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Short communication. Potential to mitigate anthropogenic CO_2 emissions by tillage reduction in dryland soils of Spain

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Abstract

Spain is one of the countries with the highest greenhouse gas (GHG) emissions within the EU-27. Consequently, mitigation strategies need to be reported and quantified to accomplish the goals and requirements of the Kyoto Protocol. In this study, a first estimation of the carbon (C) mitigation potential of tillage reduction in Mediterranean rainfed Spain is presented. Results from eight studies carried out in Spain under rainfed agriculture to investigate the effects of no-tillage (NT) and reduced tillage (RT) compared with conventional tillage (CT) on soil organic carbon (SOC) were used. For current land surface under conservation tillage, NT and RT are sequestering 0.14 and 0.08 Tg C yr^{-1}, respectively. Those rates represent 1.1% and 0.6% of the total CO_2 emissions generated from agricultural activities in Spain during 2006. Alternatively, in a hypothetical scenario where all the arable dryland was under either NT or RT management, SOC sequestration would be 2.18 and 0.72 Tg C yr^{-1} representing 17.4% and 5.8% of the total 2006 CO_2 equivalent emissions generated from the agricultural sector in Spain. This is a significant estimate that would help to achieve GHG emissions targets for the current commitment period of the Kyoto Protocol.

Additional key words: conventional tillage; dryland Spain; greenhouse gas emissions; no-tillage; soil organic carbon sequestration.

Resumen

Comunicación corta. Potencial de mitigación de emisiones de CO_2 de origen antropogénico mediante la reducción del laboreo en suelos de secano españoles

Dentro de la Unión Europea, España es uno de los países con mayores emisiones de gases de efecto invernadero (GEI). Por tanto, es urgente establecer medidas de mitigación con el fin de alcanzar los objetivos del Protocolo de Kyoto. En este estudio se presenta una primera estimación del potencial de mitigación de carbono (C) a través de la reducción del laboreo en suelos de secano en zonas mediterráneas españolas. Se utilizaron los resultados de ocho estudios llevados a cabo en España en condiciones de secano sobre la influencia del no-laboreo (NL) y del laboreo reducido (LR) frente al laboreo convencional (LC), en el carbono orgánico del suelo (COS). Para la superficie actual bajo laboreo de conservación, NL y LR están secuestrando 0,14 y 0,08 Tg C $año^{-1}$, respectivamente. Estas tasas representan el 1,1% y el 0,6%, respectivamente, del total de CO_2 equivalente generado por la actividad agrícola en España durante 2006. Alternativamente, en un hipotético escenario en el que toda la superficie de secano disponible estuviera bajo NL o LR, el secuestro de COS sería 2,18 y 0,72 Tg C $año^{-1}$, respectivamente, lo que representa el 17,4% y el 5,8% del total de CO_2 equivalente generado por la actividad agrícola en España durante 2006. Estas estimaciones confirman la idoneidad de la reducción del laboreo para cumplir el objetivo de recortar las emisiones de GEI durante el periodo actual del Protocolo de Kyoto.

Palabras clave adicionales: emisiones de gases de efecto invernadero; laboreo convencional; no-laboreo; secano español; secuestro de carbono orgánico del suelo.

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Abbreviations used: CT (conventional tillage), GHG (greenhouse gas), NT (no-tillage), RT (reduced tillage), SOC (soil organic carbon).

With more than 433 Tg CO_2 equivalent emitted in 2006 (http://unfccc.int/national_reports/annex_i_ghg_inventories/items/2715.php), Spain is one of the countries with the highest greenhouse gas (GHG) emissions rates within the EU-27. For the current commitment period (2008-2012) of the Kyoto Protocol, Spain agreed to limit its GHG emissions to 15% above to the 1990 emission level. However, in 2006 GHG emissions were 48% above the 1990 level, a value significantly greater than the emission target. Consequently, mitigation measures with short-term effects have to be implemented in Spain in order to accomplish the emission target within the current commitment period. Soil carbon (C) sequestration by tillage reduction has been reported as a promising technique to offset anthropogenic CO_2 emissions (Paustian *et al.*, 1997a; Álvaro-Fuentes *et al.*, 2009). At the field scale, a change in tillage system can result in GHG mitigation between 10 and 20 years after the beginning of the tillage change (Six *et al.*, 2004). Regional soil organic carbon (SOC) sequestration rates across Europe were estimated between 0.1 to 0.4 Mg ha^{-1} yr^{-1} (Freibauer *et al.*, 2004; Lal, 2008). Since SOC dynamics are controlled by several site-specific factors, more precise values of mitigation potential from tillage reduction have to be estimated in each country or region.

