth. Although there is no clear evidence of a unique threshold/critical level in SOC (Loveland and Webb, 2003), the value of ca. 12 g kg⁻¹ (20 g kg⁻¹ SOM) is considered the minimum for optimal agricultural use in Western Europe (Bullock, 1997).

Greater stratification of SOC with depth under NT than under CT has been widely reported under different agroclimatic regions, including semiarid areas of Spain (Álvaro-Fuentes et al., 2008; Hernanz et al., 2009; López-Fando and Pardo, 2011; Martin-Lammerding et al., 2011; Melero et al., 2012). As stated in these studies, the lack of tillage in NT involves the retention of crop residues at the soil surface, thus slowing decomposition rates and increasing SOC in the topsoil. In contrast, mouldboard ploughing in CT incorporates and distributes throughout the

plough layer almost 90-100% of surface crop residues. The stratification ratio, SR (Franzluebbers, 2002), calculated as the SOC concentration at 0-5 cm depth divided by that at 20-40 cm, increased with the reduction in intensity of soil disturbance (CT<RT<NT<NAT) (Table 3.3). Although SR values greater than the threshold value of 2 were only found in the NAT soils, the improvement of soil quality with the adoption of NT can be deduced from SR values in all cases higher than those in the tilled soils.

Table 3.3.

Stratification ratios (0-5 cm/20-40 cm) for total soil organic carbon (SOC), particulate organic C (POM-C) and mineral-associated organic C (Min-C) as affected by soil management and tillage (CT, conventional tillage; RT, reduced tillage; NT, no-tillage; NAT, natural soil). In Peñaflor, CC refers to the continuous cropping system and CF to the cereal-fallow rotation.

Fraction	Treatment	Peñaflor		Lanaja	Torres de Alcanadre		Undués	Artieda
		CC	CF		de Lerda	ns		
SOC	CT	1.05	1.03	1.09	1.31	1.21	1.31	—
	RT	1.28	1.14	—	—	—	—	—
	NT	1.55	1.34	1.54	1.61	1.48	1.39	—
	NAT	1.65	1.65	2.89	1.63	1.89	2.40	—
	LSD ^a	0.21	0.20	0.44	0.28	0.26	0.34	—
POM-C	CT	1.16	1.05	1.75	2.38	2.48	2.11	—
	RT	2.85	2.08	—	—	—	—	—
	NT	4.37	3.47	3.06	4.27	3.79	2.38	—
	NAT	2.96	2.96	7.84	3.22	3.48	4.19	—
	LSD	0.63	0.87	1.29	1.55	ns	1.13	—
Min-C	CT	1.03	1.03	0.99	1.13	1.08	1.09	—
	RT	1.10	1.06	—	—	—	—	—
	NT	1.21	1.20	1.24	1.19	1.26	1.18	—
	NAT	1.26	1.26	1.85	1.11	1.36	1.83	—
	LSD	0.18	0.20	0.24	ns	ns	0.15	—

^a LSD ($P<0.05$) least significant difference.

3.4.2. Tillage effects on soil organic carbon fractions

The effect of land use and tillage on SOC differed between the two analysed organic matter fractions, POM and Min (Table 3.4). In all cases, the highest contribution to total SOC corresponded to the Min-C fraction, accounting for ca. 70-90% of total C (Fig. 3.3). The Min fraction is a relatively inert SOM pool, selectively protected

Table 3.4.

Particulate organic C (POM-C) and mineral-associated organic C (Min-C) concentrations at different soil depths as affected by soil management and tillage (CT, conventional tillage; RT, reduced tillage; NT, no-tillage; NAT, natural soil). In Peñaflor, CC refers to the continuous cropping system and CF to the cereal-fallow rotation.

Site	Treatment	POM-C			Min-C		
		0-5 cm	5-20 cm	20-40 cm	0-5 cm	5-20 cm	20-40 cm
(g C kg ⁻¹ soil)							
Peñaflor CC	CT	1.59	1.73	1.37	10.38	9.80	10.07
	RT	2.86	2.02	1.00	10.09	9.36	9.19
	NT	4.60	1.59	1.06	10.46	8.72	8.69
	NAT	6.68	2.98	2.26	9.37	8.40	7.54
	LSD ^a	0.74	0.60	0.31	ns	ns	1.24
Peñaflor CF	CT	0.93	1.07	0.91	9.80	9.55	9.55
	RT	1.56	1.32	0.77	9.58	9.17	9.04
	NT	2.25	0.88	0.65	11.06	9.47	9.24
	NAT	6.68	2.98	2.26	9.37	8.40	7.54
	LSD	0.54	0.39	0.61	ns	ns	1.52
Lanaja	CT	2.21	1.41	1.27	8.47	8.71	8.56
	NT	5.11	2.08	1.69	10.20	8.89	8.23
	NAT	8.22	2.28	1.05	9.43	6.90	5.17
	LSD	1.39	0.43	0.47	ns	0.89	1.39
Torres de Alcanadre	CT	2.79	1.95	1.19	7.68	7.29	6.81
	NT	4.82	2.00	1.17	8.53	7.46	7.15
	NAT	8.19	3.96	2.56	8.64	7.32	7.77
	LSD	1.63	0.93	0.56	ns	ns	ns
Undués de Lerda	CT	3.22	2.03	1.36	13.69	13.03	12.63
	NT	4.41	2.22	1.16	15.49	12.63	12.26
	NAT	18.66	9.24	5.53	20.73	17.15	15.85
	LSD	4.35	2.59	1.92	3.06	3.33	ns
Artieda	CT	4.38	2.46	2.06	8.68	8.15	8.01
	NT	3.90	2.02	1.63	9.35	8.03	7.90
	NAT	12.66	5.11	3.06	17.26	11.90	9.42
	LSD	2.96	0.77	0.56	1.48	1.23	1.28

^aLSD ($P<0.05$) least significant difference.

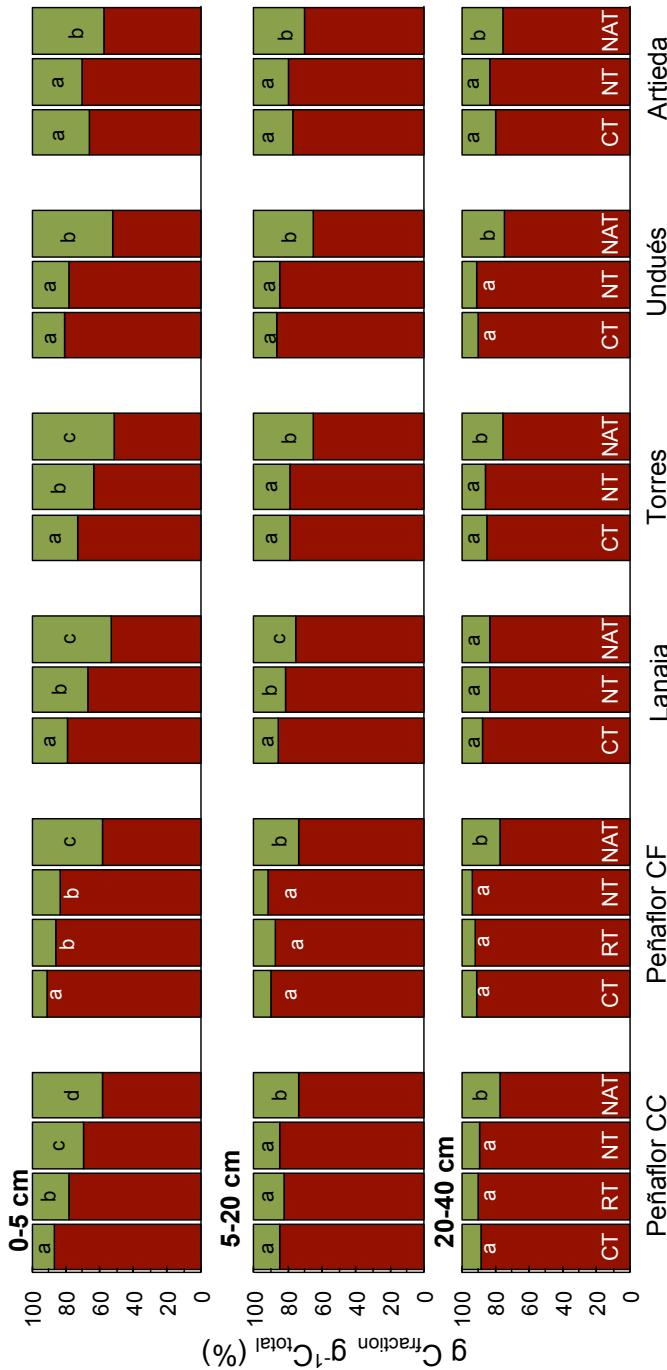


Fig. 3.3. Relative proportion of particulate organic carbon (POM-C, ■) and mineral-associated organic carbon (Min-C, ■) to total soil organic carbon (SOC) at different soil depths as affected by soil management and tillage (CT, conventional tillage; RT, reduced tillage; NT, no tillage; NAT, natural soil). In Peñafiel, CC refers to the continuous cropping system and CF to the cereal-fallow rotation. For the same study site and soil depth, different letters indicate significant differences at $P<0.05$.

by its high stabilization by silt and clay particles and/or its inherent recalcitrance (Cambardella and Elliot, 1992; Six et al., 2002b). In our study, the concentration of this fraction was not greatly affected by soil management with the exception of the Undués and Artieda sites where NAT soils had the highest Min-C contents. This effect was significant ($P<0.05$) for all soil depths but especially so for the surface where the Min-C concentration was 1.4-1.9 times higher than in the agricultural soils. In contrast, at the most arid sites, Min-C was similar or even less in NAT than in agricultural soils, as can be observed at Peñaflor and Lanaja in the deeper layers (Table 3.4). At these sites, low and variable precipitation limits primary production and soil C storage. Also, the lowest Min-C at Lanaja is explained by the semi-natural conditions of this field (Table 3.1). Despite the differences in Min-C concentration among NAT soils, the contribution to total SOC was similar, accounting for ca. 50-60% in the surface layer and 70-80% in the deep one (Fig. 3.3). In all cases, these percentages were significantly lower than those from the agricultural soils which included 80-90% of total SOC. Similarly, Llorente et al. (2010) in another semiarid region of Spain reported for the first 10 cm of soil contribution percentages of Min-C of 83 and 53% under cropped land and tree cover respectively. For different climatic conditions, Christensen (2001) and John et al. (2005) also found lower percentages in soils under permanent vegetation cover, than in cultivated soils (50-85% vs. $\geq 90\%$). This difference between land uses is explained by the reduced predominance of the POM fraction in the agricultural soils compared to the NAT soils. In cultivated fields, lower C inputs and disruption of soil aggregates by tillage and other agronomic practices led to a preferential loss of SOC from the POM fraction (Haynes, 2005; Kögel-Knabner et al., 2008), to thus increase the contribution of the Min fraction with respect to undisturbed soils.

The POM fraction is a labile SOM pool with relatively fast turnover times and consists mainly of partially decomposed plant residues (Cambardella and Elliot, 1992; Haynes, 2005). In our study, in contrast to Min-C, the C associated with this fraction was influenced not only by land use but also by tillage system (Table 3.4). The POM-C concentration in the agricultural soils was from 22 (Undués) to 77% (Lanaja) of that in the NAT soils for 0-40 cm with differences being statistically

significant throughout the whole soil profile. Within the cultivated soils, the POM-C fraction followed the same pattern as the total SOC although the effect of tillage was more pronounced. With the exception of Artieda, where crop residues were removed from the field, in the upper 5 cm soil depth the POM-C content was between 1.2 (Undués) and 3 times higher (Peñaflor CC and Lanaja) under NT than under CT (Table 3.4). At the Peñaflor site, the RT response under both CF and CC cropping systems was intermediate between CT and NT with POM-C concentrations significantly higher than those under CT (1.7-1.8 times higher). Again, the decreasing pattern in C concentration with depth was more prominent under conservation tillage, especially NT, in such a way that the average concentrations in the 0-40 cm profile were not significantly different from those under CT. This depth gradient was reflected in the values of SR for POM-C which were greater than 2 in the NT and RT soils (Table 3.3). Even under CT, SR>2 were obtained for this fraction at the most humid sites. This contrasts with the relatively low SR for Min-C and SOC, suggesting that the POM-C fraction can be a good indicator of soil quality under rainfed conditions of semiarid Aragon. The marked stratification of POM-C is generally observed under continuous NT management (Franzluebbers, 2004; Álvaro-Fuentes et al., 2008; Salvo et al., 2010) and is produced by the maintenance of crop residues at the soil surface and the absence of soil disturbance. The POM fraction represented a relatively small percentage of the total SOC in terms of C storage (9-30%; Table 3.5), in agreement with typical values of 10-30% as reported in the literature (Wander, 2004; Álvaro-Fuentes et al., 2008; Martin-Lammerding et al., 2011). However, despite its small contribution, it has a large effect on nutrient-supplying capacity and structural stability of soils and for these reasons is considered a key attribute of soil quality (Haynes, 2005).

In our study the POM-C fraction contributed to the differences between our sites based on the relative gain or loss of POM-C stock ($Mg\ C\ ha^{-1}$) under NT with respect to CT at each site (i.e. $(NT-CT)/CT$). With the exception only of Artieda, POM-C was always higher under NT than under CT in the surface layer (ratios >0) (Fig. 3.4). Such values represent between 1% less and 225% more POM-C with NT, averaging about 111% more. Fig. 3.4 shows a negative and strong relationship

Table 3.5.

Soil organic carbon (SOC), particulate organic C (POM-C) and mineral-associated organic C (Min-C) stocks in the 0-40 cm soil layer as affected by soil management and tillage (CT, conventional tillage; RT, reduced tillage; NT, no-tillage; NAT, natural soil). In Peñaflor, CC refers to the continuous cropping system and CF to the cereal-fallow rotation.

Site	Treatment	SOC	POM-C	Min-C
		Mg C ha ⁻¹		
Peñaflor CC	CT	57.36	7.60	49.76
	RT	54.89	7.95	46.94
	NT	60.23	9.57	50.66
	NAT	57.31	15.66	41.65
	LSD ^a	ns	3.30	ns
Peñaflor CF	CT	54.91	5.07	49.84
	RT	51.38	5.34	46.04
	NT	59.17	5.26	53.59
	NAT	57.31	15.66	41.65
	LSD	ns	3.21	7.77
Lanaja	CT	54.57	7.76	46.81
	NT	62.75	12.89	49.86
	NAT	48.18	12.87	35.31
	LSD	5.38	2.03	5.62
Torres de Alcanadre	CT	55.12	10.31	44.81
	NT	58.78	12.05	46.73
	NAT	63.94	20.67	43.27
	LSD	ns	4.50	ns
Undués de Lerda	CT	89.42	10.88	78.54
	NT	88.54	11.36	77.18
	NAT	129.91	42.15	87.77
	LSD	23.73	7.63	ns
Artieda	CT	59.07	13.65	45.41
	NT	65.18	12.95	52.23
	NAT	97.07	29.28	67.79
	LSD	7.09	3.00	7.50

^aLSD ($P<0.05$) least significant difference.

($P<0.01$) between the relative difference in POM-C stock at 0-5 cm depth and the mean annual precipitation at each site and indicates that the relative gain of C with the adoption of NT decreases as precipitation increases. A significant relationship was also obtained for total SOC but this property was not as responsive to precipitation as POM-C (Fig. 3.4). For the Min-C fraction, no significant influence of precipitation was observed at any of the soil depths. Although climatic factors such as precipitation have been shown to exert a control on the potential of NT to store SOC, the direction and magnitude of this potential with respect to CT systems can vary widely (VandenBygaart et al., 2003; Franzluebbers, 2004; Govaerts et al., 2009; Blanco-Canqui et al., 2011). The increase in the relative benefit of NT with reduction in precipitation is also reported by Gregorich et al. (2009) who compare

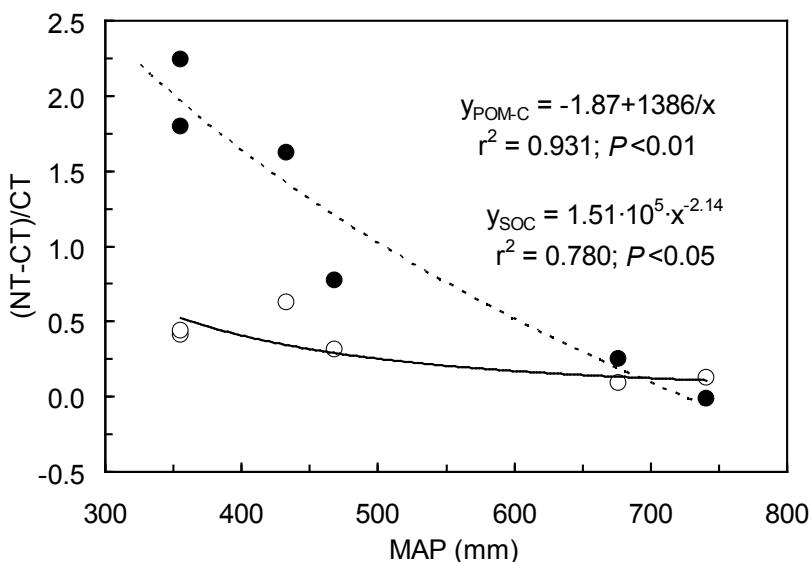


Fig. 3.4. Relative difference between no tillage (NT) and conventional tillage (CT) in total soil organic carbon content (SOC, —○—; Mg ha⁻¹) and particulate organic carbon content (POM-C, ---●---) at 0-5 cm soil depth as a function of mean annual precipitation (MAP).

SOC storage in different Canadian regions. Similar conclusions are made by Luo et al. (2010) for agricultural soils in Australia. In these studies, the authors suggest that compared to low rainfall areas, the faster decomposition of SOM in the surface layer under a more humid environment minimizes the overall change of SOC balance between input and output under NT and, therefore, the relative C gain with respect to CT.

In a similar way to previous studies, the differences between treatments in C storage at the soil surface are reduced when the whole soil profile (0-40 cm) is considered (Table 3.5). The depth of soil sampling can greatly affect conclusions on SOC sequestration rates (Blanco-Canqui and Lal, 2008; Christopher et al., 2009). At the most arid sites, Peñaflor and Lanaja, C stocks in the NAT soils were similar or even lower than those in cultivated soils, supporting the idea that native SOC levels do not necessarily represent the upper limit for SOC storage and can be exceeded by those under agricultural management (Six et al., 2002b; VandenBygaart et al., 2003). In contrast, in the more humid areas, C stocks were enhanced in the NAT soils (Table 3.5). Within the cultivated soils, although a trend of higher SOC stored under NT than under CT was generally found when the whole 0-40 cm layer was considered, the additional C was only statistically significant at Lanaja (15% more; Table 3.5) and can be attributed to the intensification of cropping system in NT (continuous cereal cropping vs. cereal-fallow rotation in CT; Table 3.1). Regardless of the potential of NT to sequester SOC, the numerous benefits to soil quality derived from the greater accumulation of SOC at the surface cannot be questioned. A study carried out under semiarid rainfed conditions in south Spain (López-Garrido et al., 2012) shows that although the increase in SOC after 16 yr of reduced tillage was only significant down to 5 cm, biological soil properties were significantly improved. Enhanced structural stability of soil is of special importance in semiarid Aragon to reduce soil susceptibility to the two main degradation processes of wind and water erosion that affect agricultural land (López et al., 2001; García-Ruiz, 2010).

