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Management of agricultural soils for greenhouse gas mitigation: Learning from a case study in NE Spain

Sánchez B[a], Iglesias A[a], McVittie A[b], Álvaro-Fuentes J[c], Ingram J[d], Mills J[d], Lesschen JP[e], Kuikman PJ[e]

[a]Department of Agricultural Economics and Social Sciences, UPM, Madrid, Spain

[b]Sustainable Ecosystems Team, Scotland's Rural College, Edinburgh, Scotland

[c]Department of Soil and Water, EEAD-CSIC, Zaragoza, Spain

[d]Countryside & Community Research Institute , University of Gloucestershire, UK

[e]Alterra, Wageningen University and Research Centre, Wageningen, The Netherlands

Corresponding Author: Berta Sánchez

Universidad Politécnica de Madrid. CEIGRAM-E.T.S. Ingenieros Agrónomos. Campos de prácticas, c/ Senda del Rey. 28040 Madrid (Spain)

Movil: 0034637166870

Email: berta.sanchez@upm.es

Abstract

A portfolio of agricultural practices is now available that can contribute to reaching European mitigation targets. Among them, the management of agricultural soils has a large potential for reducing GHG emissions or sequestering carbon. Many of the practices are based on well tested agronomic and technical know-how, with proven benefits for farmers and the environment. A suite of practices has to be used since none of the practices can provide a unique solution. However, there are limitations in the process of policy development: (a) agricultural activities are based on biological processes and thus, these practices are location specific and climate, soils and crops determine their agronomic potential; (b) since agriculture sustains rural communities, the costs and potential for implementation have also to be regionally evaluated and (c) the aggregated regional potential of the combination of practices has to be defined in order to inform abatement targets. We believe that, when implementing mitigation practices, three questions are important: Are they cost-effective for farmers? Do they reduce GHG emissions? What policies favour their implementation? This study addressed these questions in three sequential steps. First, mapping the use of representative soil management practices in the European regions to provide a spatial context to upscale the local results. Second, using a Marginal Abatement Cost Curve (MACC) in a Mediterranean case study (NE Spain) for ranking soil management practices in terms of their cost-effectiveness. Finally, using a wedge approach of the practices as a complementary tool to link science to mitigation policy. A set of soil management practices was found to be financially attractive for Mediterranean farmers, which in turn could achieve significant abatements (e.g., 1.34 $MtCO_2e$ in the case study region). The quantitative analysis was completed by a discussion of potential farming and policy choices to shape realistic mitigation policy at European regional level.

Keywords: Cost-effectiveness; Marginal abatement costs curves; Mitigation strategies; Stabilisation wedges; Soil organic carbon management.

1. Introduction

The European Union (EU) targets for reducing GHG emissions have a clear agricultural contribution, due not only to technical feasibility, but also to potential implementation since the agricultural sector is subject to intervention (EC 2013b). Therefore, the practices that could be supported by agricultural policy represent a suitable subject for research. However, given the complex interactions of agricultural production with the environment and the sustainability of rural communities, these practices need to be evaluated from agronomic and socioeconomic perspectives.

The collective EU target for all Member States together is to reduce GHG emissions by 20% in 2020 compared to the 1990 baseline. The agriculture sector is part of the Effort Sharing Decision (ESD), which regulates the emission reduction commitments of the sectors that are not part of the Emission Trading System (ETS), i.e. transport, buildings, small industry, agriculture and waste. The ESD targets are Member State specific, e.g. Spain's commitment to reduce GHG emissions in the ESD sector by 10% in 2020 compared to the 2005 baseline (EC 2013a). In the global effort to reduce GHG emissions, the mitigation potential of agriculture can significantly help to meet these emission reduction targets (IPCC 2014). The GHG emissions reductions to achieve the EU target depend on the quantitative details of mitigation potential of the practices and the agricultural policy that influences farmers' decisions (Smith et al. 2007). Agricultural emissions from livestock and soil and nutrient management contribute to approximately half of the anthropogenic GHG emission (5.0-5.8 $GtCO_2eq/yr$) of the agriculture, forestry, and other land use sector, which in turn represents a quarter of the global GHG emissions (49 ± 4.5 $GtCO_2eq/yr$) in 2010 (IPCC 2014).

The role of agricultural management to provide Soil Organic Carbon (SOC) sequestration was recognised by the Kyoto Protocol in the United Nations Framework Convention on Climate Change (UNFCCC 2008). Smith (2012) and the IPCC (2014) indicated that SOC sequestration has a large, cost-effective mitigation potential to meet short to medium term targets for reducing the atmospheric CO_2 concentration. The optimistic global estimates are challenged in some local conditions (Lam et al. 2013; Powlson et al. 2014; Derpsch et al. 2014). However, it is clear that smart soil management leads to improved soil health, reduced soil degradation and increased soil carbon, and reduced emissions (Lal 2013). Therefore soil management changes will benefit soil carbon stocks and, in turn, optimise crop productivity (Ingram et al. 2014; Lal 2004, Freibahuer 2004; Smith 2012).

A set of practices with proven benefits to the environment and farmers has been recognised (Lal 2013; Freibahuer 2004; Smith et al. 2008; Smith 2012). These practices include, among others: a more efficient use of resources and integrated nutrient management with organic amendments and compost; reduced and no tillage; crop rotations; legumes/improved species mix; growing cover crops; residue management; and land-use change (conversion to grass/trees). However, knowledge on the implementation and cost of specific mitigation practices and technologies at the farm level is limited and fragmented (MacLeod et al. 2010, Smith et al. 2007; Bockel et al. 2012; ICF 2013). This knowledge is necessary to facilitate government's understanding of potential policy development.

Here, we focus exclusively on practices that contribute to the GHG mitigation targets of the EU and also have clear benefit to soil organic carbon (SOC) content. This choice is guided by four factors: (a) SOC enhancement practices have a proven essential role for global GHG mitigation; (b) SOC enhancement practices are an indicator of long term land productivity and sustainability; (c) improved SOC content requires less nitrogen application, and in turn less N_2O emissions, a major greenhouse gas; (d) improved SOC contributes to soil water improvement by improving the physical soil properties that lead to water retention, therefore this is also an essential adaptation measure to climate change in semi-arid regions linking mitigation and adaptation practices.