The purpose of this study was to make an estimation of the C mitigation potential of tillage reduction in Mediterranean rainfed conditions of Spain. In 2008 the *«Anuario de Estadística Agroalimentaria»* (MARM, 2008) reported $9.6 \cdot 10^6$ ha of arable land within Mediterranean rainfed systems in Spain. In the most part of this land surface, agriculture is characterized by the use of intensive tillage (mainly mouldboard ploughing) together with cereal-fallow, cereal monoculture and cereal-legume rotations as main cropping systems. Consequently, because of the large agricultural land under conventional tillage (CT) in these rainfed agroecosystems, we hypothesized that in Spain a change from intensive tillage (*i.e.* CT with mouldboard plough) to a less intensive tillage method (*e.g.* reduced tillage, RT, or no-tillage, NT) might help to offset CO_2 from anthropogenic activities.

Results from eight studies carried out in Spain to investigate the effects of tillage management on SOC content were used. These studies showed data from fourteen long-term tillage comparison experiments located at eight different sites in Mediterranean Spain. Other experiments located in northwest and north central Spain, with a more humid climate were ruled out. In short, the studies reported data after 10 years since the beginning of the experiment and compiled information on the effects of NT and/or RT *vs.* CT. All the experiments selected used mouldboard ploughing as main tillage operation in the CT treatment and chisel or cultivator ploughing for RT. Depending on the study, CT was implemented to a depth of 20-30 cm. Therefore, in our study, SOC stocks were calculated up to a depth of 30 cm. Our SOC sequestration rates were reported similarly to West and Post (2002), by calculating the mean difference between tillage practices, using soil sample data from the last year available for each site.

Three scenarios with different proportions of surface land under NT and RT management were created. The first scenario presents CO_2 mitigation potential for the current surface under NT and RT in Spain. The second scenario represents a situation with 50% of the total rainfed agricultural land available in Mediterranean Spain under either NT or RT and the third scenario assumes that the 100% of the available arable land area is under either NT or RT. Values of the available arable land area under dryland conditions in Mediterranean Spain were obtained from the *«Anuario de Estadística Agroalimentaria»* (MARM, 2008).

Total CO_2 emissions were obtained from the UNFCCC emissions report for 2006 (http://unfccc.int/national_reports/annex_i_ghg_inventories/items/2715.php). In 2006, the Spanish GHG emissions inventory reported 360 Tg of total CO_2 emissions. Since Spain has not estimated agricultural CO_2 emissions because of the lack of reliable data (Lokupitiya and Paustian, 2006), a value of 46 Tg CO_2 equivalent was used. This value results from the N_2O and CH_4 emissions reported for Spain in agricultural soils and multiplying the emission of these two gases by its global warming potential (IPCC, 2007).

In Mediterranean rainfed Spain, fourteen long-term (> 10 years) tillage experiments with SOC data were identified (Table 1). We have not considered experiments younger than 10 years since potential for C mitigation of NT and RT practices has a strong time dependence (Six *et al.,* 2004). West and Six (2006) reported that SOC sequestration occurs during the 21 years after tillage ceased. In this study, the oldest long-term tillage experiment with SOC data found in Mediterranean Spain was 20 years old and more than half of the experiments were older than 15 year (Table 1).

The SOC difference in the 0-30 cm soil depth in the NT or RT systems compared with CT ranged from –2,815 to 8,006 kg ha^{-1}. Negative SOC differences (loss of SOC under tillage reduction) were only found under the RT system (Table 1). The lower SOC under RT

Table 1. Soil organic carbon (SOC) content difference between no-tillage (NT) or reduced tillage (RT) compared with conventional tillage (CT) in long-term experiments from Spain