3.5. Conclusions

The results from this on-farm study show that the increase in SOC due to long-term

NT was generally restricted to the soil surface (0-5 cm depth) where, on average, 23% more SOC was found under NT than under CT. The Min-C fraction provided the greatest contribution to total SOC in all cases (70-90%). However, the POM-C fraction was more sensitive to soil tillage and land use than Min-C and total SOC. In addition, and in contrast to total SOC, stratification ratios of POM-C were >2 under NT at all studied sites. For these reasons, POM-C can be considered a useful indicator of soil changes associated with NT. A negative and strong relationship was found between the relative difference in the surface POM-C stock (i.e. (NT-CT)/CT) and mean annual precipitation, suggesting that the relative gain in C with NT increases as precipitation decreases. Regardless of the similar potential of NT and CT to sequester SOC in whole soil profile (0-40 cm), the environmental benefits derived from the higher accumulation of SOC at the surface under NT cannot be questioned. Thus NT can be recommended as a sustainable management alternative to CT in rainfed cereal areas of Aragon in north east Spain and in other analogous areas.

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Capítulo 4

**Soil organic matter fractions as
affected by tillage
and soil texture under semiarid
mediterranean conditions**

Soil & Tillage Research (submitted)

- Etapa de separación de fracciones de materia orgánica del suelo por fraccionamiento físico.

4.1. Abstract

The inherent complexity of soil organic matter (SOM) and its stabilization processes make suitable the identification of SOM fractions that reflect the management-induced changes in soil organic carbon (SOC) dynamics. This is of special interest in semiarid regions where the capacity of soil for agricultural production is limited. This study aims to evaluate the effect of different tillage and soil management practices on the distribution of C among SOM fractions and determine the influence of soil texture on the protection of SOC in a semiarid Mediterranean region (Aragon, NE Spain). Under on-farm conditions, pairs of adjacent fields under long-term no tillage (NT) and conventional tillage (CT) were compared in five different cereal production areas. In all cases, a nearby undisturbed soil under native vegetation (NAT) was included. Results indicate that the two isolated mineral-associated OM (Min) fractions, d-Min and μ agg-Min (outside and within stable microaggregates, respectively), constituted the main part of total SOC (mean contributions of 54 and 26% respectively) and were not consistently affected by soil management. Soil clay was a determinant factor for d-Min-C and total SOC ($r^2=0.60-0.70$; $P<0.001$), indicating that chemical stabilization, through clay-organic complexes, seems to be a main preservation mechanism in the studied soils. Physical protection seems to be another SOC stabilization process in these soils due to strong correlation found between μ agg-Min-C and the mass of water-stable microaggregates ($r=0.900$; $P<0.0001$). With smaller contributions to total SOC, the two labile fractions, coarse and fine particulate OM (cPOM and fPOM) were sensitive to soil management and their concentrations decreased as soil disturbance increased (NAT>NT>CT). The highest differences between NT and CT corresponded to fPOM at the soil surface where this fraction was 1.2-3 times higher under NT. Higher soil stratification ratios in NT, always >2 for the POM fractions, indicate an improvement in soil quality with long-term NT adoption in this semiarid Mediterranean region.

4.2. Introduction

Soil organic matter (SOM) has been described as the most complex and least understood component of soils (Magdoff and Weil, 2004). The complexity is due to the fact that SOM is a heterogeneous mixture of organic substances with different chemical composition and turnover rates. This is one reason why total soil organic carbon (SOC) is not always the best indicator of changes in soil management, especially in semiarid regions where low precipitation and high temperature are limiting factors for SOC storage (Chan et al., 2003; Melero et al., 2012). Under these conditions, significant increments in SOC are only to be expected several years after adoption of sustainable management practices.

With the aim of elucidating the complex composition of SOM and understanding its dynamics and mechanisms of stabilization, the scientific community has made considerable efforts to develop techniques to separate SOM into fractions of different composition and stability (see reviews by Wander, 2004; von Lützow et al., 2007). These advances have allowed differentiate labile and recalcitrant SOC pools and identify those that can serve as early indicators of changes in soil quality. This seems to be the case of the particulate organic matter (POM) since it has been reported to be a sensitive labile fraction to management-induced changes in soil (Cambardella and Elliot, 1992; Wander, 2004). Increments in POM with the adoption of conservation tillage and, specially, with no tillage (NT) have been reported in several studies (Six et al., 1999, 2000; Dou and Hons, 2006; Virto et al., 2007; Álvaro-Fuentes et al., 2008; Martín-Lammerding, 2013). However, the magnitude of these increments is variable and the POM effectiveness as soil indicator seems to depend on different factors such as quantity and quality of crop residues, management historical and soil texture (Domínguez et al., 2009; Martín-Lammerding, 2013).

As POM decomposes, it becomes physically and/or chemically stabilized within the soil mineral component as mineral-associated organic matter (Min). The long persistence of Min-C in the soil and its high contribution to total SOC, make this fraction of particular interest in the context of the global C cycle (Schmidt et al., 2011; Feng et al., 2013). Considerable progress has been made in the characterization of this fraction and, however, our knowledge is still limited due to its heterogeneity

and to the different stabilization mechanisms involved and their interactions (von Lützow et al., 2007; Moni et al., 2010; O'Brien and Jastrow, 2013). Although there is evidence that SOC in the Min fraction is controlled by soil texture and particularly by clay content, the literature reveals that there is not always a close and direct relationship between clay and SOC concentration (McLaughlan, 2006; Sleutel et al., 2006; Zhao et al., 2006). The reason seems to be complex and can involve not only many influential factors, such as the clay mineralogy (and specific surface area) or the composition of organic C inputs, but also mechanisms other than simple monolayer sorption of SOM onto mineral surfaces as recent studies have shown (O'Brien and Jastrow, 2013; Vogel et al., 2014).

All the above information suggests that more research is necessary to advance in the characterization of SOC fractions and their dynamics, and thus, to develop soil management strategies to increase the quantity and stability of SOM. No tillage can be a sustainable strategy due to its potential to increase SOC (Govaerts et al., 2009). This is of special relevance to the Mediterranean region where a 74% of land has a surface soil horizon with less than 20 g kg⁻¹ of SOC (Van-Camp et al., 2004). In Aragon (NE Spain), as in the rest of Spain, the interest of farmers in NT has been increasing (Vallés, 2009; Gonzalez-Sánchez et al., 2015). However, there is still little available information on SOM and its fractions in agricultural soils of the region and it comes from small research plots and single soil types. The objectives of this study were to (1) determine the effect of soil tillage on the distribution of C among SOM fractions by comparing traditional tillage with long-term NT and with undisturbed soils under native vegetation, and (2) evaluate the influence of soil texture, and other basic soil properties, on SOC protection, giving special attention to the Min-C pool. The study was conducted under on-farm conditions in different cereal production areas of Aragon across different soils, microclimates and agronomic practices.

4.3. Materials and methods

4.3.1. Study sites

The study was conducted at the six long-term NT fields (9-21 years) described in the previous chapter (Chapter 3). These fields were representative of the different

scenarios of NT in Aragon (NE Spain) and located in areas receiving a mean annual precipitation ranging from 350 to 740 mm (Fig. 3.1 in Chapter 3). Information on location and soil management characteristics for each site are shown in Table 3.1. Briefly, in each site, pairs of adjacent fields under NT and conventional tillage (CT) were compared. Likewise, in all sites, a nearby undisturbed soil under native vegetation (NAT) was included. All soils were medium-textured soils (from sandy loam to silty clay loam), alkaline ($\text{pH}>8$; CaCO_3 contents of 60-560 g kg^{-1}) and generally low in OC content ($<20 \text{ g kg}^{-1}$) (Table 3.2).

4.3.2. Soil sampling and analyses

Soil samples were collected at three depths: 0-5, 5-20 and 20-40 cm. In the farmer fields, soil sampling was made in three different zones within each field (NT, CT and NAT) where two samples per depth were collected and mixed to make a composite sample. In the Peñaflor site, each of the composite samples came from each of the three tillage plots per treatment (NT, RT and CT). Thus, a total of 27 composite samples were obtained from each site (36 in Peñaflor) (3 or 4 treatments x 3 depths x 3 replicates).

Once in the laboratory, the field moist soil samples were passed through an 8 mm sieve by gently breaking up the soil clods along their natural planes of failure. Before air drying at room temperature, large rocks, visible roots and organic debris were removed by hand. Air-dry soil from each depth, field and site was physically fractionated to isolate different organic matter fractions in a simple, two-step process, modified from the Six et al. (2002a) and Plante et al. (2006a) procedures.

In a first step, whole-soil samples were partially dispersed using the microaggregate isolation method of Six et al. (2000, 2002a) to obtain three size fractions: coarse particulate organic matter fraction (cPOM, $>250 \mu\text{m}$), microaggregate fraction (μagg , 250-53 μm), and easily dispersed mineral-associated organic matter fraction (d-Min, $<53 \mu\text{m}$). Briefly, 50 g of air-dried soil was placed on a 250 μm sieve and submerged in deionized water for 30 min to allow slaking. After this time, soil was gently shaken with 50 glass beads (6 mm in diameter) in running water over the 250 μm sieve until complete macroaggregate disruption. The continuous and steady

water flow prevented the disruption of microaggregates which, together with finer particles, were immediately flushed on a 53 µm sieve. The material retained on the 53 µm sieve was wet sieved by hand for 50 strokes in 2 min to separate the water-stable microaggregates from the d-Min fraction. The three fractions were oven dried at 60 °C and weighed.

In the second step, the isolated microaggregates were subject to further fractionation to obtain two fractions: the fine particulate organic matter fraction (fPOM, 250-53 µm) and the mineral-associated fraction occluded within microaggregates (μ agg-Min, <53 µm). For this, 10 g of the microaggregate samples were dispersed by shaking for 18 h with 15 glass beads (4 mm in diameter) in 50 ml deionized water. After shaking, the suspension was poured over the 53 µm sieve and washed to separate fPOM and μ agg-Min fractions. Fractions were oven dried (60 °C) and weighed.

Organic carbon content was measured in the four isolated fractions (cPOM, fPOM, d-Min and μ agg-Min) by using a LECO analyser (RC-612 model). Total SOC was calculated as the sum of the OC fractions and, in some soil samples, total OC was also measured to compare and determine the efficiency of the fractionation procedure. Soil particle size distribution was obtained by laser diffraction analysis (Coulter LS230), CaCO₃ content by dry combustion with the LECO analyzer, and electrical conductivity (EC), pH and gypsum content by standard methods (Page et al., 1982).

4.3.3. Statistical analyses

As the study was conducted under on-farm conditions, the NT, CT, and NAT treatments were not field replicated. In each of the sites, however, the three fields were contiguous and sited on similar landscape position and same soil. Therefore, the three sampling locations within each field were used as pseudoreplicates and statistical comparisons among treatments were made using one-way ANOVA, assuming a randomized experiment (Christopher et al., 2009). In the case of the Peñaflor site, the randomized complete block design with three replicates per tillage treatment (CT, RT and NT) was also applied and statistical results were compared

with those obtained from the pseudoreplicate analysis. Duncan's multiple range test was used to compare treatment means ($P<0.05$). When data showed non-normality, transformations were made and ANOVA conducted with the transformed data. Computations were performed using SPSS 19.0 statistical software.

4.4. Results and discussion

Mass recovery after the two-step fractionation process was $97.6 \pm 1.7\%$ (mean \pm standard deviation) and OC recovery was $99.3 \pm 2.9\%$. These values, close to 100% and similar to recovery rates registered in the literature (Plante et al., 2006a,b; Moni et al., 2010; O'Brien and Jastrow, 2013), indicate that the loss of material was low, thus confirming the efficiency of the fractionation procedure.

Organic C concentrations of the four isolated fractions for each study site, soil management and soil depth are shown in Table 4.1. Average total SOC concentration in the 0-40 cm layer varied from 10 g kg^{-1} at Torres and Lanaja to 18 g kg^{-1} at Undués de Lerda (hereafter, Undués), being $\approx 11 \text{ g kg}^{-1}$ at Peñaflor and 12 g kg^{-1} at Artieda. As mentioned in the previous chapter, these contents, lower than 20 g kg^{-1} , are in agreement with the levels of SOC estimated for this region in the Map of Topsoil Organic Carbon in Europe (Jones et al., 2005) and, in general, for Southern Europe where a 74% of the land has a surface soil horizon with less than 20 g kg^{-1} of OC (Van-Camp et al., 2004). The further characterization of SOC in the present study showed that the highest contribution to total SOC corresponded to the d-Min-C fraction, accounting for ca. 40-70% of total OC (Table 4.1). It was followed by the μagg -Min-C fraction (15-40%) and, finally, by the fPOM-C (6-30%) and cPOM-C (<10%) fractions.

4.4.1. Mineral-associated organic matter fractions

The d-Min-C plus the μagg -Min-C form the total Min-C fraction ($<53 \mu\text{m}$) which constituted 70-90% of total OC in these soils.

Table 4.1. Concentrations of different soil organic C fractions (cPOM-C and fPOM-C, coarse and fine particulate organic C; μ agg-Min-C, mineral-associated organic C occluded within stable microaggregates; d-Min-C, easily dispersed mineral-associated organic C) at different soil depths as affected by soil management and tillage (CT, conventional tillage; RT, reduced tillage; NT, no tillage; NAT, natural soil). In Peñaflor, CC refers to the continuous cropping-system and CF to the cereal-fallow rotation.

Site	Treatment	0-5 cm			5-20 cm			20-40 cm		
		cPOM-C g kg ⁻¹ soil	fPOM-C agg-Min-C g kg ⁻¹ soil	d-Min-C g kg ⁻¹ soil	cPOM-C fPOM-C agg-Min-C d-Min-C g kg ⁻¹ soil	cPOM-C fPOM-C agg-Min-C d-Min-C g kg ⁻¹ soil	cPOM-C fPOM-C agg-Min-C d-Min-C g kg ⁻¹ soil			
Peñaflor	CC CT	0.46	1.12	5.64	4.75	0.41	1.32	4.58	5.21	0.32
	RT	0.74	2.12	4.72	5.37	0.50	1.52	3.86	5.50	0.25
	NT	1.33	3.27	3.51	6.95	0.38	1.21	3.99	4.73	0.25
	NAT	1.98	4.71	2.96	6.42	0.62	2.36	3.17	5.23	0.33
	LSD ^a	0.50	0.44	0.85	0.80	0.18	0.47	0.78	ns	0.53
Peñaflor	CF CT	0.30	0.64	4.30	5.50	0.22	0.85	3.36	6.18	0.21
	RT	0.53	1.04	3.75	5.83	0.38	0.94	2.66	6.50	0.18
	NT	0.82	1.42	4.04	7.02	0.24	0.64	3.65	5.82	0.16
	NAT	1.98	4.71	2.96	6.42	0.62	2.36	3.17	5.23	0.33
Lanaja	LSD	0.14	0.39	0.67	1.29	0.14	0.28	ns	0.98	0.08
	CT	0.78	1.44	2.08	6.38	0.02	1.40	2.41	6.30	0.00
Torres	NT	1.65	3.46	2.81	7.39	0.15	1.93	2.68	6.22	0.35
	NAT	2.92	5.30	3.17	6.26	0.42	1.85	2.15	4.75	0.01
	LSD	1.25	2.02	ns	ns	0.28	ns	1.34	0.14	ns
	CT	1.11	1.68	1.87	5.80	0.76	1.20	1.44	5.84	0.35
de Alcanadre	NT	1.47	3.35	2.89	5.64	0.62	1.37	1.90	5.57	0.30
	NAT	3.95	4.24	2.69	5.95	1.83	2.13	2.04	5.28	0.92
	LSD	0.51	1.26	0.99	ns	0.22	0.77	0.22	ns	0.21
	CT	0.56	2.66	3.07	10.62	0.20	1.83	2.89	10.14	0.00
Undués de Lerda	NT	0.45	3.96	3.89	11.59	0.12	2.11	3.12	9.51	0.00
	NAT	5.61	13.05	4.27	16.46	1.30	7.94	3.37	13.78	0.00
	LSD	3.00	1.55	0.99	3.07	0.67	1.95	ns	3.92	ns
	CT	2.12	2.26	3.26	5.42	1.05	1.41	2.51	5.64	0.68
Artieda	NT	1.10	2.80	4.38	4.97	0.41	1.60	2.61	5.42	0.30
	NAT	3.58	9.08	3.41	13.85	1.33	3.78	2.67	9.23	0.72
	LSD	1.62	1.49	0.95	1.16	0.61	0.25	ns	0.81	0.24

^aLSD, least significant difference ($P<0.05$).

4.4.1.1. Easily dispersed mineral-associated organic matter

The d-Min-C fraction (<53 µm outside water-stable microaggregates) was not greatly affected by soil management with the exception of the Undués and Artieda sites where NAT soils had the highest carbon contents (Table 4.1). Although this effect was significant ($P<0.05$) in all soil depths, the greatest differences occurred at the surface where the d-Min-C concentration was 1.5-2.7 times higher in NAT than in the agricultural soils. A different pattern was observed at the most arid sites where the d-Min-C was equal or even less in NAT than in agricultural soils, as can be observed in the deeper layers at Peñaflor and Lanaja (Table 4.1). This is due to the low and variable precipitation received at these sites which limits primary production and OC storage also in the NAT soils. At Lanaja, the lowest d-Min-C is explained, in addition, by the semi-natural conditions of this field (see Table 3.1 in Chapter 3). In the cultivated soils, the d-Min-C content was not significantly affected by tillage with the exception to the Peñaflor site where the soil surface (0-5 cm) under NT had a significant higher d-Min-C than the soils under CT and RT (Table 4.1). However, in depth (20-40 cm), this behavior was reversed, showing CT the highest concentration.