The methods used to evaluate the farming choices that contribute to reach a mitigation potential range from purely socio-cultural approaches (Morgan et al. 2015) to technical evaluations in field studies (Derpsch et al. 2014). A method that has been proven valuable to communicate science results for mitigation policy is the Marginal Abatement Cost Curve (MACC). The MACCs have been derived to inform policy development for major economic sectors (McKinsey & Company 2009), for waste reduction strategies (Beaumont and Tinch 2004; Rehl and Müller 2013) and for agricultural greenhouse practices in some countries such as United Kingdom (MacLeod et al. 2010; Moran et al. 2011a), Ireland (O'Brien et al. 2014), France (Pellerin et al. 2013) and China (Wang et al. 2014). Further to the MACC approach, Pacala and Socolow (2004) created the concept of stabilisation wedges to clarify how mitigation options could help stabilize atmospheric CO_2. This concept has been used widely as it provides a clear-cut way to link science to policy. The stabilisation wedges have been derived for the major carbon-emitting activities by means of decarbonisation of the supply of electricity and fuel, and also from biological carbon sequestration by forest and agricultural management (Pacala and Socolow 2004; Grosso and Cavigelli 2012).

We believe that, when implementing mitigation practices, three questions are important: Are they cost-effective for farmers? Do they reduce GHG emissions? What policies favour their implementation? This study addressed these questions in three sequential steps. First, mapping soil management practices adoption in the European Union to provide a spatial context to upscale the local results. Second, evaluating a Marginal Abatement Cost Curve (MACC) for ranking mitigation soil and crop practices in a Mediterranean region. Finally, using a wedge approach of the practices as a complementary tool to link science to mitigation policy.

To provide in-depth analysis at a regional level we selected a representative case study in NE Spain that exemplifies semiarid Mediterranean agricultural systems. This intensive agricultural region produces rainfed and irrigated crops (c.a. 89% and 11% respectively); the conventional management undertaken during decades - intensive soil tillage and low crop residue input - have led to soil degradation. Therefore we restrict our attention to strategies that are relevant for semiarid environments and may have linkages to climate adaptation. Here we consider only practices that produce additive effects, in order to calculate the aggregated abatement potential for the entire region as a result of the implementation of all the selected practices simultaneously.

2. Methods and data

2.1. Overall approach

Our approach to estimate cost-effective management of agricultural soils for greenhouse gas mitigation included three sequential steps. First, we illustrate the current use of crop and soil management with abatement potential in Europe. In this study we evaluated only the practices that require small management changes and that could be easily implemented by farmers without large investments or infrastructure. Second, we estimated the cost-effectiveness and the abatement potential of the selected practices by

MACC in a Mediterranean case study (NE Spain) and compared our results with other European regions and sectors outside the agriculture. Third, we built SOC abatement wedges to prioritize practices by abatement potential rather than monetary benefits. The level of spatial aggregation in this study is NUTS2 for both the European and the case study analysis, which is the common classification adopted by the EU to establish basic regions for the application of regional policies (Council regulation (EC) No 1059/2003).

2.2. The use of Soil Organic Carbon (SOC) management practices in Europe

To illustrate the use of soil management practices improving SOC flows and stocks in Europe, we developed a database for all EU-27 member states at regional (NUTS2, comparable to province) level. In this study we focused on the extent of adoption of the six soil management practices with abatement potential in Europe which are further analysed in the case study: P1 Cover crops; P2 Minimum tillage; P3 Residue management; P4 Animal manure fertilization; P5 Optimized fertilization; and P6 Crop rotations. We call these SOC management practices. The statistical data on current agricultural land use and application of these practices was derived from Eurostat databases and the MITERRA-Europe model. A further description of MITERRA-Europe can be found in Velthof et al. (2009) and Lesschen et al. (2011). The use of SOC management practices (i.e., the percentage of land under a certain agricultural practice which can be relevant for soil carbon, compared to the total area of arable land) was derived from the Survey on Agricultural Production Methods; see also Council regulation (EC) No 1166/2008, which was held together with the FSS in 2010. For the practice of optimized fertilization the data was not included in the Survey on Agricultural Production Methods, hence we used the indicator of N overfertilization as percentage of the crop N uptake which give an indication of where optimized fertilization is used. The data are based on model calculations using the MITERRA-Europe model for the year 2010, following the approach as described in Velthof et al. (2009).

2.3. Marginal abatement cost curves and cost effectiveness

This study includes cost-effectiveness analysis to combine the costs and effects (outcomes) of different soil management strategies. The effect is not assigned a monetary value and it is measured as soil organic carbon sequestration. The cost is measured with a monetary indicator of the cost of implementing the soil management strategy. Cost effectiveness analysis is widely used when it is difficult or inappropriate to monetize the effect, such as the health or environmental sectors. In this study we express the cost effectiveness as a ratio where the numerator is the change in an indicator of cost for implementing a certain agricultural management strategy and the denominator is a measure of the gain in soil organic carbon associated with that strategy.

In this study cost-effectiveness ratio can be expressed as the ratio between the changes in the costs of the new practice and old practice, to the changes in the effect of the new minus the old practice. For example, if minimum tillage is the new practice, then the indicator of changes in costs is measured as the additional change of inputs or productivity, and the effect is measured as the additional soil organic carbon sequestration.

In recent years it has become frequent to compare agro-environmental interventions in terms of their relative cost-effectiveness. There are two motivations behind the use of this approach: (a) to place the findings of the evaluation in a broader context; and (b) to inform decisions about the allocation of resources between alternative agricultural management practices. Cost effectiveness analysis for the purpose of analyzing agro-environmental policy is distinct from financial analysis in the private sector. First, the effect takes place over time and has a social benefit component that is not accounted for in this type of analysis. Second, the incremental costs of implementing the practice account for more than just financial costs and its monetization is highly controversial. In this study we estimate if the implementation of a new practice, makes farmers worse- or better-off. Since it is not possible to account for all the costs and benefits of a representative farming system, we calculated gross margin based on assumptions of the changes on necessary inputs (i.e., seeds, fertilisers, sprays or machinery).

Concerns about cost effectiveness analysis tend to mirror more general critiques of controversial reliance on monetization of all costs. But a clear presentation of the assumptions and bottom-up approach make the analysis useful for decision-making.