Site	Annual rainfall	Duration (years)	Cropping system	Tillage[a]	ΔSOC (kg ha^{-1})	Reference
Peñaflor, Zaragoza I	390	16	Barley-Barley	NT *vs* CT	4,570[b]	Álvaro-Fuentes *et al.* (2008b)
	390	16	Barley-Barley	RT *vs* CT	1,080[b]	Álvaro-Fuentes *et al.* (2008b)
Peñaflor, Zaragoza II	390	16	Barley-Fallow	NT *vs* CT	2,450[b]	Álvaro-Fuentes *et al.* (2008b)
	390	16	Barley-Fallow	RT *vs* CT	110[b]	Álvaro-Fuentes *et al.* (2008b)
Agramunt, Lleida	430	15	Barley-Wheat	NT *vs* CT	4,410[b]	Álvaro-Fuentes *et al.* (2008b)
	430	15	Barley-Wheat	RT *vs* CT	2,730[b]	Álvaro-Fuentes *et al.* (2008b)
Alcalá de Henares, Madrid I	430	20	Wheat-Pea	NT *vs* CT	8,006[b]	Hernanz *et al.* (2009)
	430	20	Wheat-Pea	RT *vs* CT	1,017[b]	Hernanz *et al.* (2009)
Alcalá de Henares, Madrid II	430	13	Wheat-Wheat	NT *vs* CT	5,400[b]	Hernanz *et al.* (2002)
	430	13	Wheat-Wheat	RT *vs* CT	2,600[b]	Hernanz *et al.* (2002)
Córdoba I	584	20	Wheat-Wheat	NT *vs* CT	3,500[b]	López-Bellido *et al.* (2010)
Córdoba II	584	20	Wheat-Fallow	NT *vs* CT	100[b]	López-Bellido *et al.* (2010)
Córdoba III	584	20	Wheat-Faba bean	NT *vs* CT	4,300[b]	López-Bellido *et al.* (2010)
Córdoba IV	584	20	Wheat-Sunflower	NT *vs* CT	500[b]	López-Bellido *et al.* (2010)
Córdoba V	584	20	Wheat-Chickpea	NT *vs* CT	1,400[b]	López-Bellido *et al.* (2010)
Toledo	400	12	Pea-Barley	NT *vs* CT	1,766[b]	López-Fando *et al.* (2007)
	400	12	Pea-Barley	RT *vs* CT	–2,815[b]	López-Fando *et al.* (2007)
Sevilla	500	12	Wheat-Sunflower	RT *vs* CT	3,000[c]	Murillo *et al.* (2006)
Carmona, Sevilla	515	19	Wheat-Sunflower-Legume	NT *vs* CT	5,572[b]	Ordóñez Fernández *et al.* (2007)
Olite, Navarra	525	10	Barley-Barley	NT *vs* CT	4,580[b]	Virto *et al.* (2007)

[a] NT, no-tillage; RT, reduced tillage; CT, conventional tillage. [b] In the 0-30 cm soil depth. [c] In the 0-25 cm soil depth.

compared to CT could be explained by a SOC depletion of SOC in depth soil under NT and RT compared to CT. This SOC depletion in lower soil layers could be offset by high SOC contents under NT in surface soil layers but it could not be offset under RT leading to negative SOC difference under this tillage treatment (Hernanz *et al.,* 2002). The average SOC difference between CT and NT or RT was 3,581 and 1,103 kg C ha^{-1}, respectively. When this SOC difference was expressed as a SOC sequestration rate, mean values were 226 and 75 kg C ha^{-1} yr^{-1} in NT and RT, respectively (Table 2). The NT sequestration rate was lower than that calculated by West and Post (2002) from a database of global long-term experiments. These authors calculated a mean C sequestration rate of 480 kg ha^{-1} yr^{-1}, considering a large variety of cropping systems. The lower SOC sequestration rates found in dryland Spain could be explained by the water limited conditions in some parts of Spain. The long-term experiments considered in this study ranged from 390 to 584 mm of annual rainfall (Table 1). In general, this low rainfall together with a high evapotranspiration during the growing season results in a significant water deficit for crop growth, a typical constraint under Mediterranean conditions (Cantero-Martínez *et al.*, 2007). This water deficit leads to limited crop development and consequently

Table 2. Current soil organic carbon (SOC) sequestration and CO_2 offset under no-tillage (NT) and reduced tillage (RT)

Tillage	Confidence interval	SOC sequestration rate (kg ha^{-1} yr^{-1})	Current surface under NT/RT (ha)	Current SOC sequestration (Tg C yr^{-1})	Current CO_2 offset (Tg CO_2 yr^{-1})
NT	Lower 95%	146	600,000	0.09	0.32
	Mean	226	600,000	0.14	0.50
	Upper 95%	306	600,000	0.18	0.67
RT	Lower 95%	–38	1,050,000	–0.04	–0.15
	Mean	75	1,050,000	0.08	0.29
	Upper 95%	188	1,050,000	0.20	0.72

to low crop residue inputs to the soil (Álvaro-Fuentes *et al.*, 2008a).