There are few studies in the literature that evaluate the effect of tillage on the d-Min-C fraction. These include the work of Dou and Hons (2006) who found that, after 20 years of NT, the content of this fraction at the soil surface was higher under NT than CT. However, they also observed that this difference between treatments was declining with decreasing the crop rotation intensity and it was always lower than the quantified for the coarser size fractions (>53 µm). In other study, Plante et al. (2006b), comparing forest and agricultural soils under CT and NT (NT for ≈24 years), observed that the OC content of the easily dispersed silt- and clay-sized fractions were not greatly affected by either land use or tillage system.

The relatively low responsiveness of the d-Min fraction to soil management can be explained by the nature of this fraction. The d-Min fraction consists of OM associated with soil minerals (clay and silt particles) through many different organomineral interactions (hydrogen bonds, polyvalent cation bridging, van der Waals forces, etc.) (Feng et al., 2013; Lopez-Sangil and Rovira, 2013). Although the chemical stabilization is, therefore, the main preservation mechanism of d-Min-C,

the biochemical stabilization is also involved due to the presence of recalcitrant OM in this pool (Dou and Hons, 2006; Plante et al. 2006b; Stewart et al., 2009). The high degree of OC protection from decomposition exerted by the inherent biochemical recalcitrance of the OM and by the strong associations with the active mineral surfaces explains the persistence of the Min-C during decades (biochemical stabilization) or centuries-millennia (chemical stabilization) (Schmidt et al., 2011).

Of particular interest is the role of clay particles in the OM stabilization due to their high specific surface area and charge. In fact, clay minerals are considered the most active constituents in the formation of organomineral complexes (Chenu et al., 2006) and responsible for the long-term preservation of SOM, even over millennia (Zhou et al., 2014). This predominant role of clay particles seems to be confirmed in our study through the relationships between soil texture and OC content. Although soil texture was dominated by the silt-sized particles in all of the study sites except Torres with a more sandy soil (Table 3.2 in Chapter 3), stronger relations with SOC were obtained by using clay instead of silt+clay as predictor variable. Significant positive relationships ($P<0.001$) between clay content and d-Min-C, Min-C or total SOC concentrations were found for both agricultural and NAT soils at either 0-5 or 0-40 cm depths (Table 4.2 and Fig. 4.1). Considering the total soil layer characterized (0-40 cm), the percentage of variation explained by linear regressions was, on average, 68% for d-Min-C and Min-C fractions, and 65% for total SOC. At the soil surface, these percentages reached 80% in the NAT soils and decreased to 30-50% in the agricultural soils (Table 4.2), reflecting the mixing effect of tillage in the plough layer. The greater regression slopes in NAT (Table 4.2) indicate that the differences in OC between NAT and agricultural soils were higher in the soils with higher clay contents. This observation was more pronounced at the soil surface and, especially, for total SOC. Similar results were found by Hevia et al. (2003) comparing cultivated and virgin soils in the Semiarid Pampas of Argentina, and indicate that cultivation of natural lands can lead to higher losses of OM in fine textured soils than in coarser soils.

Different previous studies have reported positive relationships between clay or clay+silt content and Min-C or total SOC using a wide variety of regression models

Table 4.2.

Regression equations relating concentrations (g kg^{-1} soil) of the easily dispersed mineral-associated organic C (d-Min-C), total mineral-associated organic C (Min-C) and total soil organic C (SOC) to soil clay content (g kg^{-1}).

Soil depth		Equation	r^2	P	n
cm	Soil type				
0-5	Agricultural	d-Min-C = 1.73 + 0.021 clay	0.429	<0.0001	42
		Min-C = 4.57 + 0.024 clay	0.534	<0.0001	42
		SOC = 8.36 + 0.021 clay	0.257	<0.001	42
	Natural	d-Min-C = 0.53 + 0.050 clay	0.803	<0.0001	15
		Min-C = 2.78 + 0.056 clay	0.808	<0.0001	15
		SOC = 4.79 + 0.104 clay	0.768	<0.0001	15
0-40	Agricultural	d-Min-C = 1.31 + 0.020 clay	0.680	<0.0001	42
		Min-C = 3.83 + 0.023 clay	0.734	<0.0001	42
		SOC = 5.43 + 0.023 clay	0.723	<0.0001	42
	Natural	d-Min-C = -1.19 + 0.040 clay	0.688	<0.0001	15
		Min-C = 0.87 + 0.044 clay	0.624	<0.001	15
		SOC = 0.63 + 0.067 clay	0.586	<0.001	15

(linear, exponential, quadratic, two-segment linear) and also showing very different coefficients of determination ($r^2=0.20-0.70$; $P<0.05$) (Six et al., 2002b; Hevia et al., 2003; Hao and Kravchenko, 2007; Shrestha et al., 2007; Gami et al., 2009). However, there are also works reporting no or little effect of soil texture on SOC (McLauchlan, 2006; Sleutel et al., 2006) probably due to differences in clay mineralogy, limited textural range, high variations in SOC pools or in environmental conditions, and, finally, to the complexity of the mechanisms of SOM stabilization (Plante et al., 2006a). In this sense, the significant relationships obtained in the present study are considered satisfactory and provide further information on the key role of the d-Min-C fraction in the stabilization of SOC by fine mineral particles since no other isolated OM fractions were correlated with soil texture.

4.4.1.2. Mineral-associated organic matter within microaggregates

The μagg -Min-C fraction (<53 μm occluded within water-stable microaggregates) in all cases contributed to total Min-C in a lesser degree than the d-Min-C fraction

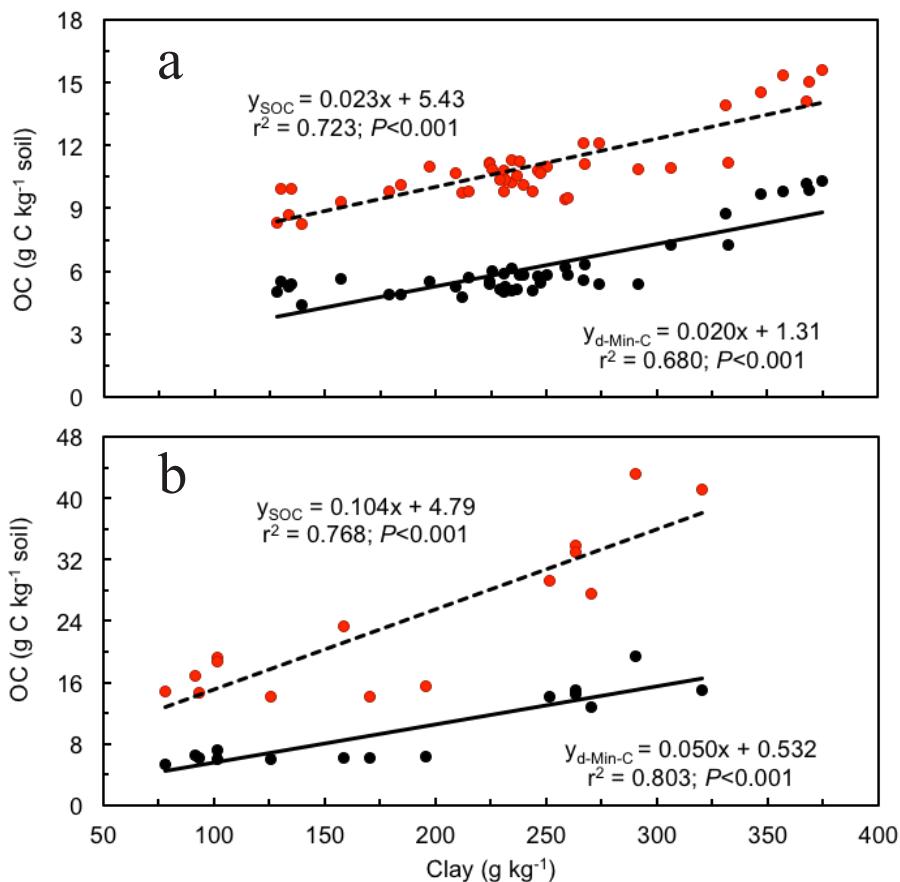


Fig. 4.1. Relationships between the concentrations of total soil organic carbon (SOC, ---●---) and easily dispersed mineral-associated organic C (d-Min-C, —●—), and the clay content in agricultural soils at 0-40 cm depth (a) and in natural soils at 0-5 cm depth (b).

(20-50% vs. 50-80%). No consistent results were found concerning the effect of land use and tillage on $\mu\text{agg}\text{-Min-C}$ (Table 4.1). At the soil surface (0-5 cm depth), this fraction was higher in the NAT than in the CT soils at Undués, Lanaja and Torres (40-50% more) whereas the opposite occurred at Peñaflor where it was, on average, 30% lower in the NAT than in the agricultural soils. Considering only the cultivated soils, with the exception of the Peñaflor site, the $\mu\text{agg}\text{-Min-C}$ content at the soil surface

was in all cases higher under NT than under CT (30-50% more). Dou and Hons (2006) also reported increments between 30 to 50% of this OC fraction in the first 5 cm of a NT soil with respect to CT for different cropping systems. Likewise, in three soils with different texture and clay mineralogy, Denef et al. (2004) found that the Min-C associated with microaggregates within macroaggregates was significantly greater under NT than under CT even to a soil depth of 20 cm. On the contrary, in the current study, at Peñaflor CC and for total soil depth (0-40 cm), the μ agg-Min-C was ca. 30 and 40% higher in CT than in NT and NAT, respectively.

The unexpected effect of CT at the Peñaflor site, and especially under the CC system, could be explained because, in contrast to the other sites, crop residues are left in the field after harvest also in this tillage treatment (see Table 3.1). During 19 years, the annual incorporation of fresh organic material into the soil by mouldboard ploughing has probably favored the occlusion of OC within soil aggregates, increasing in this way the μ agg-Min-C in the plough layer of CT compared to no tilled soils. This interpretation is supported by the results of Gregorich et al. (2009) and Andruschkevitsch et al. (2014) who found greater OC contents within stable soil aggregates in CT than in NT soils at or near the bottom of the plough layer and, sometimes, also in the surface layers.

In contrast to d-Min-C, the μ agg-Min-C fraction was not significantly correlated with soil texture variables. This implies that, at the study sites, the stabilization of Min-C within stable microaggregates was not dependent on the soil clay and/or silt content. This difference between the two Min fractions seems to be in line with previous observations on the distinct nature and behavior of both pools (Plante et al., 2006c; Stewart et al., 2009). Recent studies have demonstrated that mechanisms other than simple monolayer adsorption of SOM onto clay surfaces are implied in the SOM stabilization by fine soil particles (McCarthy et al., 2008; Moni et al., 2010; O'Brien and Jastrow, 2013; Vogel et al., 2014). More complex multilayer arrangements involving multiple mineral surfaces, i.e., clay- and silt-sized aggregates, zonal structures or OM-filled pores, would mean a Min-C content higher than that expected on the basis of the specific surface area of clays (O'Brien and Jastrow, 2013). Recently, Vogel et al. (2014), with incubation experiments,

observed that OM was preferentially attached to organo-mineral clusters with rough surfaces containing pre-existing OM and that less than 19% of the total soil mineral area was covered by OM. These findings could explain why clay and/or silt content is sometimes weakly or not related to SOC, as it can be the case of μ agg-Min-C in the present study.

The physical protection of SOM provided by soil microaggregates was confirmed by the positive correlation found between the μ agg-Min-C concentration and the mass of water stable microaggregates (sand-free basis) at either 0-5 or 0-40 cm soil depth ($r \approx 0.90$; $P < 0.0001$). The importance of SOM as cementing and stabilizing agent in soil aggregation can also be inferred from this significant relationship. Considering together all sites and treatments, multiple regression analysis showed that 80-90% of the total variation in the microaggregate mass was explained by μ agg-Min-C and, to a much lesser extent, by soil clay and CaCO_3 contents (Table 4.3 and Fig. 4.2). The very weak influence of clay and CaCO_3 (explaining only 10% of the variation) would indicate that, in the studied soils, these properties were not highly involved in the formation and persistence of water-stable microaggregates. These results are supported by the data presented in the Chapter 5 on the dynamics of aggregate destabilization by water in these same soils. That study showed that slaking was the dominant process of aggregate destabilization by water in these soils, being strongly and negatively affected by the aggregate-associated OC content and not by other soil variables such as clay or CaCO_3 . In this same sense, Wuddivira and Camps-Roach (2007) showed that the positive influence of SOM on structural stability was more pronounced in soils with low clay content. Furthermore, these authors reported that both clay and calcium may either favour or prevent slaking and dispersion depending on their interactions with SOM and on the clay mineralogy. In Mediterranean soils, Boix-Fayos et al. (2001) found that, at low SOC concentration, the water stability of macroaggregates was enhanced by carbonates but not in the case of microaggregates. Anyway, further research on the interaction between organic and inorganic soil components is required to improve our understanding of protection mechanisms of SOM in microaggregates.

Table 4.3.

The optimum regression equations to estimate the mass of water-stable soil microaggregates (sand-free basis; $\text{Mass}_{\mu\text{agg}}$, $\text{g kg}^{-1}\text{soil}$) as a function of the mineral-associated organic C occluded within stable microaggregates ($\mu\text{agg-Min-C}$, g C kg^{-1} soil) and clay and CaCO_3 contents (g kg^{-1}).

Soil depth cm	Equation	r^2	P	n
0-5	$\text{Mass}_{\mu\text{agg}} = 13 + 56 \mu\text{agg-Min-C} - 9076/\text{clay} + 0.121 \text{CaCO}_3$	0.841	<0.0001	55
0-40	$\text{Mass}_{\mu\text{agg}} = 43 + 53 \mu\text{agg-Min-C} - 8709/\text{clay} + 0.120 \text{CaCO}_3$	0.899	<0.0001	55

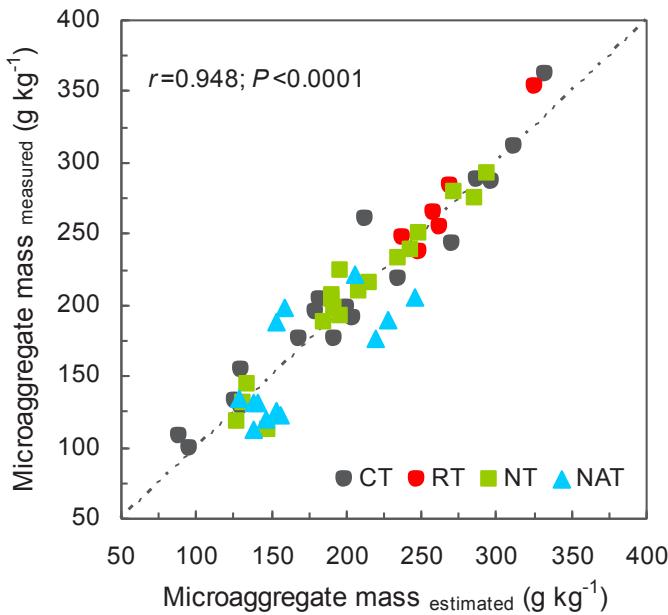


Fig. 4.2. Relationship between measured and predicted mass of water-stable soil microaggregates (sand-free basis) using equation in Table 4.3 for the 0-40 cm soil depth. Data come from soils under different tillage and management systems (CT, conventional tillage; RT, reduced tillage; NT, no tillage; NAT, natural soil).

4.4.2. Particulate organic matter fractions

The cPOM-C plus the fPOM-C form the total POM-C fraction which constituted 10-30% of total OC in these soils. The fPOM-C was always present at a higher concentration than cPOM-C (Table 4.1). The fPOM/cPOM ratio averaged 2 at the soil surface and increased to over 6 in the deeper soil layer. Moreover, in some cases, as Lanaja or Undués, fPOM was the only POM fraction present in depth since the amount of cPOM was negligible. It is important to remind that, in the present study, the total POM was divided by size and that we did not differentiate between free and occluded POM. However, the cPOM-C ($>250\text{ }\mu\text{m}$) constitutes an unprotected OC pool (as free or within macroaggregates) and represents the easily decomposable SOM (Six et al., 2002b). In contrast, part of the fPOM-C isolated in our study is a physically protected OC pool since it was protected within stable microaggregates. The rest of fPOM-C, resulting from the breaking up of macroaggregates (inter-microaggregate fPOM) and unstable microaggregates, can be considered unprotected OC (Six et al., 2002b). The fPOM represents an intermediate or transitional status between the cPOM and the Min fractions and, in general, it is not as dynamic and variable as cPOM (Duval et al., 2013).

In contrast to the Min-C fractions, the POM-C fractions were clearly influenced not only by land use but also by tillage system (Table 4.1). The fPOM-C concentration in the agricultural soils was from 24 (Undués) to 84% (Lanaja) of that in the NAT soils for 0-40 cm with differences being statistically significant throughout the whole soil profile. In the case of the cPOM-C, these percentages were lower (10-63%) and the differences between agricultural and NAT soils decreased with soil depth, disappearing in the 20-40 cm layer. For different regions of the Argentinean pampas, Duval et al. (2013) also found a depletion of fPOM and, especially, of cPOM by cultivation with reductions of 20-70% as compared to natural soils.

Within the cultivated soils, the largest differences among tillage systems were found at the soil surface (Table 4.1). In the upper 5 cm depth, the fPOM-C content was between 1.2 (Artieda) and 3 times higher (Peñaflor CC) under NT than under CT. With the exception of Artieda, the cPOM fraction followed a similar pattern as fPOM although the tillage effect was less pronounced. At Artieda, the lower

cPOM-C content under NT than under CT in the three soil layers (2-2.6 times less) can be explained by the farmer's practice of removing crop residues from the NT field (see Table 3.1.). At the Peñaflor site, under both CF and CC cropping systems, the RT response was intermediate between CT and NT with cPOM-C and fPOM-C concentrations significantly higher than those under CT (1.6-1.9 times higher).