Here, the cost-effectiveness assesses the potential of the selected SOC management practices by determining the specific marginal cost of reducing emissions. Following the approach of previous studies to analyse the cost-effectiveness of mitigation practices in agriculture (e.g. Moran et al. 2011b), we assumed that maximising benefits is one of the key objectives to the farm decision making. We acknowledge the limitations of this view, as Moran et al. (2013) point out mitigation win-win messages tend to over-simplify farmer motivation. A range of socio-cultural factors such as farmers´ environmental values, traditions, beliefs about climate change, or awareness of and attitudes towards carbon sequestration have been shown to influence farmers decisions as well, however these have been difficult to include in this analysis (Cook and Ma 2014; Arbuckle et al. 2014). Ultimately, SOC management and/or GHG mitigation may not be among farmers' objectives; hence the potential for their cost-effective achievement will not influence decisions. Uptake would instead require the demonstration that SOC management can help achieve objectives such as increased yields or reduced costs. Here, we estimated the cost-effectiveness in terms of € per tonne of CO_2e abated, where the cost is the impact on the typical gross margin for implementing each SOC management practice in the case study region. Gross margin is calculated as the difference between gross revenue and variable cash costs. Depending on which costs are included in the calculation, there can be multiple measures of gross margin. We calculated the change on the typical gross margin related to the implementation of each SOC management practice p and crop c,$\Delta GM_{p,c}$:

$$\Delta GM_{p,c} = (Y_c \times P_c \times YI_{\mathrm{p},c}) - VC_c - IC_{p,c} - DC_{p,c} - GM_c \quad (1)$$

Where Y_c is the typical yield for the crop c (including grain and straw products), P_c is the typical price for the crop c products and $YI_{\mathrm{p},c}$ is the yield impact of the practice p for the crop c (in percentage). VC_c are the variable costs for the crop c before the practice implementation. $IC_{p,c}$ is the implementation cost of the practice p for the crop c, including investment costs (e.g., machinery, new seeds) and operational costs (e.g. nutrient inputs, crop protection) less avoided costs (i.e., cost savings from reduced need of inputs or operations). $DC_{p,c}$ is the displacement cost of the practice p for the crop c including loss of production or loss of saleable product (e.g., cereal straw). GM_c is the typical gross margin for the crop c without the practice implementation.

The cost-effectiveness for each practice p and crop c, i.e., $CE_{p,c}$ is then expressed as:

$$CE_{p,c} = \frac{\Delta GM_{p,c}}{\Delta GHG_p} \quad (2)$$

Where $\Delta GM_{p,c}$ is the change in gross margin for the practice p and the crop c and ΔGHG_p is the abatement effect in GHG with the implementation of the practice p. The calculations of cost-effectiveness were undertaken at the per hectare level. The effect on GHG was extended to the regional scale by multiplying by the production level (area planted) of each crop.

Figure 1 outlines the MACC approach to rank the mitigation practices in terms of their cost-effectiveness in € per tonne of CO_2e abated and at the same time to show the total abatement potential in tonnes by practice for the case study region. Each of the bars represents an individual mitigation practice. The vertical axis represents the cost-effectiveness, where negative abatement cost values (less than zero) mean savings. The horizontal axis represents total abatement potential, the wider these bars the greater its abatement potential.

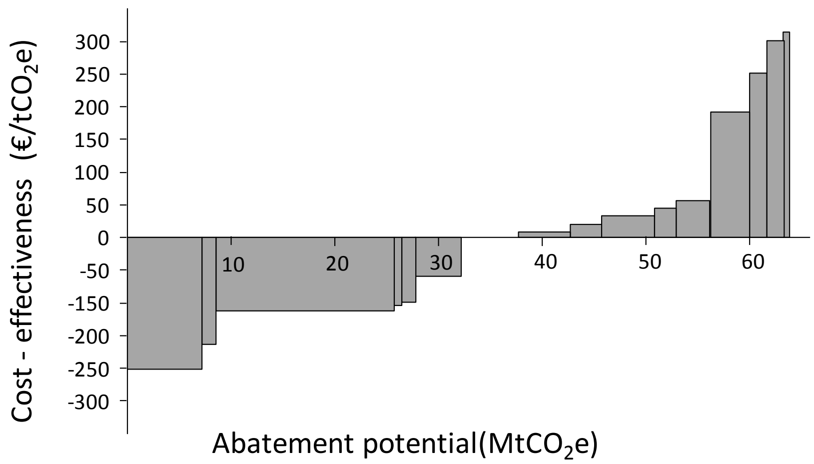

Figure 1. A schematic example of a Marginal Abatement Cost Curve (MACC), where the mitigation practices (bars) are ranked in order of decreasing cost-effectiveness from left to right. The MACC plots the abatement potential that could be achieved by practices that generate negative abatement cost values (i.e., incur cost-savings) and practices that generate positive abatement cost values (i.e., incur a positive cost)

2.4. Generating SOC abatement wedges

An abatement wedge represents a practice that can contribute to reduce GHG emissions to the atmosphere (e.g. by sequestering soil organic carbon), which starts at zero today (i.e. not implementation) and increases linearly until it accounts for the reduced carbon emissions achieved by the full implementation of the practice (based on the stabilization concept of Pacala and Socolow 2004).

Here we applied the stabilisation wedges concept (Pacala and Socolow 2004) to illustrate the regional abatement potential of the selected practices in order to inform agricultural and climate policy. In Figure 2, the area of the polygon A represents the projections of GHG emissions in a business as usual scenario. The area of the triangle B represents the stabilization wedge of the SOC strategies; this area is further composed of the contribution from each individual practice.

To develop the SOC stabilization wedges in this study, we made three simplistic assumptions: i) we assumed that net GHG emissions remained constant over time based on the current projections (i.e., 1.85 million tCO_2eq released by crop cultivation in the case study region; MAGRAMA 2012); ii) we assumed a mitigation scenario of full implementation over time where, although it is uncertain how much SOC management practices adoption will be undertaken by farmers, they would be incentivised to implement them by some policy intervention; therefore iii) we assumed that adoption costs and benefits were unaffected over time. The SOC stabilization wedges help to display in a simple and comprehensible diagram the minimum and maximum potential of the different SOC management practices considered (Table 2) that can contribute to reduce GHG emissions to the atmosphere by sequestering soil organic carbon.