For the estimation of the SOC sequestration rates (Table 2), confidence interval values (upper and lower 95% limits) have been reported to account for the uncertainty associated with our estimates (Smith *et al.*, 1998). In Mediterranean Spain, estimations of the current surface under NT and RT made by the Spanish Association for Conservation Agriculture (personal communication) are $0.6 \cdot 10^6$ and $1.05 \cdot 10^6$ ha, respectively. Under this arable land area, NT and RT are sequestering 0.14 and 0.08 Tg C yr^{-1}, respectively. These rates of C sequestration would offset 0.50 and 0.29 Tg CO_2 yr^{-1} in NT and RT, respectively (Table 2). Furthermore, these rates represent 0.1% of the total anthropogenic CO_2 emissions in Spain during 2006. If only emissions from the agricultural sector are considered, the current adoption of NT and RT would be offsetting 1.1% and 0.6% of the annual total agricultural emissions.

In a scenario with all the potential arable land (considering only the surface of dryland agricultural soils in Mediterranean Spain) under either NT or RT management, SOC sequestration rates would be 2.18 and 0.72 Tg C yr^{-1}, respectively (Table 3). This gain could potentially offset 2.2% and 0.7% of the total 2006 anthropogenic CO_2 emissions in Spain. Furthermore, these sequestration rates would offset 17.4% and 5.8% of the annual total emissions generated from agricultural activities in Spain (Table 3). Accounting for the upper 95% confidence interval, this potential offset under NT could be up to 23.5% (Table 3). Smith *et al.* (1998) estimated a SOC sequestration potential of 43.4 Tg C yr^{-1} for European agricultural soils with 100% conversion to NT. The C gain estimated in our study under full conversion to NT would represent the 5% of the total C gain obtained by Smith *et al.* (1998) for European agricultural soils. Also, in our study, there is a significant loss of SOC under RT within the lower bounds of the 95% confidence interval (Tables 2 and 3). Therefore, despite showing a positive mean C sequestration potential, the implementation of RT in Mediterranean Spain has the risk of losing SOC compared to CT.

Our study is based upon fourteen long-term experiments established within the $9.6 \cdot 10^6$ ha of arable land within Mediterranean rainfed systems in Spain (MARM, 2008). These long-term experiments cover a wide range of conditions (*e.g.* precipitation, cropping systems, soil types) that are typical of the Mediterranean Spanish agroecosystems. However, the results shown in our study have to be taken with caution since some uncertainties exist with the estimation procedure used. Obviously, the different conditions and management practices that affect SOC dynamics were not fully represented by the fourteen long-term experiments used in our study. More realistic approaches like the use of dynamic simulation systems linked to geographic information systems (GIS) would allow better assessments of SOC stocks at a regional or national level (Paustian *et al.*, 1997b; Fallon *et al.*, 2002). However, despite the limitations, our study has provided a feasible first estimation for the potential of tillage reduction in agricultural soils of Mediterranean Spain to mitigate GHG emissions.

Table 3. Potential soil organic carbon (SOC) sequestration and CO_2 offset under no-tillage (NT) and reduced tillage (RT)

Tillage system	Confidence interval	Mean SOC sequestration rate (kg ha^{-1} yr^{-1})	Surface under NT or RT (%)	Potential surface (ha)	Potential SOC sequestration (Tg C yr^{-1})	Potential CO_2 offset (Tg CO_2 yr^{-1})
NT	Lower 95%	146	100	9,648,200	1.41	5.17
	Mean	226	100	9,648,200	2.18	8.00
	Upper 95%	306	100	9,648,200	2.95	10.83
RT	Lower 95%	–38	100	9,648,200	–0.37	–1.34
	Mean	75	100	9,648,200	0.72	2.65
	Upper 95%	188	100	9,648,200	1.81	6.65
NT	Lower 95%	146	50	4,824,100	0.70	2.58
	Mean	226	50	4,824,100	1.09	4.00
	Upper 95%	306	50	4,824,100	1.48	5.41
RT	Lower 95%	–38	50	4,824,100	–0.18	–0.67
	Mean	75	50	4,824,100	0.36	1.33
	Upper 95%	188	50	4,824,100	0.91	3.33

As we have shown, C mitigation in Mediterranean Spanish soils can be achieved through the adoption of conservation management practices (NT and RT). This strategy has the potential for offsetting up to 23% of the agricultural CO_2 emissions. Also, it is worth pointing out that our study did not account for savings of agricultural fossil fuel-carbon in NT and RT compared with CT. In semiarid Spain, energy savings under NT and RT were estimated up to 15% and 10% compared with CT, respectively (Hernanz *et al*., 1995). Concurrently, tillage reduction has other positive side effects on soil quality and productivity that have to be also considered in rainfed soils in Spain.

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