In our study conditions, both fPOM and cPOM fractions contributed to the differences among sites based on the relative gain or loss of OC under NT with respect to CT at each site (i.e. (NT-CT)/CT). With the exception of cPOM at Artieda and Undués, POM-C was always higher under NT than under CT in the surface layer (Table 4.1). These values represent between 24 and 191% more fPOM-C with NT, averaging about 105% more. For cPOM, this range varied from 48% less to 187% more, with an average value of 74% more. Figure 4.3 shows negative and strong relationships ($P<0.01$) between the relative difference in the concentration of both fPOM-C and cPOM-C at 0-5 cm depth and the mean annual precipitation at each site thus indicating that the relative gain of OC with the adoption of NT decreases

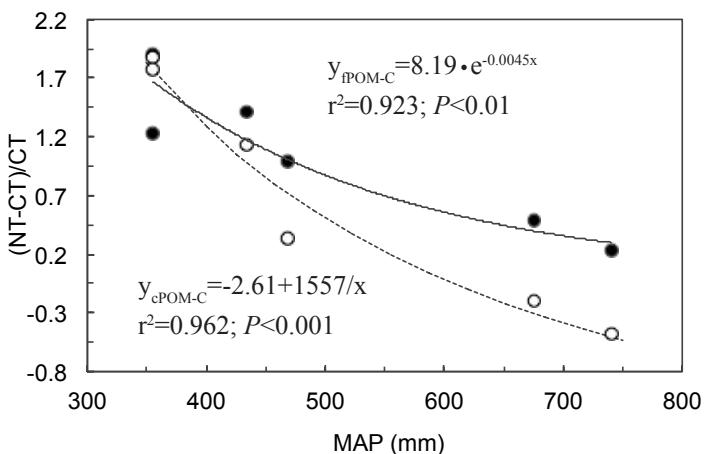


Fig. 4.3. Relative difference between no tillage (NT) and conventional tillage (CT) in fine (fPOM-C, —●—; g C kg⁻¹ soil) and coarse particulate organic C (cPOM-C, ---○---) at 0-5 cm soil depth as a function of mean annual precipitation (MAP).

as precipitation increases. Total SOC was also influenced by precipitation but was much less responsive than POM fractions ($r^2=0.588$). As discussed in the previous Chapter, although climatic factors, such as precipitation, have been shown to exert a control on the potential of NT to store SOC, the direction and magnitude of this potential with respect to CT systems can vary widely. However, our finding on the increase in the relative benefit of NT with reduction in precipitation is supported by Gregorich et al. (2009) who compare SOC storage in different Canadian regions. Similar conclusions are made by Luo et al. (2010) for agricultural soils in Australia. In these studies the authors suggest that compared to low rainfall areas, the faster decomposition of SOM in the surface layer under a more humid environment minimizes the overall change of SOC balance between input and output under NT and, therefore, the relative OC gain with respect to CT.

4.4.3. Soil organic matter stratification ratio

For both cPOM and fPOM fractions, the decreasing pattern in OC concentration with depth was more prominent under conservation tillage, especially NT, in such a way that the average concentrations in the 0-40 cm profile were not significantly different from those under CT. This depth gradient was reflected in the values of the stratification ratio, SR (Franzluebers, 2002), calculated as the OC concentration at 0-5 cm depth divided by that at 20-40 cm (Table 4.4). In addition to NAT soils, in NT and RT soils the SR for both POM fractions was greater than the threshold value of 2. Even under CT, SR>2 were obtained for these fractions at the most humid sites. This contrasts with the relatively low SR for μ agg-Min-C, d-Min-C and SOC. The marked stratification of POM-C is generally observed under continuous NT management (Álvaro-Fuentes et al., 2008; Salvo et al., 2010) and is produced by the maintenance of crop residues at the soil surface and the absence of soil disturbance

The POM-C, disproportionately to its small contribution to total SOC, has a large effect on nutrient-supplying capacity and structural stability of soils, and for these reasons it is considered a key attribute of soil quality (Haynes, 2005). Of the two POM fractions isolated in the present study, fPOM was, in general, more sensitive to soil tillage and land use than cPOM. On the other hand, cPOM is more dependent on

Table 4.4.

Stratification ratios (0-5 cm/20-40 cm) for total soil organic carbon (SOC) and different fractions of SOC (cPOM-C and fPOM-C, coarse and fine particulate organic C; μ agg-Min-C, mineral-associated organic C occluded within stable microaggregates; d-Min-C, easily dispersed mineral-associated organic C) as affected by soil management and tillage (CT, conventional tillage; RT, reduced tillage; NT, no tillage; NAT natural soil). In Peñaflor, CC refers to the continuous cropping-system and CF to the cereal-fallow rotation.

Site	Treatment	cPOM-C	fPOM-C	μ agg-Min-C	d-Min-C	SOC
Peñaflor CC	CT	1.44	1.07	1.25	0.85	1.05
	RT	2.92	2.85	1.13	1.07	1.28
	NT	5.33	4.06	1.00	1.34	1.55
	NAT	5.91	2.44	0.88	1.54	1.65
	LSD ^a	1.54	0.75	0.25	0.18	0.21
Peñaflor CF	CT	1.39	0.91	1.05	1.01	1.03
	RT	2.94	1.74	0.88	1.22	1.14
	NT	5.11	2.91	1.00	1.35	1.34
	NAT	5.91	2.44	0.88	1.54	1.65
	LSD	1.57	0.84	ns	0.28	0.20
Lanaja	CT	-	1.14	1.02	0.98	1.09
	NT	4.75	2.58	1.68	1.13	1.54
	NAT	-	5.07	1.67	1.91	2.89
	LSD	-	2.61	ns	0.15	0.44
Torres de Alcanadre	CT	3.15	2.01	0.93	1.21	1.31
	NT	4.86	3.85	1.13	1.23	1.61
	NAT	4.28	2.59	0.91	1.24	1.63
	LSD	1.49	1.62	ns	ns	0.28
Undués de Lerda	CT	-	1.96	1.10	1.08	1.21
	NT	-	3.40	1.16	1.30	1.48
	NAT	-	2.36	0.94	1.46	1.89
	LSD	-	1.00	ns	ns	0.26
Artieda	CT	3.13	1.63	1.14	1.06	1.31
	NT	3.70	2.10	1.51	0.99	1.39
	NAT	4.98	3.88	1.66	1.88	2.40
	LSD	ns	0.76	0.37	0.18	0.34

^aLSD, least significant difference ($P<0.05$).

plant derived C inputs and, therefore, more variable in time and space (also in depth) than fPOM (Lee et al., 2009; Duval et al., 2013). For those reasons, fPOM can be considered more reliable and useful indicator of soil changes associated with tillage and crop residue management.

4.5. Conclusions

This on-farm study reinforces the importance of analyzing SOC fractions to improve our understanding of the management-induced changes in SOC dynamics. Among the four isolated fractions, the d-Min-C (<53 µm, outside water-stable microaggregates) provided the highest contribution to total SOC (40-70%) and was not greatly affected by soil management. Soil clay content was a determinant factor for d-Min-C, indicating that chemical stabilization, through clay-organic complexes, seems to be a main preservation mechanism of OC in the studied soils. In contrast, soil texture did not influence the Min-C content occluded within water-stable microaggregates (μ agg-Min-C, 15-40% of total SOC). However, the strong relationship found between this fraction and the mass of stable microaggregates indicated that physical protection is also a stabilization process of OC involved in these soils. The two labile fractions isolated, cPOM- and fPOM-C, despite their small contributions to total SOC (<10% and 6-30%, respectively), were sensitive to soil management and their concentrations decreased as soil disturbance increased (NAT>NT>RT>CT). The highest differences between NT and CT corresponded to fPOM-C and were generally restricted to the soil surface where this fraction was 1.2-3 times higher under NT. This relative gain with respect to CT increased in the most arid locations of the agroclimatic gradient. Likewise, higher soil stratification ratios under NT, always >2 for the POM-C fractions, suggest an improvement in soil quality with the long-term NT adoption in this semiarid Mediterranean region.

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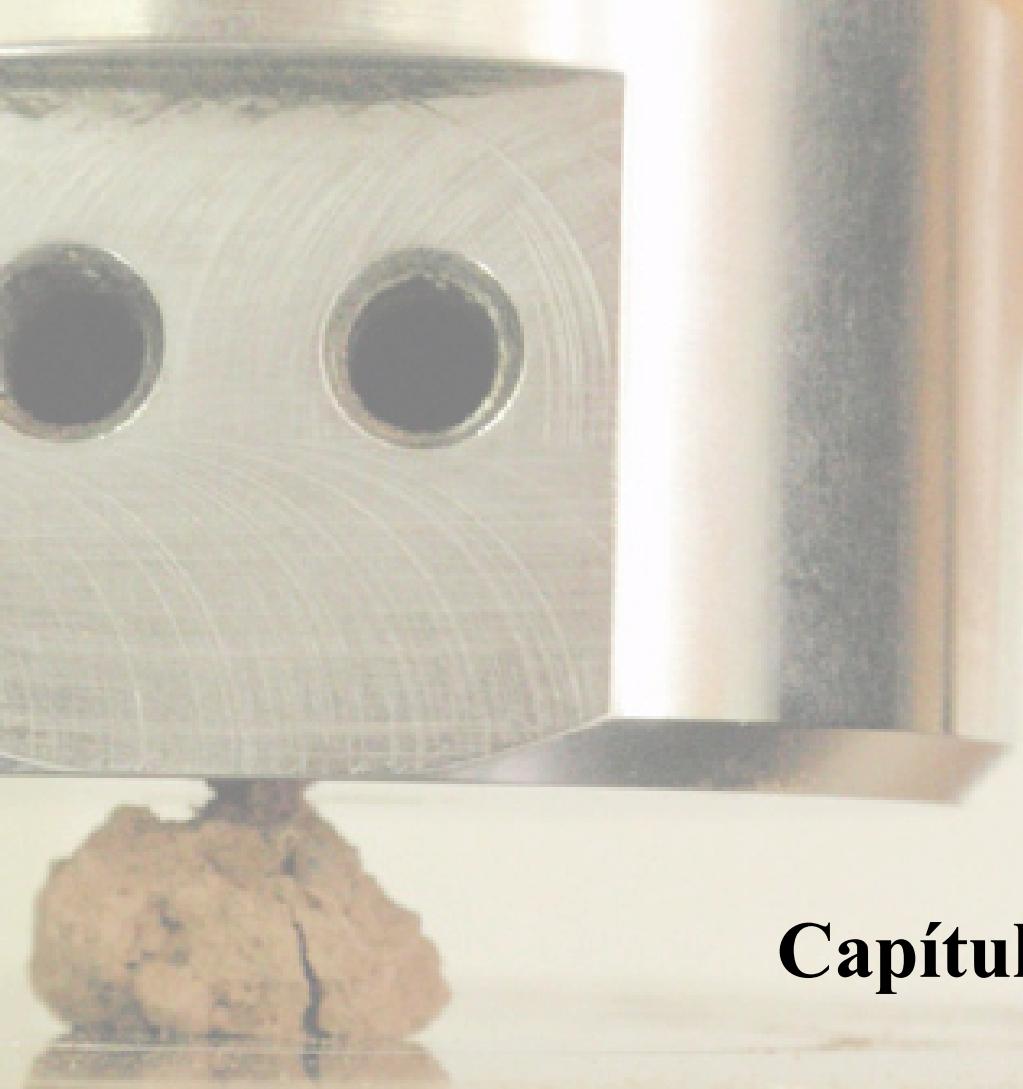
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Capítulo 5

Tensile strength and organic carbon of soil aggregates under long-term no tillage in semiarid Aragon (NE Spain)

Geoderma (2012) 189–190, 423–430

- Detalle de la rotura de un agregado de suelo (16-8 mm de diámetro) durante un ensayo de compresión con una máquina universal de ensayos INSTRON.

5.1. Abstract

Tensile strength (TS) of soil aggregates is recognized as a useful parameter to detect structural changes associated with soil management. Although conservation tillage has been encouraged as a management alternative to preserve soil and water resources in semiarid Aragon (NE Spain), little information concerning soils on which these techniques are applied is available for this region. The main objective of this study was to assess the effect of long-term no tillage (NT) on TS, rupture energy (*E*) and organic carbon (OC) of soil surface aggregates (0-5 cm depth) in five different cereal production areas of Aragon. In four of the sites, the study was conducted under on-farm conditions where pairs of adjacent fields under NT and conventional tillage (CT) were compared. In the last site, the study was carried out in research plots from a long-term tillage experiment where a third tillage treatment was also considered (reduced tillage). In all cases, a nearby undisturbed soil under native vegetation was included. Results indicate that NT reduced aggregate TS and *E* with respect to CT systems through lower soil disturbance and higher OC content. Aggregate size (16-8, 8-4, 4-2 and 2-1 mm in diameter) and aggregate-associated OC explained 70-80% of the variation in TS and *E*. Strength properties varied with OC in quadratic way with minimum values at about 20 g kg⁻¹ of OC. This behavior can be explained by the significant interactions found between clay and OC in such a way that in the soils with the highest values of clay and OC, aggregate strength increased considerably. This study shows that, under the rainfed conditions of semiarid Aragon, NT improves soil physical conditions by reducing aggregate strength at the soil surface. This means, for example, that NT could provide a more favorable environment for seedling emergence and root growth than the traditional practices in the area.

5.2. Introduction

A good soil structure is essential to ensure sustainable agriculture. Many physical and biological soil processes depend, besides on the architectural organization of soil aggregates, on the internal micro-scale or aggregate structure (Horn 1990; Blanco-Canqui et al., 2005a). Aggregate structural properties influence seedling emergence and root growth, water and gas transfer, organic matter protection and dynamics, and soil susceptibility to wind and water erosion. For these reasons, there is an increasing interest in knowing the properties of individual soil aggregates to understand the behaviour of the whole soil and its response to management (Park and Smucker, 2005; Munkholm et al., 2007; Blanco-Canqui and Lal, 2008).

Despite the attention now focused on soil organic matter and soil biology, research on soil physical and mechanical properties should not be underestimated since the two aspects are closely related (Dexter et al., 2008; Ritz and Young, 2011). One of the most useful mechanical properties of soil aggregates and a very sensitive indicator of soil structural stability is the tensile strength (TS) (Dexter and Kroesbergen, 1985; Watts and Dexter, 1998). The TS is defined as the force per unit area required to break soil aggregates into smaller particles. It is considered a valuable parameter of soil microstructure since its measurement implies the formation of a fracture surface in the aggregate which usually incorporates pre-existing points of weakness, such as microcracks or pores (Horn and Dexter, 1989; Hallett et al., 1995). Tensile strength has been measured in studies that evaluate energy efficiency and ease of tillage operations (Wolf and Hadas, 1987; Munkholm and Kay, 2002), seedling emergence and root growth (Materechera et al., 1994) and wind erosion (Hagen et al., 1995). This parameter is currently being considered in the assessment of the potential of conservation tillage to improve soil physical conditions (Urbanek and Horn, 2006; Blanco-Canqui and Lal, 2007a; Abid and Lal, 2009). However, data on TS from long-term conservation tillage practices are still scarce and also variable, indicating that the impact of these practices is site specific. In fact, the literature shows that the relationships of TS and other soil properties, such as organic carbon, are not well resolved due to many factors involved, e.g. soil texture, porosity, water content (Zhang, 1994; Imhoff et al., 2002; Munkholm and Kay, 2002).

Due to particular soil and climate conditions and inappropriate agricultural practices, Aragon (NE Spain) is a region prone to land degradation by wind and water erosion (López et al., 1998, 2001; López-Vicente et al., 2008). For this reason, the adoption of conservation tillage has been encouraged as an alternative to preserve soil and water in this region. In fact, according to previous results on soil and crop response in cereal production areas of Aragon (López et al., 2005; Moret et al., 2007; Álvaro-Fuentes et al., 2009), conservation tillage could be regarded as a viable management alternative. Furthermore, a recent survey conducted by the Department of Agriculture and Food of the Government of Aragon (Vallés, 2009) found a very positive perception of the advantages of these tillage systems by farmers and an increasing adoption in the last years, especially of no tillage (NT). However, this report also highlights the lack of knowledge about the soils on which these systems are applied.

The little available information on aggregate properties of cultivated soils in Aragon has been mainly focused on water stability and size distribution of soil aggregates and it has been collected from small research plots and from single soil types (López et al., 2000; Álvaro-Fuentes et al., 2008). However, farming practices applied by farmers in their fields can be very diverse and differ from those in experimental plots. For these reasons, direct measurements under on-farm conditions across different soils, microclimate and agronomic practices are necessary to get a broad knowledge of the potential of conservation tillage in the region. In order to remedy this lack of information, the objectives of this study were to (1) assess the effect of long-term NT on TS of soil aggregates compared with traditional tillage practices and undisturbed soils under native vegetation in different cereal production areas of Aragon, and (2) establish relationships between TS and aggregate-associated organic carbon (OC) to understand the role of soil OC on soil strength properties.

5.3. Materials and methods

5.3.1. Study sites

The study was based on the six long-term NT fields (9-21 yr) described in the previous chapters (Chapters 3 and 4, see Table 3.1 and Fig. 3.1). Basic properties of

the study soils for the first 5 cm depth are shown in Table 5.1 since it was the depth at which we have focused for the characterization of TS.

5.3.2. Soil sampling and analyses

Tensile strength and OC content of soil aggregates were determined for the first 5 cm of soil depth. In the farmer fields, soil sampling was made in three different zones within each field (NT, CT and NAT) where three soil samples were collected and mixed to make a composite sample. In the Peñaflor site, each of the composite samples came from each of the 3 tillage plots per treatment (NT, RT and CT). Once in the laboratory, soil samples were air-dried at room temperature ($\approx 20^\circ \text{ C}$) and dry sieved through a nest of sieves with 16, 8, 4, 2 and 1 mm openings to obtain aggregates of four different size classes (16-8, 8-4, 4-2 and 2-1 mm in diameter).

The TS of individual soil aggregates was determined by an indirect test using the crushing method (Dexter and Kroesbergen, 1985; Dexter and Watts, 2000) with a universal testing machine (INSTRON model 5565). The tests consisted basically of crushing an individual aggregate between two flat parallel plates and recording the force required to break it. Soil aggregates were previously oven dried at 105° C during 24 h to obtain a standard condition of soil humidity (Dexter and Watts, 2000). Depending on the variability of the measurements, at least 12 aggregates of each size class and field were measured. Therefore, a minimum of 144 tests per site was made (192 in Peñaflor) (4 aggregate sizes x 3 or 4 treatments x 3 replicates x 4 tests). The compression tests were performed at a constant displacement rate of 2 mm min^{-1} . Load cells of 5 kN (kiloNewton) and 100 N (Newton) were used, respectively, for the largest aggregates, 16-8 and 8-4 mm in diameter, and the smallest ones, 4-2 and 2-1 mm.

The TS (kPa) of soil aggregates was computed using Eq. (1) (Rogowski et al., 1968):

$$\text{TS} = 0.576 F/d^2 \quad (1)$$

where F (N) is the breaking force and d (m) is the mean aggregate diameter. The 0.576 value is a constant based on the assumption of spherical form and perfect elastic behavior (Poisson ratio=0.5) (Dexter, 1975). On the assumption that aggregate

Table 5.1. Selected properties of the studied soils in the 0–5 cm depth (CT, conventional tillage; RT, reduced tillage; NT, no tillage; NAT, natural soil). In Peñaflor, CC refers to the continuous cropping system and CF to the cereal-fallow rotation.