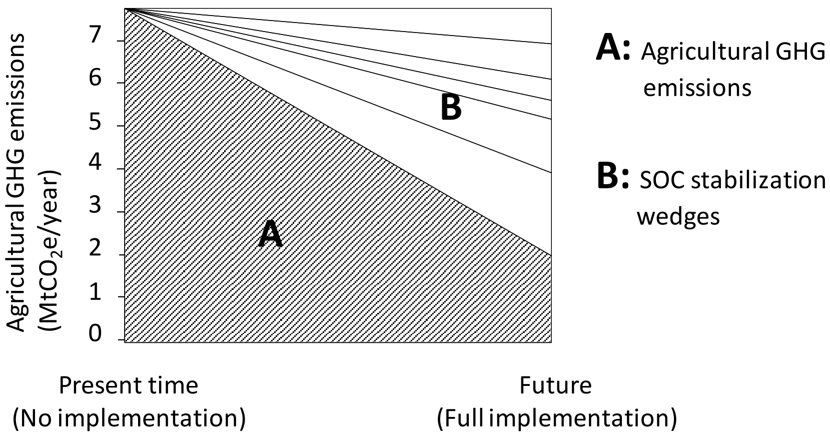

Figure 2. Simplified representation of the stabilization wedges of the SOC strategies based on the concept of Pacala and Socolow (2004)

2.5. Case study analysis

The case study region of Aragón is a semiarid region located in NE Spain of 47,700km^2 (the fourth largest agricultural region in the country). About one fourth of this territory is agricultural land. The climate in the agricultural area is Mediterranean with continental influence; with mean annual temperatures ranging from 7 ºC to 15 ºC and mean annual precipitation from 300 to 800 mm. At present, agricultural activities in Aragón are responsible for about 3.8 million tCO_2eq, over 20 % of total GHG emissions in the region and from which 1.85 million tCO_2eq are released by crop cultivation (MAGRAMA 2012). In most cases, the current agricultural management is based on intensive tillage, high mineral and organic fertilization and the use of monocultures (Álvaro-Fuentes et al. 2011), although more sustainable practices are evolving in recent years. Consequently, small changes in the current management could have large potential for improving regional and national mitigation commitments (Sánchez et al. 2014).

First, we selected the target crops representative of the case study region, second the most relevant mitigation practices and finally we estimated the costs and the barriers for implementing the practices in the region. The sources of data included: (a) national statistical databases; (b) local and European published databases (EUROSTAT; Sánchez et al. 2014; Smith et al. 2008); (c) existing experimental evidence and literature; and (d) data derived from an expert group.

Target crops

The most significant crop systems were identified and their gross margin was estimated as the difference between gross revenue and variable cash costs (see Table 1). The database used was published by the Spanish Agricultural Census. The most significant crops are wheat (rainfed and irrigated), barley (rainfed and irrigated), maize (irrigated), alfalfa (irrigated), almonds (rainfed), vineyards (rainfed) and olives (rainfed). These selected crops account for 75% of the total cropland area of the region.

Table 1. Distribution of the significant crops and elements of gross margin calculation for the Aragón region in 2011

Crop	Area planted (ha)	Yield (tonnes/ha)		Price (€/tonne)		Gross revenue (€/ha)	Variable costs (€/ha)			Gross margin (€/ha)
		Crop	Straw	Crop	Straw		Seed	Fertiliser	Sprays	
Wheat ra.	209,586	2.1	4.9	214	35	621	52	88	14	467
Wheat ir.	57,540	4.4	6.6	210	35	1,155	70	168	26	891
Barley ra.	339,275	2.5	5.8	186	35	669	42	114	20	493
Barley ir.	77,801	4.1	6.2	184	35	970	54	163	32	721
Maize ir.	71,043	11.9		184		2,190	246	422	78	1,444
Alfalfa ir	73,154	15.4		107		1,648	9	145	36	1,458
Almond ra.	59,022	0.6		730		641	2	33	50	556
Vineyard ra.	29,064	3.8		360		1,368	198	30	138	1,002
Olives ra.	35,797	1.0		336		336	2	46	19	269
Other crops	315,961									
Total	1,268,243									

Notes: ra. means rainfed; ir. means irrigated; Data for calculation are derived from the national database (MAGRAMA 2011a, 2011b) and straw values are derived from Moragues et al. 2006; Urbano 2002; Francia et al., 2006; Pordesimo et al. 2004

Practices with abatement potential

The selection of practices (Table 2) was based on previous studies and the abatement potential measured as CO_2 equivalent including direct CO_2 and N_2O reductions (Sánchez et al. 2014; Smith et al., 2008). The six practices identified are already implemented by some farmers in the case study region, and could be scaled up further to contribute to mitigation policy in other European regions; the practices are defined below.

Table 2. Summary of the selected mitigation practices and the abatement rate estimations for the Aragón region

No	Mitigation practices	Description	Estimated abatement rate ($tCO_2e\ ha^{-1}yr^{-1}$)		
			Mean	Low	High
P1	Cover crops in field crops Cover crops in tree crops	Cover crops in cereals and orchards are planted crops in order to improve soil fertility and water use (Marquez-Garcia et al. 2013). The cover crop practice may increase soil carbon, reduce soil erosion and also has a high potential to reduce GHG emissions, especially N_2O, in the Mediterranean areas (Sanz-Cobena et al. 2014).	0.42 1.10	-0.21 0.65	1.05 1.55
P2	Minimum tillage	Minimum tillage implies avoiding as far as possible tillage practices. Soil carbon storage is increased through reducing microbial decomposition and, particularly in rainfed systems, through the increase in C input (Álvaro-Fuentes et al. 2014).	0.47	0.23	0.71
P3	Residue management	Residue management is defined here as the practice that retains crop residues on soil surface, eliminating stubble burning or stubble removal for livestock use. It may be highly effective to reduce GHG emissions (Smith et al. 2008).	0.17	-0.52	0.86
P4	Manure fertilization	Manure fertilization is the use of animal manures for crop fertilization and to enhance carbon return to the soil. An increase in N_2O emissions can be associated with the type of manure management undertaken (Freibauer et al. 2004).	0.22	0.10	0.33
P5	Optimized fertilization	Optimized fertilization is defined here as the increase in nitrogen use efficiency by adjusting the application rates to crop needs, fertilizer placement or split applications. Precise application of fertilizers can help to reduce nitrate leaching losses and N_2O emissions (Smith et al. 2008).	0.49	0.36	0.62
P6	Crop rotations (with legumes)	Crop rotation with legumes is recognized for its capacity to increase soil carbon content and to reduce the requirement for nitrogen fertilizer, thereby reducing N_2O emissions from fertilizer use (Lal 2004).	0.84	0.08	1.60

Note: The estimated abatement rate (CO_2 mitigation) were derived from Sanchez et al. (2014) for most of the practices except cover crops for cereals and residue management which were derived from Smith et al. (2008), and validated by the Expert Group (Feb 2014). Positive values represent SOC increases

Costs

Table 3 provides the assumptions and estimations of private costs and benefits (i.e. to the farmer) and yield effect of implementing each practice per crop in the region.