Site	Treatment	pH	EC (1:5) ^a	Sand		Silt	Clay	CaCO ₃	Organic carbon
		(H ₂ O, 1:2.5)	dS m ⁻¹				g kg ⁻¹	g kg ⁻¹	
Peñaflor CC	CT	8.1	0.61	293	456	251	449	12.0	
	RT	8.3	0.26	335	444	221	452	13.0	
	NT	8.3	0.27	392	406	202	446	15.1	
	NAT	8.1	0.80	635	258	106	563	16.1	
Peñaflor CF	CT	8.4	0.23	287	463	250	462	10.7	
	RT	8.4	0.19	318	439	243	466	11.1	
	NT	8.3	0.31	313	451	236	473	13.3	
	NAT	8.1	0.80	635	258	106	563	16.1	
Lanaja	CT	8.4	0.23	134	589	277	439	10.7	
	NT	8.3	0.30	145	587	268	396	15.3	
	NAT	8.3	0.24	310	516	174	310	17.6	
Torres de Alcanadre	CT	8.4	0.15	584	281	135	235	10.5	
	NT	8.2	0.25	615	269	116	223	13.4	
	NAT	8.4	0.15	695	215	90	233	16.8	
Undúes de Lerda	CT	8.1	0.18	121	526	354	54	16.9	
	NT	8.2	0.17	136	525	339	84	19.9	
	NAT	8.1	0.24	240	469	291	108	39.4	
Artieda	CT	7.9	0.37	365	393	242	177	13.1	
	NT	8.2	0.19	333	431	236	228	13.2	
	NAT	8.1	0.21	352	387	261	68	29.9	

^aEC, electrical conductivity.

density is constant, the value of d was estimated from Method 4 as described by Dexter and Watts (2000):

$$d = d_o (m/m_o)^{1/3} \quad (2)$$

where m is the mass of an individual aggregate, m_o is the mean mass of a batch of aggregates of the same size class and d_o is the mean of the openings of the upper and lower sieves for that size class.

Together with the TS measurement, the rupture energy for each soil aggregate was calculated by integrating the area under the F vs. displacement curve. The specific rupture energy (E , J kg⁻¹) was obtained by dividing the rupture energy by the aggregate mass. For the same size class, the OC content of soil aggregates was determined directly by dry combustion with a LECO analyser (RC-612 model), without requiring correction for carbonates.

For the general characterization of soils, particle size distribution was obtained by laser diffraction analysis (Coulter LS230), OC and CaCO₃ contents by dry combustion with the LECO analyser, and electrical conductivity and pH by standard methods (Page et al., 1982).

5.3.3. Statistical analysis

Within each study site, statistical comparisons among treatments were made using one-way ANOVA, assuming a randomized experiment. As in each of the sites, the fields were contiguous and sited on similar landscape position and same soil, the three sampling locations (i.e. sampling zones within each field) were used as pseudoreplicates (Christopher et al., 2009). In the case of the Peñaflor site, the randomized complete block design with three replicates per tillage treatment (CT, RT and NT) was also applied and statistical results were compared with those obtained from the pseudoreplicate analysis. Duncan's multiple range test was used to compare treatment means ($P < 0.05$). Correlation and regression analyses were performed to identify and evaluate the degree of relationship among the measured properties. Special attention was paid to the relationship of TS and E with OC as predictive variable. In these cases, simple regressions were done by averaging the four aggregate size classes for each treatment and site with the objective to eliminate

the variability due to aggregate size. When data showed non-normality (Kolmogorov-Smirnov test), logarithmic transformations were performed and ANOVA conducted with the transformed data. Computations were performed using SPSS 19.0 statistical software.

5.4. Results and discussion

5.4.1. Soil tillage effects on tensile strength

Mean values of TS and E for each of the study sites are shown in Figs. 5.1 and 5.2, respectively. The TS values ranged from 20 to 700 kPa (30-1040 J kg⁻¹ for E), varying not only with the soil management or tillage treatment but also with the aggregate size. Thus, the figures clearly illustrate an increase in TS, and generally also in E , with decreasing the aggregate size (differences among sizes significant at $P<0.05$). The higher resistance of small aggregates against applied forces is supported by previous studies (Perfect and Kay, 1994; Chan et al., 1999; Blanco-Canqui et al., 2005a,b), suggesting that they contain less points of weakness, such as microcracks and pores, and stronger bonds between particles than larger aggregates (Utomo and Dexter, 1981; Horn and Dexter, 1989).

Soil management and tillage system had a significant effect on TS and E (Figs. 5.1 and 5.2). With the exception of the NAT soils of the Undués de Lerda (hereafter, Undués) and Artieda sites, results showed a general trend of increase in TS with the degree of soil disturbance (i.e. NAT<NT<RT<CT). Within the cultivated soils, the lowest TS values were always recorded under NT, following by RT in the Peñaflor site. The magnitude of the tillage differences varied among sites, indicating that the response is site-specific. Thus, while mean TS was 3.2 times lower under NT than under CT in the Peñaflor CF site, it was only 1.3 times in Lanaja. Similar results were shown by Blanco-Canqui et al. (2005a) who found lower TS values by a factor of 2.5 in a silt loam soil under NT than under CT. Abid and Lal (2009), also working with a soil of medium texture, observed a clear relation between aggregate strength and tillage intensity, with lower TS in NT than in CT by factors of 1.5-1.6. The same trend has been recently observed by Li et al. (2011) in a long-term tillage/stubble experiment conducted in a clay loam soil where TS values under NT were 1.4 to 2.6

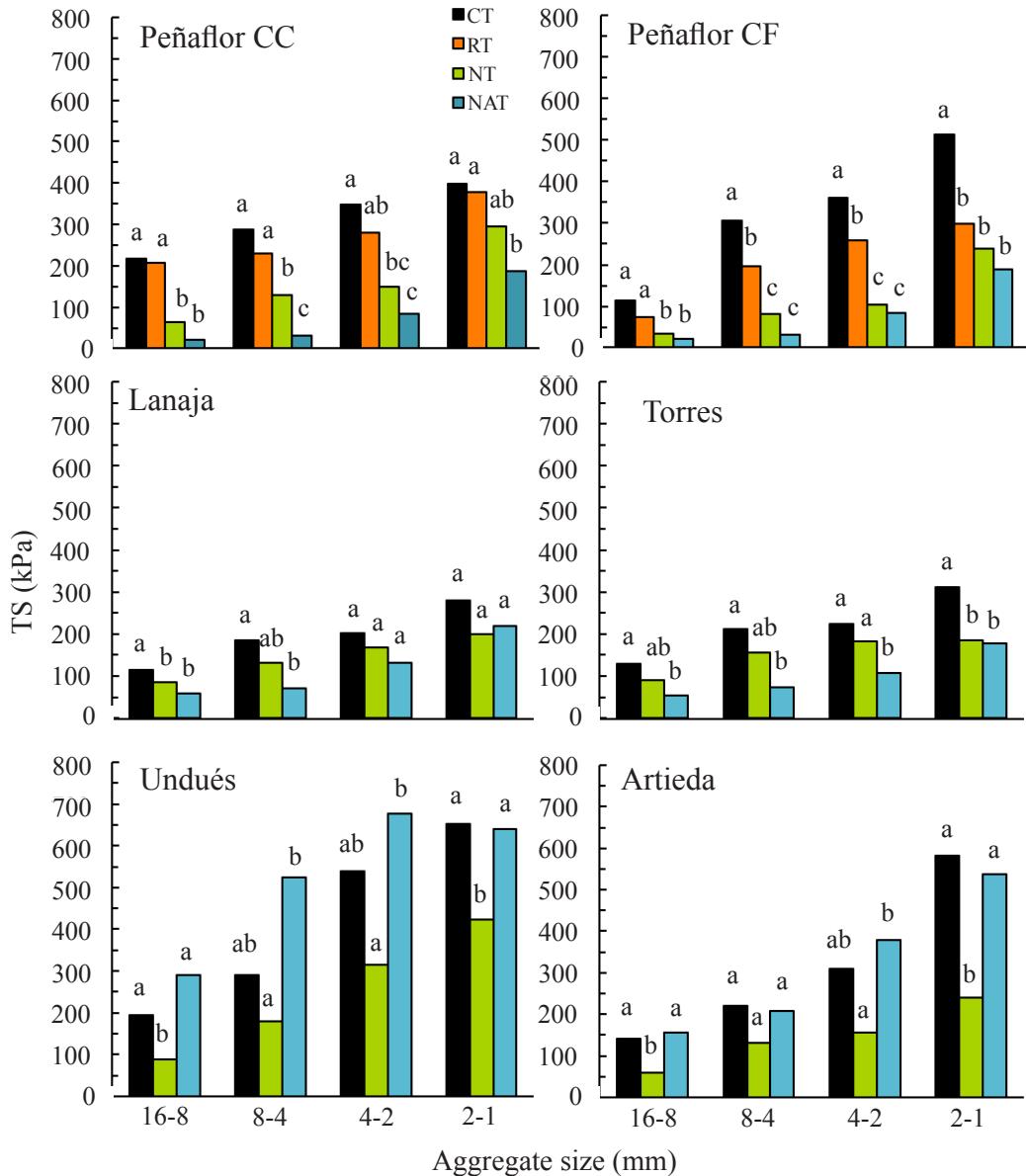


Fig. 5.1. Tensile strength (TS) of soil aggregates of different size classes as affected by soil management and tillage (CT, conventional tillage; RT, reduced tillage; NT, no tillage; NAT, natural soil). In Peñaflor, CC refers to the continuous cropping system and CF to the cereal-fallow rotation. For the same aggregate size, different letters indicate significant differences at $P < 0.05$.

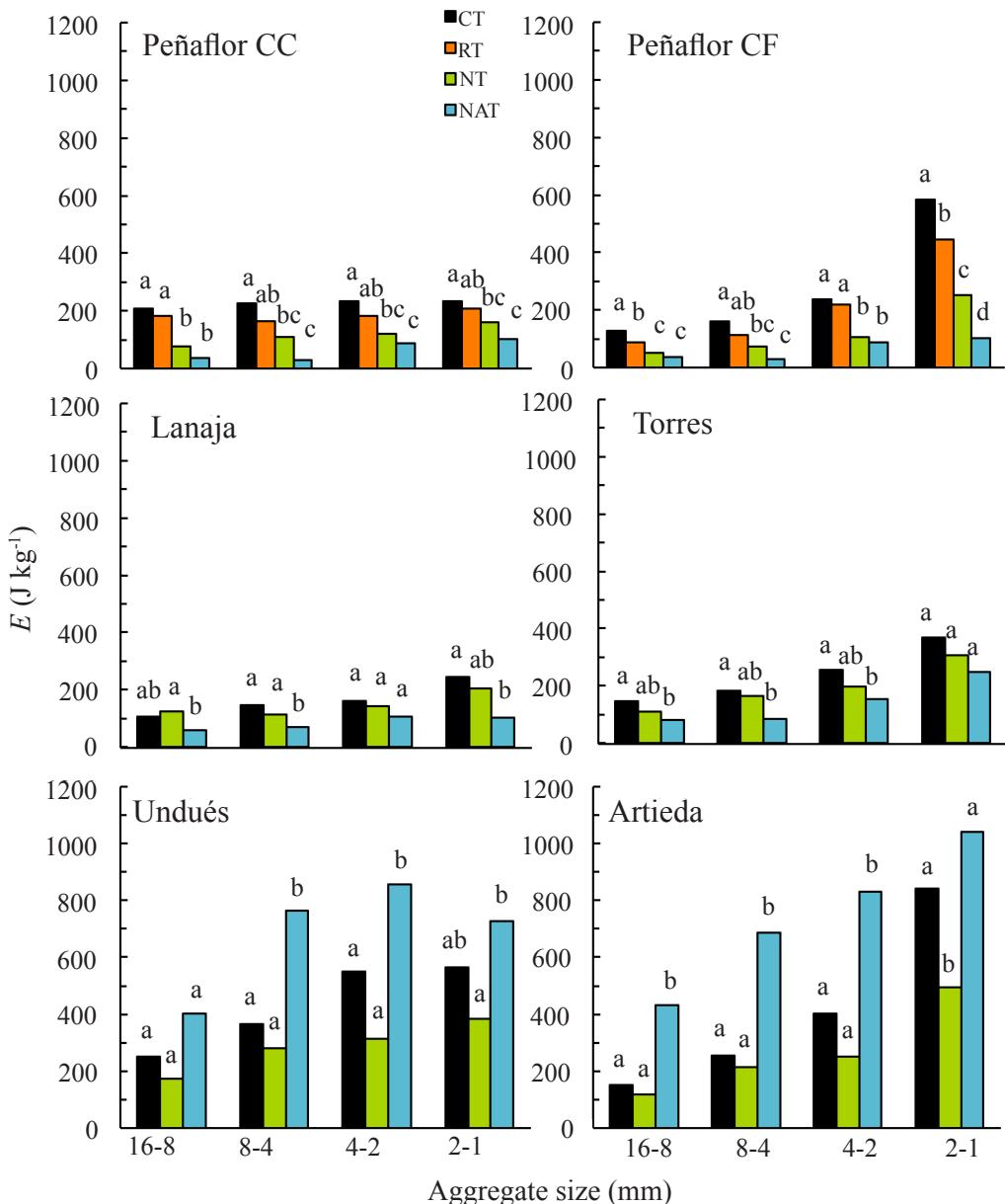


Fig. 5.2. Specific rupture energy (E) of soil aggregates of different size classes as affected by soil management and tillage (CT, conventional tillage; RT, reduced tillage; NT, no tillage; NAT, natural soil). In Peñaflor, CC refers to the continuous cropping system and CF to the cereal-fallow rotation. For the same aggregate size, different letters indicate significant differences at $P<0.05$.

times lower than those under CT. As suggested in the above studies, the low TS of NT aggregates responds to a higher biological activity, promoted by the minimum soil alteration which results in more bioporosity (faunal and root channels) and, therefore, higher susceptibility to fracture than in aggregates from tilled soils. In CT systems, tillage operations increase the aggregate TS by disrupting surface connected pores and causing rapid post-tillage consolidation (Watts and Dexter, 1998; Munkholm and Schjønning, 2004). Increment of mechanically dispersible clay and depletion of soil OC with tillage seem to be two processes involved in the formation of strong soil aggregates under CT systems. Following Dexter and Watts (2000) and Kay and Munkholm (2004), the clay dispersed by tillage in wet conditions is deposited in microcracks and pores as soil dries, thus increasing its strength. It is expected that the reduction of soil OC will promote this effect although, as it will be discussed below, the relationship between TS and OC seems to be more complex (Imhoff et al., 2002; Munkholm and Kay, 2002).

The TS and E results from the comparison of NT vs. CT systems could have important agronomic implications. Thus, under the conditions of semiarid Aragon, this study shows that NT practices lead to better soil physical conditions by reducing aggregate strength at the soil surface. This means, for example, that this alternative system could provide a more favorable environment for seedling emergence and root growth than the traditional practices in the area. In the NAT soils, it would be expected that TS and E values would be lower than those registered under NT and, especially under CT, due to the lack of soil disturbance and the highest contents of soil OC (Table 5.1). However, in the present study, TS in the NAT soils showed a high variability with values ranging from 22 to 677 kPa (31-1040 J kg⁻¹ for E) and, contrary to the expected, the stronger aggregates came from the soils with the highest OC contents, i.e. the soils of the Artieda and Undués sites (Figs. 5.1 and 5.2; Table 5.1). In Undués, the mean TS in the NAT soil was 1.4 times higher than that in CT (1.6 for E) while in Artieda it was similar in both soils (E was 2.2 times higher in NAT). The general trend observed in the rest of the sites on the increase in TS and E with the degree of soil disturbance, was not followed in these two cases. A possible explanation for this behavior could be related to the high biological activity observed

in these two NAT soils. In fact, Artieda and Undués are the two study sites with the highest precipitation (≈ 700 mm of mean annual rainfall) and, therefore, where an abundant and diverse plant community has developed an extensive root system with numerous fine roots and root hairs growing within soil aggregates. Under these conditions, aggregate TS would increase since the radial pressure exerted by the growing roots compresses the soil around the root (Dexter, 1987), resulting in a decrease of the porosity in that zone (Bruand et al., 1996) and in an increase of the intra-aggregate bonds by root exudates (Czarnes et al., 2000). Pore disruption and blocking by dispersed clay particles is also a possible mechanism of increasing aggregate strength in these more humid environments. In any case, these results show that the increase of soil OC does not always lead to a reduction in aggregate TS and support previous studies indicating that the effect of soil OC on TS is variable and the need for further local research (Kay and Munkholm, 2004; Blanco-Canqui et al., 2005b; Park and Smucker, 2005).

5.4.2. Aggregate tensile strength and organic carbon

With the goal to advance, as far as possible, in the understanding of the complexity of the relationships between structure and organic matter, the OC content for the different aggregate size classes was determined (Table 5.2).

Aggregate-associated OC ranged from 9.3 (CT at Peñaflor CF) to 39 g kg⁻¹ (NAT at Undués). No effect of aggregate size on OC was observed in any of the study sites; however, within each aggregate size class, differences among soil management and tillage treatments were significant in all sites (Table 5.2). Aggregates from the NAT soils have significant higher OC than those from the cultivated soils in the Torres, Undués and Artieda sites (1.5-2.6 times higher) and only than those from the CT and RT in Peñaflor and Lanaja (1.6-2.2 times higher). With the exception of the Artieda site, soil aggregates under NT were between 20 (Undués) and 50% (Lanaja) richer in OC than those under CT and RT. In Artieda, the management of crop residues in the NT field explains the lack of differences between cultivated soils. As previously indicated, in the areas with higher rainfall and hence higher production, as it is the case of Artieda, farmers remove the straw from the field to prevent later

Table 5.2.

Organic carbon content (g kg^{-1}) of soil aggregates of different size classes as affected by land use and tillage (CT, conventional tillage; RT, reduced tillage; NT, no tillage; NAT, natural soil). In Peñaflor, CC refers to the continuous cropping system and CF to the cereal-fallow rotation.