Table 3. Assumptions and estimations of costs and yield effect of implementing the mitigation practices by crop type in Aragón

Measure Crop	Private costs (€/ha)	Private benefits (€/ha)	Yield effect (%)
1. Cover crops	Seeds + annualized cost for a pneumatic seed-drill for woody crops (MAGRAMA 2008; Steenwerth and Belina 2008; Gómez et al. 2011)	N purchase costs reduced by 23% in cereals (Gabriel and Quemada 2011)	Yield increase for maize and unaffected for woody crops (Gabriel and Quemada 2011)
Maize ir.	31 (vetch); 42 (barley)	68.7	1.11% (vetch); 1.06% (barley)
Almond ra.	58.4	0	0
Vineyard ra.	53.9	0	0
Olives ra.	57.4	0	0
2. Minimum tillage	Annualized cost for a direct seed drill (MAGRAMA 2008)	Avoided costs of mouldboard plow (MAGRAMA 2008)	Yield increase (Morell et al. 2011)
Barley ra.	73.4	84.7	1.55%
Barley ir.	73.4	84.7	1.55%
3. Residue management	Loss of straw value for incorporation into soil (MAGRAMA 2011a)	Not benefit accounted (expert judgement)	Yield unaffected (expert judgement)
Wheat ra.	171.5	0	0
Wheat ir.	231.0	0	0
Barley ra.	204.2	0	0
Barley ir.	215.3	0	0
4. Manure fertilization	Operational cost of manure transport (max 3km) and applying (LIFE ES-WAMAR 2010)	Mineral fertilizer cost avoided for barley and N purchase costs reduced by 60% for maize (Meijide et al. 2007)	Yield unaffected (expert judgement)
Barley ra.	75	114	0
Barley ir.	75	88	0
Maize ir.	82	277	0
5. Optimized fertilization	Soil testing to optimize fertilizer applications (MAGRAMA 2011a)	N purchase costs reduced by 23% for wheat and doses lower than 60kgN/ha for barley (Morell et al. 2011)	Yield increase (Van Alphen and Stoorvogel 2000; Morell et al. 2011)
Wheat ra.	6	20.2	1.03%
Wheat ir.	6	20.2	1.03%
Barley ra.	6	30.8	1.05%
6. Crop rotations (legumes)	Not cost accounted (expert judgement)	N purchase costs reduced by 50% (expert judgement)	Yield increase (López-Bellido and López-Bellido 2001; Díaz-Ambrona and Mínguez 2001)
Wheat ra.	0	44	1.40%
Barley ra.	0	57	1.35%

Notes: ra. means rainfed; ir. means irrigated; n.a. means not available

The private costs of implementation included i) investment costs needed for seeds, machinery or equipment; ii) cost of farm operations associated with the practice such as additional spraying or nutrients inputs, costs from manufacturing processes (e.g., stock, treatment or nutrient testing of manure) were not included and neither fuel or labour costs; and iii) displacement cost of the practice such as loss of production or saleable product (e.g. loss of cereal straw value for incorporation into soil). The private benefits were the cost savings from reductions of inputs or operation needs.

We used regional data in most cases (over 80 percent of the variables), which were collected from published peer reviewed experimental evidence in the region, data published in the statistical yearbooks of the Ministry of Agriculture (MAGRAMA), and a report of pilot demonstration projects financed by the European Commission (LIFE ES-WAMAR 2010). A few exceptions of additional data were necessarily made to complete the database. First, the expert group was used in five cases to estimate the private costs and benefits, in particular for the effect of crop rotations with legumes, and the yield effect of residue management and manure fertilisation. Second, the yield effect of minimum tillage and optimised fertilisation was derived from peer reviewed published studies made outside the region.

The expert group was convened as a workshop in February 2014 with 10 participants from the policy and farm advisory communities, to validate the databases, to assess the applicability and relevance of theoretical abatement practices and to validate costs data.

The group consisted of two policy makers from the public administration and the Ministry of Agriculture, Food and Environment, and eight farmers' representatives from different farmer advisory services (3), cooperatives and unions (2) and academia (3). Participants were selected using UPM (Technical University of Madrid) networks on the basis of their relevant experience and understanding of farming and/or soil management in the region, knowledge on GHG mitigation in agriculture and, in most cases, regular contact with farmers. The workshop participants were presented at the beginning with key information on typical cropping systems, SOC management practices and their effects which framed a discussion about potential practices and the barriers and opportunities with respect to their implementation. A plenary group was conducted for feedback, and in order to get specific input from the participants, a work document was developed and distributed to all the participants. The document included tables and exercises to be filled individually by the participants, as well as instructions with examples and guidelines. The discussion around the completion of the exercises was also recorded and reported. Analysis of feedback was carried out quantitatively using the completed exercises and by identifying common themes and viewpoints in the plenary discussions about applicability and relevance of theoretical abatement practices and validity of costs data. This is reported in detail in the European Commission research project SmartSOIL (www.smartsoil.eu). The inclusion of a group of experts to validate statistical data and provide additional qualitative information on barriers and incentives has been used in similar studies (Moran et al. 2011b; MacLeod et al. 2010).

Barriers and incentives

The expert group provided further information about the barriers and incentives for implementing the practices. The barriers included climatic constraints (such as limiting precipitation threshold for applying rotations with legumes in arid areas), agronomic constraints (such as the possible water and nutrients competition between crops in rainfed systems with cover crops), and social constraints (such as acceptance). Incentives included demonstration of the benefits of practices at farm level and direct policy support. Although barriers and incentives were not considered quantitatively in our analysis, we used the information to include a qualitative narrative that contributed to the interpretation and discussion of the results.

2.6. Limitations and assumptions

There are important limitations of our analysis. First, we addressed only crop and grassland farming systems and crop and soil mitigation practices. Although livestock systems were not considered explicitly in the study, it was included in the farming classification of the inventory (i.e., mixed systems). Second, the static nature of our MACC, is a limitation as it just considered a single year for the calculation, which was also outlined by Ward (2014). Consequently, our MACC is unable to account for the effects of temporal changes in the SOC sequestration rate of the mitigation measures (Álvaro-Fuentes et al. 2014) or cumulative improvements in soil structure and workability that might reduce costs and change the cost-effectiveness of the measures.