Site	Treatment	Aggregate size class (mm)			
		16-8	8-4	4-2	2-1
Peñaflor	CT	11.7	11.4	11.9	12.0
	CC	11.4	11.3	11.7	12.1
	NT	14.1	14.8	15.4	15.8
	NAT	19.6	22.3	21.5	21.5
	LSD ^a	6.8	2.1	2.0	1.9
	CF	9.7	9.6	9.4	9.5
Peñaflor	RT	10.4	10.5	9.4	9.7
	NT	14.5	14.6	13.7	14.0
	NAT	19.6	22.3	21.5	21.5
	LSD	2.7	1.4	2.1	1.6
	CF	10.1	10.1	10.7	11.0
Lanaja	CT	15.2	15.3	16.4	17.6
	NT	16.7	16.1	16.6	18.3
	NAT	2.6	3.4	4.1	4.1
	LSD	10.5	10.3	9.8	10.1
Torres de Alcanadre	CT	15.4	15.0	12.2	13.7
	NT	21.7	19.3	13.9	16.7
	NAT	4.2	2.4	2.2	2.3
	LSD	17.9	16.8	16.6	16.8
Undués de Lerda	CT	21.6	20.8	20.6	21.1
	NT	39.0	37.4	37.4	38.6
	NAT	2.4	1.8	1.6	4.0
	LSD	12.5	11.1	10.0	11.3
Artieda	CT	12.8	10.1	10.6	12.1
	NT	29.3	28.6	28.4	28.9
	NAT	4.2	5.8	6.2	5.3
	LSD	12.8	10.1	10.6	12.1

^aLSD, least significant difference ($P<0.05$).

problems with seeding. In some cases, soil cover by residues retained in the field was low (<30%) and, strictly speaking, this would not be a conservation tillage system. However, it was considered in the present study because it is a common practice in some areas of Aragon. The NAT soil of Lanaja is also notable for the relatively low OC content, similar to that of the NT soil. As detailed in Table 3.1 (in Chapter 3), this soil is located in an abandoned agricultural terrace (>40 years) that is frequently grazed by livestock.

Figure 5.3 shows the TS and *E* variation as a function of aggregate-associated OC considering together all sites and treatments. A simple regression analysis showed that OC significantly affected TS in a quadratic manner ($P<0.001$) with a minimum value at about 19-20 g kg⁻¹ of OC. For lower OC values, an increase in OC caused a decrease in TS and, in contrast, for OC contents higher than \approx 20 g kg⁻¹, the increase in OC resulted in an increase in TS. This finding seems to support previous and contrasting results on the relationship between TS and OC. Thus, positive relationships were found by Rahimi et al. (2000) for loam and clay loam soils and soil OC contents >20 g kg⁻¹, and by Blanco-Canqui and Lal (2007b) for a silt loam soil and a range of aggregate OC of about 15-100 g kg⁻¹. Working with three different soils (silt loam-clay loam), Blanco-Canqui et al. (2006) also reported positive correlations between both soil parameters for OC concentrations >20 g kg⁻¹. In contrast, negative relationships have been described by Abid and Lal (2009) in a silt loam soil with OC contents of 15-22 g kg⁻¹ or by Blanco-Canqui et al. (2005a) with silt loam soils and aggregate OC ranging from about 10 to 70 g kg⁻¹. No or little effect of soil OC on TS was also reported in other studies (Watts and Dexter, 1997; Blanco-Canqui et al., 2005b). These contrasting results indicate that other soil properties may be influencing TS, such as soil texture (Imhoff et al., 2002), organic matter type (Ekwue, 1990) or soil porosity (Zhang, 1994).

From all soil variables considered in the present study, besides OC, clay content was significantly and positively correlated with the strength properties ($r=0.630$ for TS and $r=0.552$ for *E*; $P<0.001$). Furthermore, positive interactions between OC and clay content were found, affecting TS and *E* as follows:

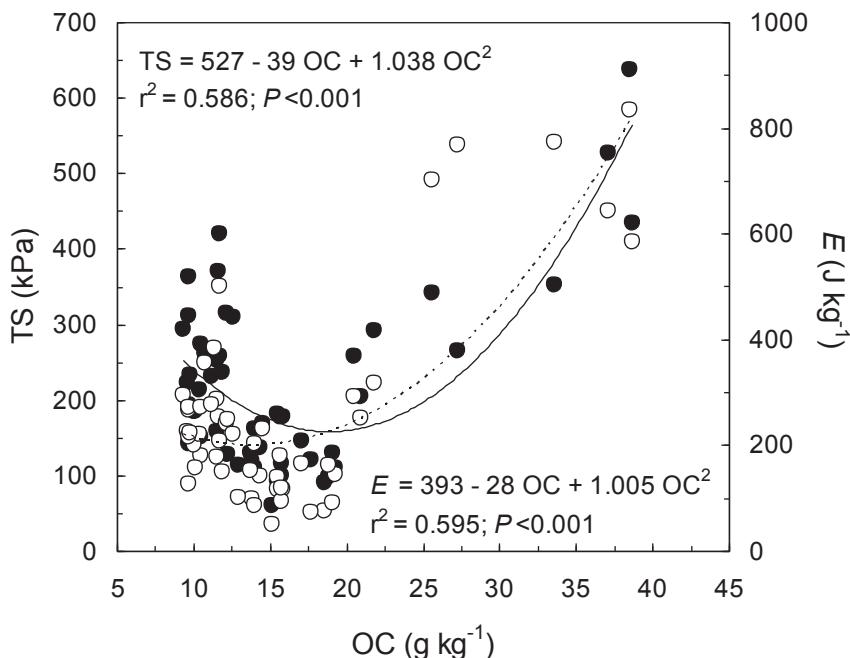


Fig. 5.3. Variation in aggregate tensile strength (TS, —●—) and specific rupture energy (E , - -○- -) with aggregate organic carbon (OC) from soils under different tillage and management systems (cultivated soils under conventional and conservation tillage and natural soils).

$$TS = 1749 - 864 \log OC - 369 \log \text{clay} + 0.094 (\text{OC} \times \text{clay}) \quad r^2=0.668; P<0.001$$

$$E = 2001 - 821 \log OC - 533 \log \text{clay} + 0.123 (\text{OC} \times \text{clay}) \quad r^2=0.660; P<0.001$$

This interaction may explain the quadratic variation of the strength properties with the OC and, more precisely, the unexpected high values of TS and E registered in the NAT soils of the Undués and Artieda sites where the highest OC is accompanied by relatively high clay content ($\approx 300 \text{ g kg}^{-1}$). Interactions between the soil mineral and organic fractions have been found in previous studies. Thus, Imhoff et al. (2002) indicated that, while at high clay+silt content an increase in OC resulted in an increase in TS, at low clay+silt content the increase in OC caused a decrease in TS. Park and Smucker (2005) and Blanco-Canqui et al. (2006) also showed that OC contributed to strengthening aggregates in more clayey soils but it reduced aggregate

strength in coarser textured soils. According to these studies, strong bonding of organic substances with clay particles upon soil drying is a major mechanism for increasing aggregate TS in clay and silt loams. Likewise, the increase in OC causes a higher porosity in coarser textured soils than in fine soils, thus contributing to the loss of soil strength.

Stepwise multiple regression analyses were carried out to obtain predictive equations for TS and E . With the objective to provide simple equations and, taking into account the quadratic relation between aggregate OC and strength properties, we decided to establish different equations for OC higher and lower than a fixed threshold value of 20 g kg^{-1} . The most predictive equations are shown in Table 5.3 and Fig. 5.4 and explained between 68 and 84% of the total variation in TS and E as a function of aggregate size and aggregate OC. Note that, for OC contents $<20 \text{ g kg}^{-1}$, the regression was better described by a curvilinear function ($\log \text{TS}$ or $\log E$) while for higher contents, the linear regression is more significant. This can be also deduced from the Fig. 5.3, where a more pronounced curvilinear form can be observed for $\text{OC} < 20 \text{ g kg}^{-1}$ than for that $> 20 \text{ g kg}^{-1}$. In any case, these significant relationships were considered satisfactory considering the heterogeneity of soil, climate and management conditions.

5.4.3. Relationship between aggregate tensile strength and specific rupture energy

Perfect and Kay (1994) recommended the use of E over TS for the characterization of dry aggregate strength in tillage studies. These authors explained that tension is not the only form of loading and that soil compression and shear also occur during tillage (Vomocil and Chancellor, 1969). Unlike TS, E is an integral parameter and, therefore, no assumptions are necessary regarding the exact mode of loading by which the soil fails.

In the present study, a high correlation between E and TS (Fig. 5.5) was expected given the same data trend, similar response to soil management and tillage, and very similar prediction equations. Thus, the more resistant an aggregate is to breaking, more energy is required to pulverize it. There are relatively few tillage studies determining E and even less comparing E and TS. Munkholm and Kay (2002), in two

Table 5.3.

The optimum regression equations to estimate soil aggregate tensile strength (TS, kPa) and specific rupture energy (E , J kg $^{-1}$) as a function of aggregate organic carbon (OC, g kg $^{-1}$) and aggregate diameter (d , mm).

Strength property	OC (g kg $^{-1}$)	Equation	r^2	P	n
TS	<20	$\log TS = 4.01 - 0.511 \log d - 1.34 \log OC$	0.702	<0.0001	54
	>20	$TS = -61 - 330 \log d + 21 OC$	0.836	<0.0001	17
E	<20	$\log E = 2.62 + 0.638/d - 0.048 OC$	0.675	<0.0001	54
	>20	$E = 1524 - 22 d - 25261/OC$	0.749	<0.0001	16

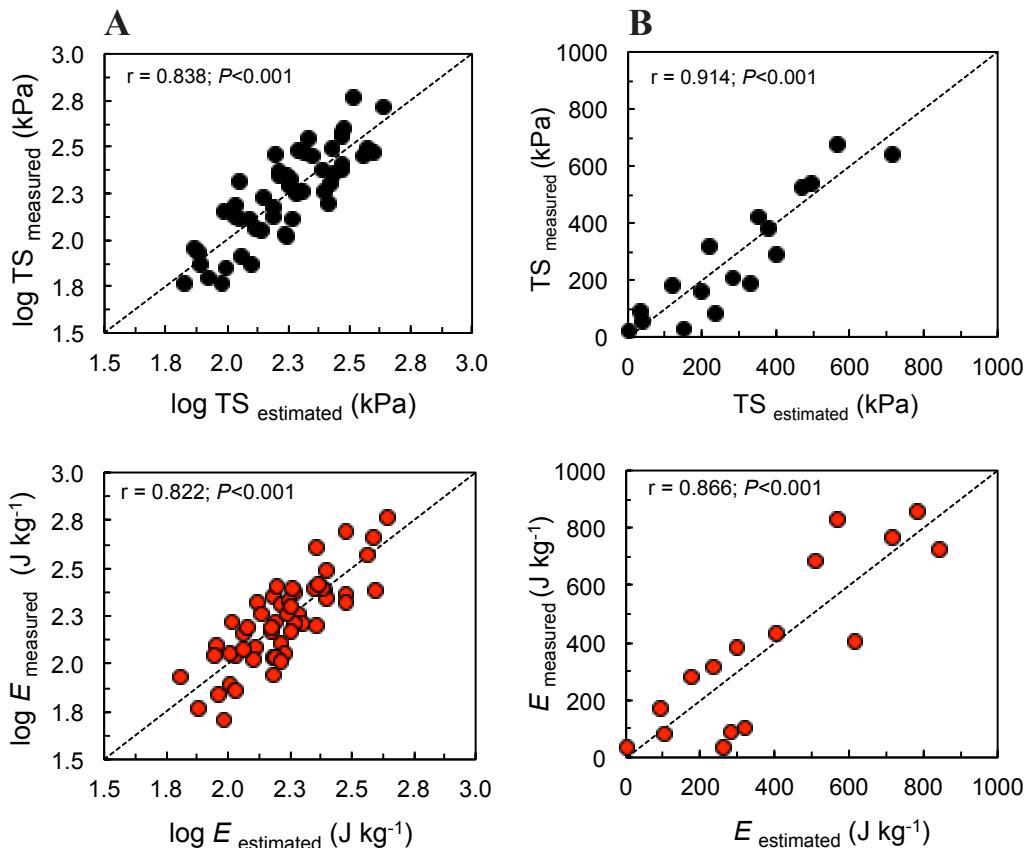


Fig. 5.4. Relationships between measured and predicted soil strength properties (TS, tensile strength and E , specific rupture energy) using Eqs. of Table 5.3 for organic carbon (OC) contents lower (A) and higher than 20 g kg $^{-1}$ (B).

different experiments carried out on the same soil type, found similar trend between E and TS in one of the experiments and clear differences in the other one. In the later case, the authors attributed the lack of correlation between the two strength variables to a complex soil pore structure which results in fracture at more points within the soil mass. This is due to the fact that E not only depends on the force needed to break the weakest intra-aggregate bond but also on the nature of the total bonds within the aggregate. In this sense, a further analysis of E could provide fruitful information about the distribution and strength of the inter- and intra-aggregate bonds and, ultimately, about the hierarchical organization of soil structure.

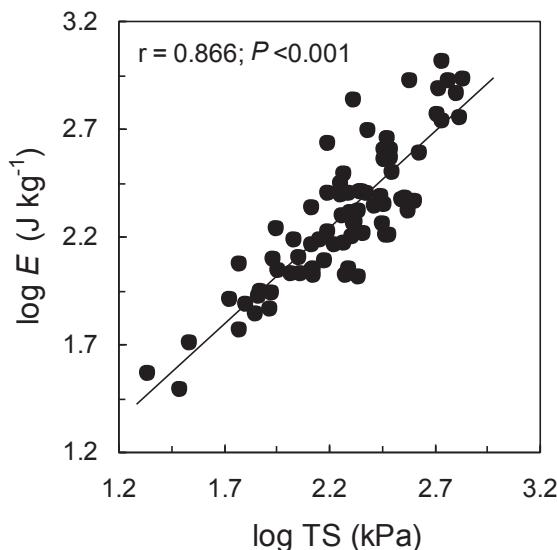


Fig. 5.5. Relationship between aggregate tensile strength (TS) and specific rupture energy (E) from soils under different tillage and management systems (cultivated soils under conventional and conservation tillage and natural soils).

5.5. Conclusions

Results from this study indicate that soil management and tillage exert a great influence on soil strength properties in rainfed cereal areas of Aragon. Long-term NT reduced aggregate TS and *E* with respect to CT systems through lower soil disturbance and higher OC content at the soil surface (0-5 cm depth). Aggregate size and aggregate-associated OC explained 70-80% of the variation in TS and *E*. The relation with OC was complex since, for soils with OC lower than about 20 g kg⁻¹, TS and *E* were reduced with the increase in OC. In contrast, for OC higher than 20 g kg⁻¹, the strength properties increased with increasing in OC. This behavior was explained by the interaction of OC with the clay content in such a way that in the soils with the highest values of both OC and clay, the aggregate strength was considerably high. This was the case of some of the NAT soils considered in this research. Overall, results from this study suggest that aggregate TS and *E* can be used as sensitive indicators of soil structural changes associated with tillage and management systems.

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Capítulo 6

**Dynamics of aggregate destabilization
by water in soils under long-term
conservation tillage in semiarid Spain.**

Catena (2012) 99, 34–41

- Desestructuración de un agregado de suelo (16-8 mm de diámetro) al inicio de una humectación rápida.

6.1. Abstract

Due to particular soil and climate conditions and inappropriate agricultural practices, Aragon (NE Spain) is a region prone to land degradation by water erosion. For this reason, the adoption of conservation tillage systems has been encouraged as an alternative to preserve soil and water in this region. However, little information concerning soils on which these techniques are applied is available. The main objectives of this study were to assess the effect of long-term no tillage (NT) on water aggregate stability in five different cereal production areas of Aragon and identify the main mechanisms involved on aggregate breakdown. The study was conducted under on-farm conditions where In all cases, a nearby undisturbed soil under native vegetation was included. Soils were slightly to highly calcareous with medium textures ranging from sandy loam to silty clay loam. Results indicate that NT increased surface aggregate stability with respect to CT systems through lower soil disturbance and higher organic carbon (OC) content at the soil surface (0-5 cm depth). Slaking was the dominant disaggregation process of the cultivated soils, representing 40-80% of total soil disruption, and was strongly and negatively affected by aggregate-associated OC. This soil property together with the silt content (weak and positive effect) explained more than 80% of the slaking variation. Swelling and clay dispersion were less frequent processes and their occurrence seemed to be associated with high silt and CaCO_3 contents. This study shows that, under the rainfed conditions of semiarid Aragon, NT reduces the susceptibility of soil surface to crusting and water erosion as compared to CT systems.

6.2. Introduction

Characterization of near-surface soil water stability is essential to predict soil susceptibility to crusting and erosion. This acquires special relevance in agricultural soils where a stable soil structure is required for good water infiltration and aeration, optimal seedling emergence and root growth, and, finally, sustainable productivity (Carter, 2004; Bronick and Lal, 2005). Soil aggregate stability is being used as an indicator of soil quality since soil structural stability depends on the presence of stable aggregates (Amézketa, 1999; Nimmo and Perkins, 2002). However, the determination and interpretation of this parameter is often difficult due to the numerous factors affecting it as well as to the interactions among them. As it is detailed in the review of Amézketa (1999), these factors can be classified into soil internal and external factors. Internal factors include, among others, organic matter, texture, clay mineralogy, electrolyte and sesquioxides (Chenu et al., 2000; Six et al., 2000; Kaewmano et al., 2009; Reichert et al., 2009). Climate, biological activity and soil management are identified as external factors affecting water aggregate stability (Blanco-Canqui et al., 2009; Pikul et al., 2009; Peng et al., 2011). However, despite much research effort, there are still many contradictory results and further understanding of the different processes of soil destabilization in water is necessary. In addition, there are numerous different methods for measuring soil water stability which complicates the interpretation of results and the comparison among different studies (Amézketa, 1999; Díaz-Zorita et al., 2002; Nimmo and Perkins, 2002).

The wet sieving procedure proposed by Kemper and Koch (1966), and later improved by Kemper and Rosenau (1986), is the most widely used method to determine water aggregate stability (WAS). However, this method does not discriminate among the different destabilizing mechanisms of soil aggregates in water (slaking, swelling, clay dispersion and mechanical breakdown by abrasion). To overcome this limitation, Le Bissonnais (1996a) proposed a new method based on the use of pretreatments and wet sieving in ethanol. Although this method has been shown to be suitable in rainfall erosion studies (Amézketa et al., 1996; Legout et al., 2005), it is not a routine procedure in soil laboratories. This is probably because it is a laborious and time-consuming method, especially when there are many samples to

analyze. Another approach was proposed by Zanini et al. (1998) who established an exponential equation to describe the dynamic features of soil aggregate breakdown as a function of wet sieving time. In this way, the loss of aggregates caused by water abrasion is separated from that due to initial wetting phase. This has not been a widely used method in spite of it has been validated and proved its usefulness to distinguish among soils and even among horizons of the same soil (Scalenghe et al., 2004; Falsone and Bonifacio, 2006).

Due to particular soil and climate conditions, Aragon (NE Spain) is a region prone to land degradation by water erosion (Lasanta et al., 1995; García-Ruiz, 2010). In addition, inappropriate agricultural practices, such as cropping systems that leave soil surfaces bare during long periods of time (fallowing), excessive tillage and overgrazing are main driving forces for agricultural soil degradation in the region. For this reason, the adoption of conservation tillage systems has been encouraged as an alternative to preserve soil and water in this region. In fact, according to previous results on soil and crop response in cereal production areas of Aragon (López et al., 2005; Moret et al., 2007; Álvaro-Fuentes et al., 2009), conservation tillage could be regarded as a viable management alternative. Furthermore, a recent survey conducted by the Department of Agriculture and Food of the Government of Aragon (Vallés, 2009) found a very positive perception of the advantages of these tillage systems by farmers and an increasing adoption in the last years, especially of no tillage (NT). However, this report also highlights the lack of knowledge about the soils on which these systems are applied.