Furthermore, we did not consider issues such as potential SOC saturation or the effects of occasional tillage. Third, our analysis did not consider ancillary costs and benefits of the GHG emissions reduction and omits the interaction of measures (MacLeod et al. 2010), since it required a detailed assessment of interaction factors which were not available in literature. Neither was considered the interaction with behavioural aspects which can have a substantial influence on farmer decision making. As an alternative, we involved the expert judgment in our study to outline the uptake barriers and incentives of practices according to technical, social and economic drivers. Finally, the lack of existing key data and empirical evidence with respect to the effect of implementing practices in terms of SOC, GHG emissions, yield impact and costs at the regional level was a limiting factor. Some of the additional costs of using the SOC management practices cannot be included in our gross margin calculations, making profits more apparent than real. Where possible we used regional specific data, but some of the elements for the calculations had to be based on assumptions from studies conducted in other semiarid areas and on the expert group.

The derived shortcomings of our cost-effectiveness analysis mean that the results are only indicative of the relative ranking of mitigation practices rather than absolute values and further research is needed to extend the knowledge of the underlying reasons for their implementation. Despite these limitations, the analysis advances our understanding of the cost and the abatement that might be achieved by small changes in crop and soil management which could be used as a complementary tool in mitigation policy development and support.

3. Results and Discussion

3.1. SOC management in Europe

Figure 3 provides an overview of the current use of some of the relevant SOC management practices in Europe. Most of the EU-27 regions seem to have limited implementation of the six selected SOC management practices. For instance, the current EU-27 average use of cover crops in percentage of arable land was 7%. None of the regions showed percentages higher than 50% of cover crop use, compared to the total area of arable land, and only three regions of Austria (Salzburg, Tirol and Vorarlberg) and one in Spain (Asturias) showed percentages between 40 and 45%. The average use of minimum tillage for EU-27 in percentage of arable land was higher than cover crops and at about 18%. However, there are still low percentages of minimum tillage implementation in the EU-27 regions and only Cyprus (which showed the maximum use of the practice with ca. 66%) and several regions in Germany and Bulgaria, showed percentages more than 50% of minimum tillage compared to the total area of arable land. For the use of residue management, the EU-27 average was 9% compared to the total area of arable land and none of the regions showed more than 50% of residue management implementation. There were only two regions from Portugal (Algarve and Alentejo) which showed percentages of the use of residue management between 40 and 45%. The average use of manure fertilization in percentage of arable land for the EU-27 was 14% and none of the countries showed percentages more than 50%. Only Malta, Austria and Slovenia showed percentages higher than 25% compared to the total area of arable land. The map on the use of optimized fertilization shows both areas where not enough N was applied (negative values), as well as areas where too much N was applied (positive values, we consider those regions above 25%). The average of N overfertilization for EU-27 in percentage of the crop N uptake was 57%, which means that some of the European farmers are applying more than the double of N that the plant needs. The regions with the highest percentages of overfertilization were located in different countries such as Cyprus (with the highest percentage of overfertilization), Belgium, Greece, Spain, Finland, Malta, Netherlands and Portugal. The crop rotation seems to be the practice most widely undertaken among the European regions. The EU-27 average for the use of crop rotation was 86% compared to the total area of arable land. Conversely to the other mentioned practices, almost none of the regions showed percentages less than 50%, and only some regions of Greece, Sweden and UK recorded percentages between 20 and 50%. However, in practice these crop rotations may not optimise SOC accumulation.

The results illustrate the large potential to mitigate GHG emissions that the EU-27 regions have by increasing the adoption of SOC management practices. However, the farmer's awareness of and attitudes toward practices that contribute towards improved soil carbon (Cook and Ma 2014), the farming systems and the agronomic and climate conditions vary considerably across the European regions (Ingram et al. 2014). Therefore the identification and understanding of potential areas of common ground is necessary to enhance the adoption of farming practices and engage strategies for carbon sequestration and climate change adaptation and mitigation (Arbuckle et al. 2014; Prokopy et al. 2015). Social and cultural factors can often be equally, if not more important, than ecological and economic factors in influencing farmer decision making (Baumgart-Getz et al. 2012; Feliciano et al. 2014). Having access to, and the quality of, information, financial capacity, and being connected to agency or local networks of farmers may have a large influence on the adoption of conservation practices (Baumgart-Getz et al. 2012). Cook and Ma (2014) proposed strategies for adoption of SOC management practices by increasing the farmer interest with information on ecological benefits associated with sequestering carbon or with the cooperation between agricultural organizations and policy makers.