The little available information on WAS of cultivated soils in Aragon has demonstrated the high susceptibility of these soils to surface sealing and crusting (Martí et al., 2001; Amézketa et al., 2003; Ries and Hirt, 2008). In this regard, Álvaro-Fuentes et al. (2008) showed the suitability of NT to increase wet stability of soil aggregates in semiarid Aragon. This study was carried out in small research plots and for single soil types and, however, farming practices applied by farmers in their fields can be very diverse and differ from those in experimental plots. For these reasons, direct measurements under on-farm conditions across different soils, microclimate and agronomic practices are necessary to get a broad knowledge of

the potential of conservation tillage in the region. In order to remedy this lack of information, the objectives of this study were to (1) assess the effect of long-term NT on WAS compared with traditional tillage practices and undisturbed soils under native vegetation in different cereal production areas of Aragon, (2) identify the main destabilization processes of soil aggregates in water, and (3) establish relationships between WAS and aggregate-associated organic carbon (OC) to understand the role of soil OC on soil structural stability.

6.3. Material and methods

6.3.1. Study sites

The cultivated soils, under NT and CT, and the NAT soils described in detail in the Chapter 3 and following Chapters, were the soils in which the present study was conducted. Information on location and soil management characteristics for each site are shown in Table 3.1 (Chapter 3). It should be noted, briefly, the case of Artieda where, as a common practice in this area, farmer removes the straw from the NT and CT fields to prevent later problems with seeding.

The studied soils were medium-textured soils, varying from sandy loam to silty clay loam, alkaline ($\text{pH} > 8$; CaCO_3 contents of 50-560 g kg^{-1}) and generally with low OC contents ($< 20 \text{ g kg}^{-1}$ for agricultural soils) (Table 3.2 in Chapter 3). Basic properties of the study soils for the first 5 cm depth are shown in Table 5.1 (Chapter 5) since it was the depth at which we have focused for the characterization of the water aggregate stability.

6.3.2. Soil sampling and analyses

In the farmer fields, soil surface sampling (0-5 cm in depth) was made in three different zones within each field (NT, CT and NAT) where three soil samples were collected and mixed to make a composite sample. In the Peñaflor site, each of the composite samples came from each of the 3 tillage plots per treatment (NT, RT and CT). Once in the laboratory, soil samples were air dried at room temperature ($\approx 20^\circ\text{C}$) and dry aggregates of 1-2 mm in diameter were obtained by dry sieving to determine WAS and OC content.

Water aggregate stability was measured following the single-sieve method of Kemper and Rosenau (1986) by using a modified Yoder apparatus (Yoder, 1936). Two approaches were used to estimate the relative importance of the different mechanisms of destabilization of soil aggregates in water. The first involved the application of the exponential model proposed by Zanini et al. (1998) to the wet sieving data at different time intervals. In this way, the breakdown of soil aggregates caused by water abrasion (time dependent) can be discriminated from that due to the fast wetting (slaking, swelling and clay dispersion). Following Falsone and Bonifacio (2006), the second approach included prewetting soil aggregates with ethanol to prevent aggregate disintegration by slaking (Le Bissonnais, 1996a).

In the first step, 10 g of 1-2 mm aggregates were placed on the top of a 0.25 mm mesh sieve and sieved in distilled water during 1, 5, 10, 20, 40 and 60 minutes (34 strokes min⁻¹; stroke length of 1.3 cm). After these times, the soil retained on the sieve was transferred to an aluminium pan, oven-dried and weighed. Sand correction was made by dispersing stable aggregates with sodium polyphosphate (5 g L⁻¹) and sieving through the 0.25 mm sieve. The percentage of unstable aggregates (100-WAS) after the different time intervals was fitted to the exponential model of Zanini et al. (1998):

$$y(t) = a + b (1 - \exp(-t/c)) \quad (1)$$

where y is the percentage of broken aggregates in a given time, t the sieving time, a estimates the losses of aggregates during fast wetting, b is the maximum estimated abrasion loss of aggregates and c is a time controlling factor equal to 1/3 of the time interval at which approximately 95% of the total loss ($a+b$) is reached. All determinations were done in duplicate, obtaining a minimum of 18 destabilization curves per site (24 in Peñaflor) (3 or 4 treatments x 3 replicates x 2 tests).

In the second step, another sample of 10 g of 1-2 mm aggregates was gently immersed in ethanol (96%) for 10 min before being sieving in water for other 10 min. Then, the amount of aggregates that had resisted the sieving were collected and dried, and its weight corrected for sand. The percentage of disintegrated aggregates

by slaking was then calculated as the difference between the aggregate loss after 10 min of sieving with and without the ethanol pretreatment.

6.3.3. Statistical analyses

The statistical analyses of data is described in the previous Chapter (Chapter 5) and in the Chapter 3. Wet sieving data obtained at the different time intervals were fitted to the proposed exponential model (Eq. (1)). Correlation and regression analyses were performed to identify and evaluate the degree of relationship among the measured properties. Computations were performed using SPSS 19.0 statistical software.

6.4. Results and discussion

6.4.1. Tillage effects on water aggregate stability

Figure 6.1 shows the dynamics of soil aggregate breakdown during wet sieving as function of soil management and tillage for each of the study sites. In all sites, significant differences between cultivated and NAT soils were evident during all the sieving time. With the exception of the Lanaja site, NAT soils were highly resistant to water action since the loss of aggregates after 60 min of sieving never exceeded 50% (Fig. 6.1 and Table 6.1).

The high percentage of loss in the NAT soil of Lanaja (nearly 80%) can be explained because this soil is located in an abandoned agricultural terrace (>40 years) that is frequently grazed by livestock (see Table 3.1). In contrast, the cultivated soils showed low structural stability with losses of soil aggregates of 30-90% already after the first min of wet sieving. A general trend of decreasing soil resistance from the most humid sites ($\approx 700 \text{ mm yr}^{-1}$ in Undués de Lerda and Artieda; see Table 3.1) to the drier ones ($300-500 \text{ mm yr}^{-1}$ in Peñaflor, Lanaja and Torres) can be observed. This high susceptibility of the cultivated soils to disruption by water is common in arid and semiarid regions due to their limited biomass production, poor soil cover and, generally, low soil OC content. Zanini et al. (1998) found mean percentages of aggregate breakdown of 80% in a wide range of Italian agricultural topsoils against 18-60% in natural soils. In SE Spain, Caravaca et al. (2004) obtained disruption

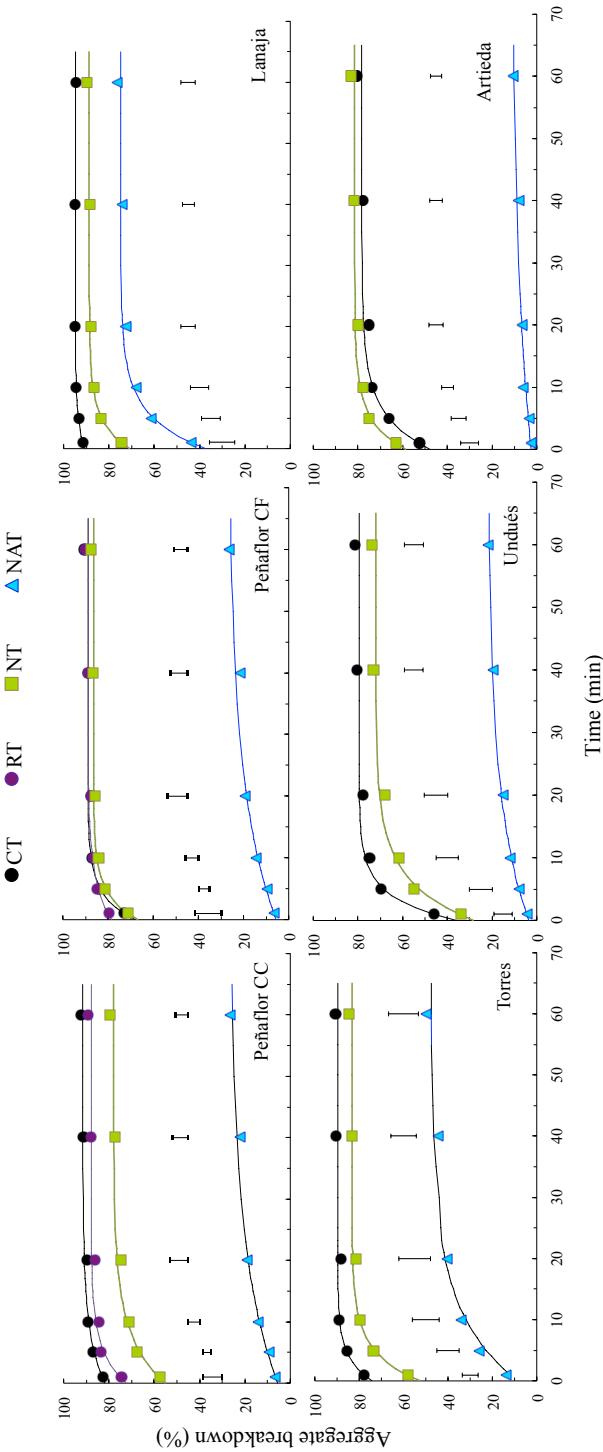


Fig. 6.1. Dynamics of soil aggregate breakdown (1-2 mm in diameter) during wet sieving according to soil management and tillage (CT, conventional tillage; RT, reduced tillage; NT, no tillage; NAT, natural soil). In Peñafiel, CC refers to the continuous cropping system and CF to the cereal-fallow rotation. The curves were obtained by fitting the experimental data to the Eq. (1). Bars indicate LSD ($P<0.05$) for comparisons at the same sieving time, where significant differences were found.

Table 6.1.

Disaggregation kinetic parameters and loss of soil aggregates (2-1 mm in diameter) due to different mechanisms of soil destabilization by water as affected by soil management and tillage (CT, conventional tillage; RT, reduced tillage; NT, no-tillage; NAT, natural soil). In Peñaflor, CC refers to the continuous cropping system and CF to the cereal-fallow rotation.

Site	Treatment	Kinetic parameters [†]				Aggregate loss			
		<i>a</i>	<i>b</i>	<i>c</i>	<i>r</i> ²	In 5 min		Slaking	%
						%	min		
Peñaflor CC	CT	81.6	9.9	7.5	0.977	86.9	92.1	70.9	10.7
	RT	72.2	15.7	5.1	0.940	83.6	89.2	64.2	8.0
	NT	55.2	22.7	7.5	0.974	67.9	79.6	55.0	0.2
	NAT	5.5	21.1	20.6	0.983	9.5	26.4	4.9	0.6
	LSD	11.9	10.0	12.3		3.3	5.6	5.2	ns
Peñaflor CF	CT	68.0	20.9	3.8	0.977	83.7	90.6	68.0	0.0
	RT	78.4	10.5	6.2	0.958	84.7	90.0	74.3	4.1
	NT	66.8	19.6	4.0	0.987	81.5	87.2	66.5	0.3
	NAT	5.5	21.1	20.6	0.983	9.5	26.4	4.9	0.6
	LSD	16.5	ns	11.7		4.8	5.8	4.3	ns
Lanaja	CT	90.7	4.1	4.3	0.949	93.4	94.2	31.5	59.2
	NT	71.0	17.7	4.3	0.990	83.4	89.7	52.1	18.8
	NAT	37.5	37.3	5.3	0.990	61.4	76.7	37.0	0.5
	LSD	11.7	6.5	ns		8.2	6.2	7.9	6.0
Torres de Alcanadre	CT	74.2	15.6	3.6	0.968	85.9	90.6	61.6	12.6
	NT	52.4	30.9	4.5	0.991	73.4	84.7	52.3	0.1
	NAT	11.8	36.0	11.1	0.981	26.2	50.2	11.8	0.0
	LSD	6.7	8.2	4.2		10.1	13.4	10.0	9.5
Undués de Lerda	CT	36.1	43.5	3.7	0.987	69.6	81.2	36.0	0.1
	NT	28.4	43.7	6.3	0.983	55.0	73.6	28.4	0.0
	NAT	3.6	18.4	18.3	0.994	8.0	21.6	3.5	0.1
	LSD	6.0	4.2	11.6		10.6	8.6	5.3	ns
Artieda	CT	47.8	30.5	5.5	0.978	66.3	80.5	47.5	0.3
	NT	58.7	22.8	4.5	0.973	75.2	83.0	58.4	0.3
	NAT	2.5	8.9	31.5	0.948	3.5	10.6	2.0	0.5
	LSD	9.3	6.9	25.2		6.7	5.0	6.3	ns

[†] *a*, percentage of initial failure of soil aggregates by fast wetting; *b*, percentage of aggregate loss by mechanical abrasion; *c*, time controlling factor equal to 1/3 of the time interval at which 95% of the total loss is reached; *r*², coefficient of determination for the adjustment of experimental data to the Eq. (1). LSD, least significant difference (*P*<0.05).

percentages of about 60% which represented approximately twice that in the natural soils of the area. Percentages greater than 80-90% have been registered in cultivated soils of other semiarid regions of Spain (Hernanz et al., 2002; Fernández-Ugalde et al., 2009; Martin et al., 2011), indicating the negative effect of cultivation on soil structural stability in these environments.

With respect to tillage system, soil aggregates from the NT fields were, in general, more resistant to water action than those from CT and RT though not always in a significant way (Fig. 6.1). This indicated a site specific response to soil management. Likewise, an exception was found in the Artieda site where aggregate losses were slightly lower under CT, especially during the first minutes of wet sieving (12% lower in 5 min; Table 6.1). As previously indicated, in the areas with higher rainfall and hence higher production, as it is the case of Artieda, farmers remove the straw from the field to prevent later problems with seeding. In some cases, soil cover by residues retained in the field was low (<30%) and, strictly speaking, this would not be a conservation tillage system. However, it was considered in the present study because it is a common practice in some areas of Aragon. This decrease in WAS with crop residue removal can be, probably, due to a concomitant reduction in stover-derived organic binding agents required for the formation of stable aggregates. At the rest of the sites, aggregates from NT soils were between 1.1 and 2.5 times more stable compared to those from CT and RT (calculated from the 5 min values; Table 6.1). These figures are within the range of increments registered for different regions of the world, including Spain, (1.1-3.7 times greater with NT than with CT) (Mrabet et al., 2001; Hernández-Hernández and López-Hernández, 2002; Hernanz et al., 2002; Abil and Lal, 2008; Álvaro-Fuentes et al., 2008; Fernández-Ugalde et al., 2009; Pikul et al., 2009; Martin et al., 2011). As explained in these studies, with NT the suppression of tillage and the OC enrichment in soil surface leads to an enhanced biological activity and more stabilizing organic compounds, thus contributing to soil stability with respect to CT systems.

Water aggregate stability can be also affected by cropping system (Hernanz et al., 2002; Álvaro-Fuentes et al., 2008). In the present study, at the Peñaflor site the differences among tillage treatments were lower under the cereal-fallow rotation

(CF) than under the continuous cereal cropping (CC) (Fig. 6.1). This was due to both an increase in WAS in CT and a reduction in NT under CF as compared with CC. In the case of the CT treatment, the soil is less frequently disturbed by tillage under CF (tillage every two years vs. all years in CC) which leads to a reduction in the aggregate breakdown and, therefore, in the formation of weak aggregates. In contrast, in the NT treatment a better soil condition was observed under CC probably due to the annual input of crop residues to the soil surface in CC and only every two years in CF. As shown below, in NT the higher OC of both bulk soil and 1-2 mm aggregates under CC than under CF seems to reinforce this idea (Table 5.1 in Chapter 5; Figure 6.2). Likewise, these results are supported by previous studies (Saber and Mrabet, 2002; Shaver et al., 2002; Álvaro-Fuentes et al., 2008) that conclude that, in NT soils, the suppression of long fallowing can significantly increase surface OC and WAS.

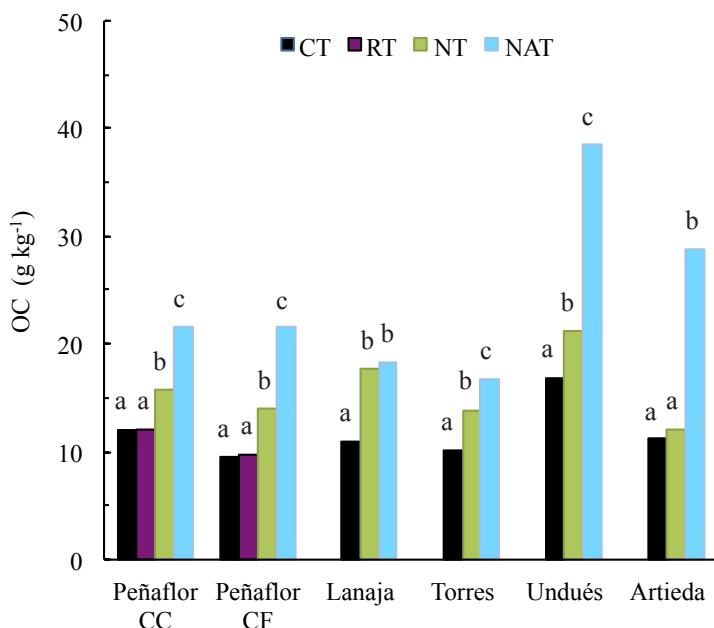


Fig. 6.2. Organic carbon (OC) content of soil aggregates 2-1 mm in diameter as affected by land use and tillage (CT, conventional tillage; RT, reduced tillage; NT, no tillage; NAT, natural soil). In Peñaflor, CC refers to the continuous cropping system and CF to the cereal-fallow rotation. For the same study site, different letters indicate significant differences at $P<0.05$.

6.4.2. Mechanisms of aggregate destabilization by water

With the purpose of identifying the main mechanisms of aggregate destabilization by water, the exponential model proposed by Zanini et al. (1998) (see Eq. (1)) was fitted to the experimental data. The adjustment was considered satisfactory with r^2 values of 0.940-0.994 (Table 6.1 and Fig. 6.1). Data on Table 6.1 show that abrasion by agitation in water was the main process of aggregate disruption in the NAT soils ($b=9\text{-}37\%$ aggregate losses). In contrast, in the cultivated soils, with the exception of Undués de Lerda (hereafter, Undués), initial fast wetting was the primary disruptive mechanism ($a=48\text{-}91\%$ losses). In Undués, 44% of aggregates from the CT and NT soils were broken by mechanical abrasion (b) and around of 30-40% during initial wetting (a). As discussed below, the greater resistance of the cultivated soils at this site can be related to the comparatively high OC contents in both bulk soil and 2-1 mm aggregates (Table 5.1 and Figure 6.2).

Among the mechanisms responsible for the destabilization of soil aggregates during the initial wetting, slaking was the dominant or sole process, representing between 70 and 100% of the initial breakdown (Table 6.1). The unique exception was found at the Lanaja site in CT with a 30% of slaking. Slaking is caused by the compression of air entrapped inside dry aggregates during rapid wetting and it is associated with the disruption process occurring during heavy rainfall on dry soils (Le Bissonnais, 1996a; Amézketa, 1999). Intense rain after long dry periods is common in the study area (Beguería et al., 2009) and, therefore, it is expected that considerable particle detachment occurs on weak structured soils when rain starts to fall. Slaking was also affected by soil management and tillage (Table 6.1). The soils most resistant were the NAT soils with low percentages of slaking (<12%). This percentage reached nearly 40% at Lanaja due to the semi-natural conditions of this field. Regarding the cultivated soils, slaking was significantly reduced with NT as compared to CT and RT (10-20% less) in 4 of the 6 study sites. The same exceptions observed for aggregate breakdowns after 5 and 60 min repeated here. Thus, in the case of Artieda, the opposite behaviour can be explained again by the negative impact of crop residue removal from the NT field. At Lanaja, the also greater slaking in NT than in CT was offset by the lower aggregate loss by swelling

and clay dispersion (Table 6.1). With the exception of this site, soil disintegration by swelling and clay dispersion was low or null and, when it occurred, only affected the CT soils. Probably, in these highly disturbed soils, dispersion of cementing material can be facilitated by slaking (Le Bissonnais, 1996a; Zaher and Caron, 2008).

6.4.3. Water aggregate stability and organic carbon

With the goal to advance, as far as possible, in the understanding of the effect of soil organic matter on soil structural stability, relationships between aggregate-associated OC and different aggregate breakdown processes were established. With the exception of Lanaja, aggregates from the NAT soils had the highest OC contents (1.2-2.6 times higher than cultivated soils) (Fig. 6.2). Regarding the cultivated soils, NT enhanced aggregate-associated OC with concentrations between 30 and 60% higher than those from CT and RT. The exception was again Artieda where OC content was nearly the same under NT and CT.

Significant negative relationships ($r^2=0.739-0.762$; $P<0.001$) were obtained between aggregate-associated OC and the percentage of aggregate breakdown produced by slaking, during initial fast wetting (a) and after 60 min of wet sieving (T_{60}) (Fig. 6.3). These results are consistent with numerous studies showing the role of soil organic matter in the formation and stabilization of soil aggregates (Chenu et al., 2000; Bronick and Lal, 2005). In our study, the similar response of the three above processes of aggregate disruption to the change in OC (Fig. 6.3) seems to further support the finding that slaking is the dominant process of soil disaggregation by water in the study area. This observation implies that the beneficial effect of soil organic matter in stabilizing aggregates against slaking is crucial to control soil crusting and erosion in the region. The literature shows that soil organic matter provides this protection through two main characteristics. First, organic matter increases intra-aggregate cohesion through binding mineral particles by organic substances or through physical entanglement of soil particles by fine roots, fungi, bacteria and other microorganisms (Wuddivira et al., 2008; Chenu and Cosentino, 2011). Second, organic matter increases aggregate hydrophobicity slowing down the rate of water penetration in the aggregate porosity and stabilizing soil pores (Chenu

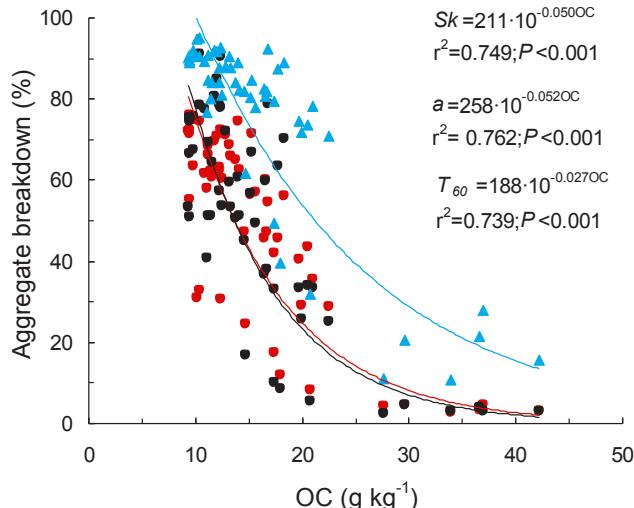


Fig. 6.3. Relationships between the loss of soil aggregates (1-2 mm in diameter) by different mechanisms of soil destabilization in water (*a*, fast wetting, —●—; *Sk*, slaking, —●—; *T₆₀*, wet sieving during 60 min, —▲—) and the aggregate-associated organic carbon (OC, g kg⁻¹). Data come from soils under different tillage and management systems (cultivated soils under conventional and conservation tillage and natural soils).

et al., 2000; Pikul et al., 2009). These protection mechanisms could explain the very low slaking found in the NAT soils, especially at Artieda and Undués, where, besides high soil biological activity, entangled meshes of soil aggregates, fine roots and organic debris were easily observed in the field. Although to a lesser extent, this same effect of soil OC is also applicable to the NT soils. In these soils, the lack of tillage can also result in the formation and maintenance of a network of interconnected pores within soil aggregates that serves as direct conduits to the surface for air flow. In this way, slaking in the NT soils is reduced with respect to the tilled soils when aggregates are fast wetted (Pikul et al., 2009).

Figure 6.3 shows a fast increment in the aggregate loss for OC contents less than about 17-20 g kg⁻¹. Curvilinear relationships between WAS and OC have been also described for other soil types and conditions (Kemper and Koch, 1966; Le Bissonnais, 1996b). Following Le Bissonnais (1996b), these non-linear relations could be due to the interactions between soil organic matter and other soil cementing components. In our study, the OC content of 17-20 g kg⁻¹ could be considered as a critical value

for aggregate stability of the soils in Aragon. This critical value corresponds to 30-34 g kg⁻¹ in organic matter and it is within the range of threshold values found in the literature for different types of soils, 15-35 g kg⁻¹ (De Ploey and Poesen, 1985; Albrecht et al., 1992; Le Bissonnais and Arrouays, 1997; Kay and Munkholm, 2004). This indicates that for soils poor in organic matter, small increments in OC may conduct to a significant improvement in structural stability. Results from the present study show that this improvement can be achieved by replacing CT with NT systems.

Aggregate-associated OC did not affected soil destabilization by swelling and clay dispersion. The fact that these disruption processes were only significant in Lanaja (especially under CT) indicates that other soil properties should be influencing WAS. Correlation analysis among the different aggregate destabilization mechanisms and soil basic properties (texture, EC, pH, CaCO₃) showed that silt content was significantly and positively related to the percentage of disaggregation by swelling plus clay dispersion, by slaking as well as to that produced during initial fast wetting and after 60 min of wet sieving ($r=0.298-0.386$; $P<0.05$). The silt influence, although weak (explaining only 9-15% of the variation), is supported by previous observations on the instability to water of soils with high silt contents (Dimoyiannis et al., 1998; Grønsten and Børresen, 2009; Reichert et al., 2009). In Spain, Ramos et al. (2003) found an increased soil susceptibility to seal formation with silt content for cultivated soils with silt concentrations similar to ours (300-600 g kg⁻¹). Le Bissonnais (1996b) noted that the increase in soil erodibility with the amount of silt is due to the low capacity of aggregation of these particles and the facility to be transported for its small size. Other authors pointed that, in silty soils with low OC content, organic anions could not be large enough to attach the edge of mineral particles and bind them together (Emmerson, 1977; Shanmuganathan and Oades, 1983; Amézketa, 1999). According to these relations, the elevated silt content (reaching 600 g kg⁻¹) together with the low OC (11-18 g kg⁻¹) of the soils at Lanaja could explain the high soil instability at this site. Furthermore, the regression between swelling plus clay dispersion and silt content was slightly improved when CaCO₃ was included (Table 6.2).

Table 6.2.

The optimum regression equations for the estimation of loss of soil aggregates (1-2 mm in diameter) produced by fast wetting (a , %), slaking (Sk , %), swelling+dispersion ($S+D$, %) and the total produced after 60 minutes of wet sieving (T_{60} , %) as a function of aggregate organic carbon (OC, g kg⁻¹) and silt and CaCO₃ contents (g kg⁻¹).

Dependent variable	Regression equations	r^2	P	n
a	$\log a = 2.88 - 0.053 \text{ OC} - 182/\text{silt}$	0.869	<0.0001	55
Sk	$\log Sk = 2.70 - 0.051 \text{ OC} - 144/\text{silt}$	0.821	<0.0001	55
$S+D$	$S+D = -22.6 + 0.050 \text{ silt} + 0.025 \text{ CaCO}_3$	0.229	<0.001	57
T_{60}	$T_{60} = 88.4 - 2.83 \text{ OC} + 0.076 \text{ silt}$	0.878	<0.0001	55

The destabilizing role of CaCO₃ is not surprising since there are studies showing that the direction of this effect depends on other soil properties, such as organic matter content, clay mineralogy and size distribution of the carbonate particles (Le Bissonnais, 1996b; Dimoiannis et al., 1998; Bronick and Lal, 2005; Wuddivira and Camps-Roach, 2007). In contrast to slaking, dispersion produces elementary particles rather microaggregates, resulting in one of the most effective processes of soil destructure (Le Bissonnais, 1996a). For this reason, the availability of a wider range of soil types could help to accurately identify the soil properties and conditions affecting soil dispersion in the study area.

Stepwise multiple regression analyses were carried out to obtain predictive equations for the different processes of soil destabilization. The most predictive equations are shown in Table 6.2 and explained between 80 and 90% of the total variation in soil loss by slaking, by fast wetting and in total loss after 60 min of wet sieving as a function of aggregate OC and silt content. Organic C, however, was the most important predictor variable with partial correlation coefficients of 0.865-0.873 in comparison to 0.269-0.341 from the silt content. In these analyses, the CaCO₃ content was dropped out of the equations, in contrast with the estimation of swelling and clay dispersion. These relationships were considered satisfactory considering the heterogeneity of soil, climate and management conditions covered in the study.

6.5. Conclusions

Soil management and tillage exert a great influence on water aggregate stability in rainfed cereal areas of Aragon. Cultivated soils had very low structural stability with losses of soil aggregates of 30-90% already during initial fast wetting. Long-term NT increased surface aggregate stability with respect to CT systems through lower soil disturbance and higher OC content at the soil surface (0-5 cm depth). Slaking was the dominant disaggregation process of the cultivated soils, representing 40-80% of total soil disruption. In the NAT soils, the most stable soils of the study, the main cause of aggregate breakdown was abrasion by agitation in water. Swelling and clay dispersion were less frequent processes and their occurrence seemed to be associated with high silt and CaCO₃ contents. In contrast, slaking was strongly and negatively affected by aggregate-associated OC. Thus, this soil property together with the silt content (weak and positive effect) explained more than 80% of the slaking variation. Overall, results from this on-farm study indicate that NT can be recommended as a viable alternative to CT to reduce the susceptibility of soil surface to crusting and erosion in cereal production areas of Aragon.

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A close-up photograph of a white plastic tray containing twelve circular wells. Each well contains a different sample of soil or sediment, ranging in color from dark brown to light tan. Some samples appear more granular, while others are more compact or crumbly. The tray is set against a dark background.

Capítulo 7

Conclusiones generales

- Pruebas de estabilidad en agua de agregados de suelo procedentes de las localidades de Artieda y Undués de Lerda ambas en la provincia de Zaragoza. De arriba a abajo suelos naturales, bajo siembra directa y bajo laboreo tradicional.

De los resultados obtenidos en el presente trabajo de Tesis Doctoral sobre el efecto a largo plazo del no laboreo en el almacenamiento de carbono orgánico y en la estructura del suelo en distintas áreas del secano aragonés, pueden destacarse las siguientes conclusiones:

1. El estudio de localización y caracterización de campos de no laboreo (NT) muestra la gran diversidad de prácticas de manejo que el agricultor realiza en sus campos (diferente manejo de residuos de cosecha, de sistemas de cultivo y rotaciones, de aplicación de purines, etc.) y refleja la realidad de la agricultura de conservación en la región.
2. El contenido de carbono orgánico del suelo (SOC) es superior bajo NT que bajo laboreo convencional (CT) en el horizonte superficial del suelo (0-20 cm). Las mayores ganancias corresponden a los campos de NT de mayor duración (>10 años) y/o manejados con prácticas que llevan un mayor aporte de biomasa al suelo (completa retención de residuos de cosecha, intensificación del sistema de cultivo y aplicación de purines).
3. Los suelos agrícolas en el área de estudio presentan contenidos de SOC siempre inferiores a 20 g kg^{-1} en los primeros 20 cm de profundidad, en concordancia con los niveles de SOC estimados para la región en el Mapa de Carbono Orgánico del Suelo en Europa elaborado por la Comisión Europea.
4. Las diferencias entre NT y CT en el contenido de SOC en la superficie del suelo se reducen o invierten en los horizontes inferiores de tal forma que, considerando la profundidad de la capa arable (0-40 cm), el potencial del NT para almacenar C orgánico es similar o sólo ligeramente superior al del CT.
5. La marcada estratificación de SOC con la profundidad bajo NT se traduce en valores del índice de estratificación significativamente mayores que bajo CT. Aunque de este índice se deduce una mejora en la calidad del suelo

con NT, en todos los casos su valor es inferior al valor umbral de 2, lo que cuestiona la idoneidad del contenido total de SOC como indicador sensible a los cambios producidos por el manejo del suelo en el área de estudio.

6. El fraccionamiento físico de la materia orgánica del suelo muestra que en los suelos de estudio la mayor parte del SOC se encuentra en la fracción organo-mineral (Min) y, más concretamente, en la fracción Min fácilmente dispersable (d-Min) que, junto a la fracción Min ocluida dentro de microagregados estables (μ agg-Min), contribuyen con un 80% al SOC total. El resto del C se encuentra en forma de materia orgánica particulada (POM), principalmente como POM fina (fPOM).
7. El manejo del suelo afecta significativamente al cPOM-C y fPOM-C cuyas concentraciones disminuyen a medida que aumenta el grado de alteración del suelo (CT<RT<NT<NAT). Por el contrario, no se observa un efecto significativo y consistente sobre los contenidos de d-Min-C y μ agg-Min-C.
8. El contenido de arcilla del suelo influye positivamente en la acumulación de d-Min-C y de SOC total. De este resultado podría deducirse que la estabilización química es un mecanismo principal de protección del C orgánico tanto en suelos agrícolas como en naturales del área de estudio. La protección física, a través de la oclusión de la materia orgánica dentro de microagregados estables, parece ser también un proceso importante de estabilización del C orgánico en estos suelos, tal y como se deduce de las estrechas relaciones encontradas entre el μ agg-Min-C y el peso de microagregados estables en agua.
9. El POM-C y, más concretamente el fPOM-C, se comportan como indicadores sensibles de los cambios producidos en el suelo por efecto del laboreo y de cambios en el uso del suelo. El índice de estratificación de estas fracciones, siempre mayores que 2 bajo NT, refleja una mejora en la

calidad del suelo tras la práctica continuada y prolongada de este sistema de laboreo de conservación. El efecto beneficioso de acumulación de POM-C con respecto al sistema de CT aumenta en las zonas de mayor aridez del gradiente agroclimático.

10. El laboreo y manejo del suelo ejercen una gran influencia en la resistencia a la compresión (TS) y la energía de rotura (*E*) de agregados de suelo. Ambas propiedades tienen un comportamiento muy similar y, en general, sus valores aumentan a medida que lo hace el grado de alteración del suelo (NAT<NT<RT<CT).
11. En los suelos con NT, la ausencia de alteración mecánica y el mayor contenido en SOC explican la disminución de TS y *E* con respecto a los sistemas con laboreo lo que puede traducirse en unas condiciones de la superficie el suelo más favorables para la emergencia y desarrollo radicular del cultivo.
12. Los valores de TS y *E* varían de forma cuadrática con el contenido en C orgánico de los agregados de suelo con un punto de inflexión de aproximadamente 20 g kg⁻¹ por encima del cual incrementos en C conllevan aumentos considerables en TS y *E*. Esta compleja relación se explica por una interacción positiva entre el C y la arcilla que confiere una alta resistencia a los agregados en aquellos suelos donde coinciden los valores más elevados de SOC y arcilla.
13. Los agregados de menor tamaño son significativamente más resistentes a la rotura por compresión que los de mayor tamaño. Así, el diámetro medio de los agregados de suelo junto a su contenido en C orgánico explican un 70-80% de la variabilidad encontrada en los valores de TS y *E*.
14. En comparación con los suelos naturales, los suelos agrícolas del área de estudio presentan una baja estabilidad estructural en agua, produciéndose

la mayor pérdida de agregados ya en los momentos iniciales de una humectación rápida (30-90% de la pérdida total).

15. El estallido de agregados (*slaking*) es el principal proceso de desagregación de la superficie de los suelos agrícolas por efecto del agua y está negativa y significativamente afectado por el contenido en C orgánico. El hinchamiento y la dispersión de arcillas son procesos menos frecuentes y su ocurrencia parece estar asociada con altos contenidos de limo y CO_3Ca en el suelo.
16. El sistema de NT aumenta la estabilidad estructural en húmedo de la superficie del suelo con respecto al CT gracias a la falta de labores y al efecto protector que ejerce el mayor contenido en C orgánico frente al estallido del agregado.
17. Las propiedades de los agregados de suelo caracterizadas, TS y estabilidad estructural en húmedo, pueden utilizarse como indicadores sensibles de los cambios en la estructura del suelo debidos al laboreo y manejo del suelo.

Como síntesis de las conclusiones arriba enumeradas, podrían hacerse las siguientes consideraciones. Si bien el sistema de NT presenta un similar potencial de secuestro de C orgánico que el CT considerando todo el perfil del suelo (0-40 cm), los beneficios medioambientales derivados de una mayor acumulación de C en la superficie del suelo bajo NT no pueden ser cuestionados. Así, el NT puede plantearse como una alternativa de manejo de los suelos de secano en Aragón con el objetivo de mejorar la calidad estructural del suelo y disminuir su susceptibilidad a procesos de degradación. Pero el éxito de este sistema en el almacenamiento de SOC sólo es posible si viene acompañado de prácticas de manejo que optimicen el aporte de biomasa al suelo a través, por ejemplo, de un manejo adecuado de los residuos post-cosecha o la intensificación del sistema de cultivo.