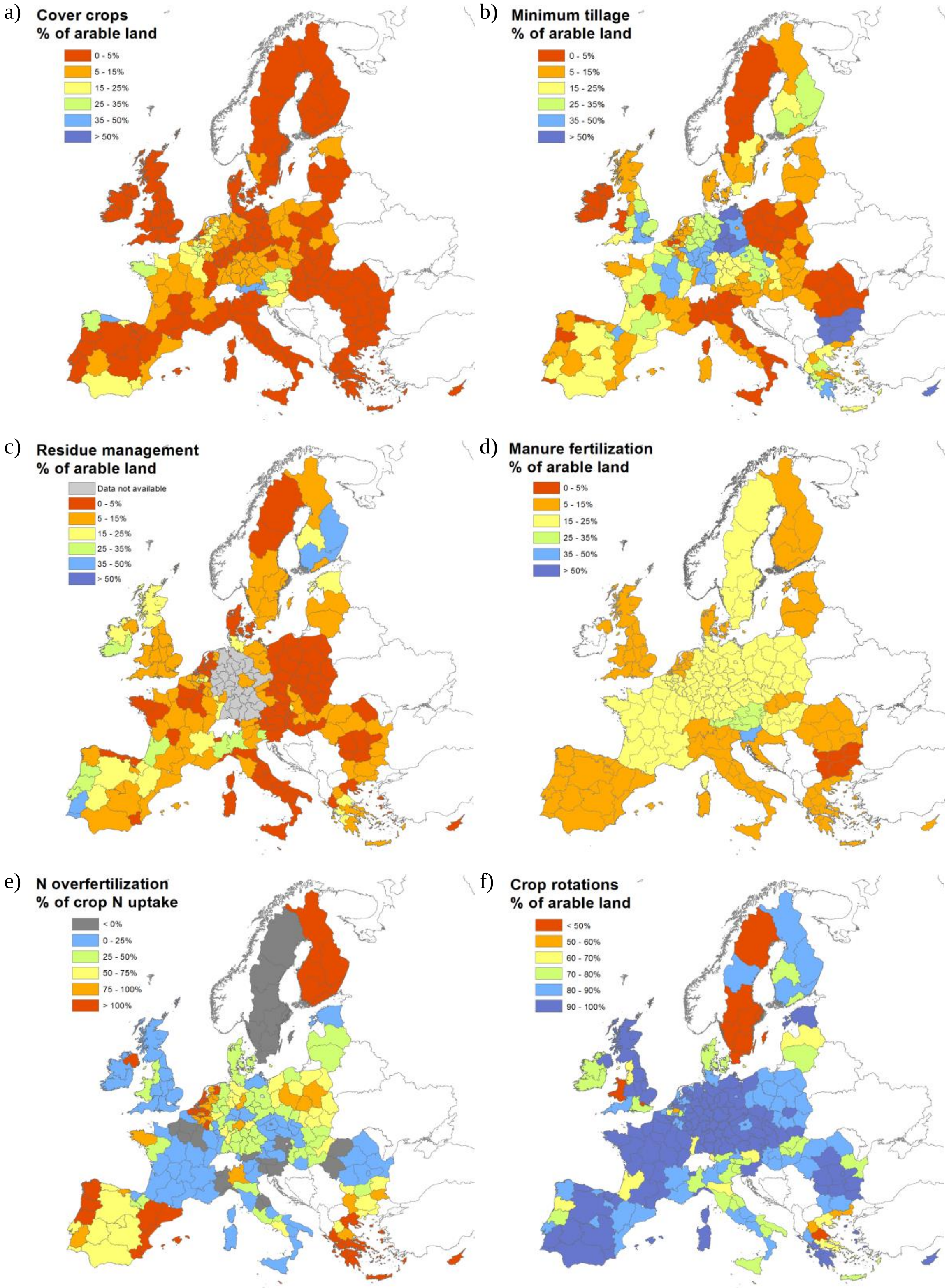

Figure 3. The use of SOC practices in EU-27 regions (based on Survey on Agricultural Production Methods 2010 and FSS statistics at regional level from EUROSTAT 2010); a) Cover crops % of arable land; b) Minimum tillage % of arable land; c) Residue management % of arable land; d) Manure fertilization % of arable land; e) N Overfertilization % of crop N uptake; f) Crop rotation % of arable land

3.2. Abatement potential and costs

The annual abatement potential ($MtCO_2e\ y^{-1}$) and cost (€/$tCO_2e\ ha^{-1}\ y^{-1}$) per mitigation practice by crop type are ranked according to the cost-effectiveness estimation in the MACC in Figure 4 (the data are listed in supplementary information; Table S1). The y-axis in Figure 4 shows the change in gross margin, therefore practices below zero (i.e. negative values) actually indicate an increase in gross margin or cost savings due to either increased yield or reduced costs. The x-axis in Figure 4 illustrates the annual abatement potential per crop up-scaled for the entire case study region, and since the practices are considered additive, the cumulative abatement is accounted for as the combined uptake.

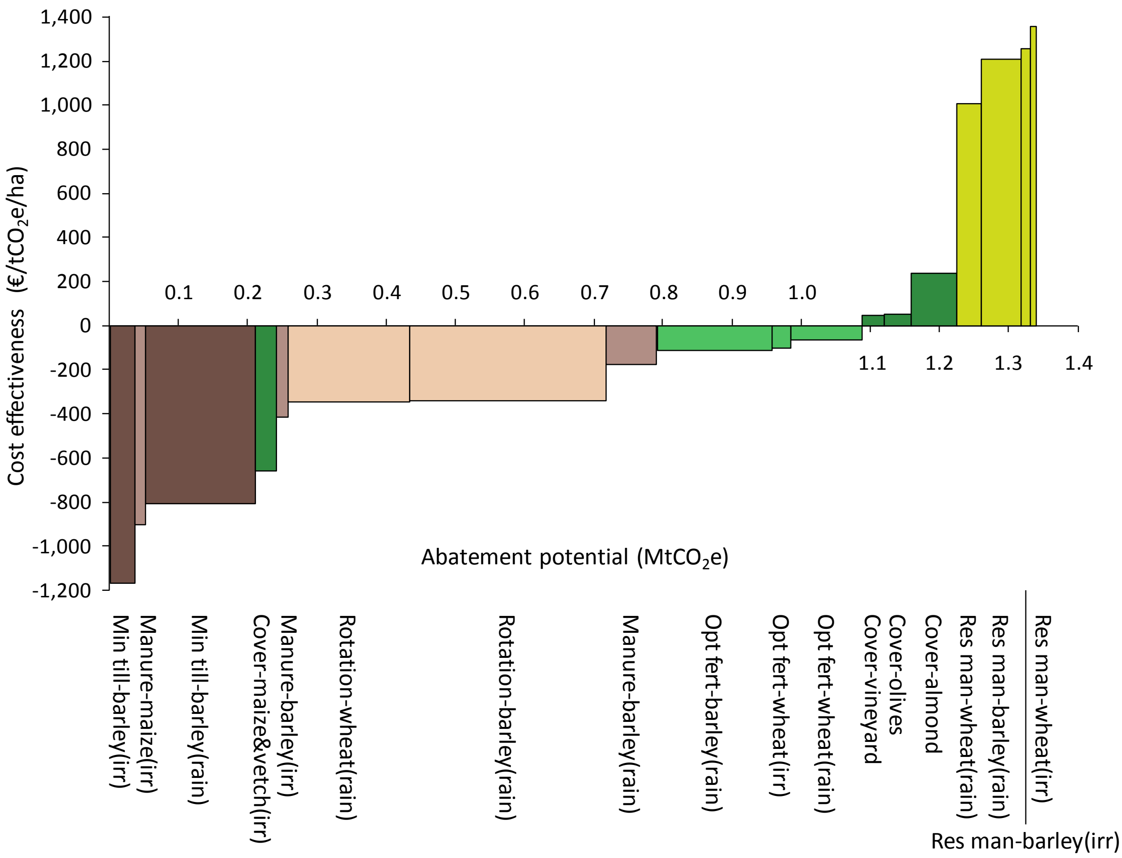

Figure 4. MACC for mitigation practices and crops in NE Spain (Aragón region)

The annual abatement potential in the NE Spanish region could reach 1.34 $MtCO_2e$ by the complete adoption of the practices (ca. 73% of the emissions released by crop cultivation). The results show that mitigation practices that generate negative abatement cost values (i.e., incur cost-savings) might reduce annual emissions by 1.09MtCO_2e. They were (a) minimum tillage; (b) animal manure fertilization; (c) cover crops in field crops; (d) the inclusion of legumes in rotations; and (e) optimized fertilization. An additional 0.25MtCO_2e might be achieved by practices that generate positive abatement cost values (i.e., incur a positive cost). They were (f) cover crops in vineyards and olives, (g) cover crops in almonds and (h) residue management. There are farmers who are already employing the considered practices (as illustrated in Figure 3), however a number of barriers are hindering a larger adoption. The cost-effectiveness and barriers to adoption of these practices are discussed below.

(a) Minimum tillage in barley can provide significant abatements of about 0.2 MtCO_2e at the negative cost from -1,168 to -807€/tCO_2e $ha^{-1}yr^{-1}$. Long-term experiments have already proven the potential of these practices to maximize SOC sequestration in the case study area (Álvaro-Fuentes et al. 2014). However, in some regions where every few years the soil needs to be cultivated conventionally, the SOC benefit is lost and thus its abatement potential can be overstated (Derpsch et al. 2014; Powlson et al. 2014). Moran et al. (2011b) reported cost findings of about -£1,053/tCO_2e $ha^{-1}yr^{-1}$ for reduced tillage in UK, consistent with our estimations. Pellerin et al. (2013) estimated that these practices would not have significant cost for the farmers in France (c.a. -3 to 12€/tCO_2e $ha^{-1}yr^{-1}$). Minimum tillage has less fuel and time requirements when comparing to conventional tillage. However, experts at the workshop pointed out agronomic and economic barriers, namely the initial cost of a direct seed-drill and the additional need of spraying might cause low acceptance by farmers, especially for the small sized farms to absorb such costs. Additionally, they noted a strong tradition of conventional tillage practices in the region and an elderly farming population, as reported by Sánchez et al. (2014).

(b) The cost of manure applied in irrigated maize are about -905 €/tCO_2e $ha^{-1}yr^{-1}$ to achieve abatements of about 0.01MtCO_2e. Irrigated maize in the case study region is grown in an intensive cropping system with high fertilizer requirements and yields can reach up to 14 tonnes/ha (MAGRAMA 2011c). This crop has high requirements of N that could be covered by the manure produced by the farmer or bought from surrounding farms at low cost. Manure in barley might also provide abatement of about 0.09MtCO_2e at a negative cost of -416 to -177€/tCO_2e $ha^{-1}yr^{-1}$. The use of animal manures is proven to enhance carbon return to the soil (Freibauer et al. 2004). MacLeod et al. (2010) also estimated a negative cost of using manure in UK. Experts consulted in the workshop pointed out that the restrictive legislative requirements for manure management, treatment and transportation may limit its use by many farmers in Spain (EU Nitrates Directive 91/676/EEC). Furthermore availability and cost of manure in areas with low livestock numbers were highlighted as agronomic and economic barriers to its use. The potential impact on surrounding farms and issues with odour for farmers located near to urban areas, were also recognised as social constraints.

(c) Cover crops with irrigated maize can achieve about 0.03$MtCO^2e$ at negative cost of -650 to -400 €/tCO_2e ha-1yr-1. The possible interference of cover crop by risk of water competition with the cash crop (i.e., maize) is avoided in irrigated systems and benefits tend to be higher (Snapp et al. 2005). In Aragon, the use of winter cover crops in irrigated maize systems has been demonstrated as an interesting technique to reduce N leaching risks and to increase nitrogen use efficiency (Salmerón et al., 2010). Although the inclusion of a winter cover crop does not result in significant maize yield increases, it allows reducing N fertilizer rates without compromising maize yields (Salmerón et al., 2011). However, in Aragón where precipitation is low, the use of winter cover crops before irrigated maize is not a common practice (Salmerón et al., 2011). Also, the economic cost associated with the growth of a cover crop may be a barrier for implementation despite this cost being more than offset by economic saving of decreasing N fertilization rates during the following maize crop.

(d) The inclusion of legumes in rotations with barley and wheat results in abatements of about 0.46$MtCO_2e$ at the negative cost of -343€/tCO_2e $ha^{-1}yr^{-1}$. Pellerin et al. (2013) found a low positive cost of 19€/tCO_2e $ha^{-1}yr^{-1}$ for legume introduction in crop rotations in France. Lal (2004) reported by meta-analysis that implementing legume-based rotations in semiarid regions may have a positive impact on the SOC pool. In Aragón, the use of crop rotations is a key agricultural practice. Depending on the location, the selection of crops can vary since rainfall determines the possible crop sequences (Álvaro-Fuentes et al. 2009). In Mediterranean environments the use of legumes (e.g., vetch, pea) and cruciferous crops (e.g., rapeseed) in rotation with winter cereals (e.g., barley, wheat) is a common practice. In Mediterranean Spain, several experiments have reported the optimal benefits of crop rotations on grain yield and plant production (Álvaro-Fuentes et al. 2009). Moreover, improvements in soil quality and biodiversity with the use of alternative crops have also been reported for these same agroecosystems (Hernanz et al. 2002; Melero et al. 2011). The expert group stressed that including legumes where the annual precipitation is less than 350mm can be unworkable due to crop failure. Further concerns expressed by the expert group included higher costs to control weeds, greater difficulties in selling legumes compared to cereal grains and competition with soybean imports. The discrediting of this practice in the past was also considered a significant barrier for the adoption. However, the new CAP includes incentives for growing legumes, e.g. under the greening measures.

(e) Optimized fertilization in barley and wheat might provide abatement of about 0.30MtCO_2e at negative cost of about -94€/tCO_2e $ha^{-1}yr^{-1}$. Other studies have shown that adjusting the application rates can be essential to reduce N_2O emissions at negative cost (Moran et al. 2011b; Pellerin et al. 2013; Wang et al. 2014). Experts highlighted agronomic and economic barriers such as the need for infrastructure (e.g. fertigation systems) and the cost entailed in using precise fertilization techniques (e.g. sensors, GPS, software, remote sensing) and soil analysis. However the main uptake barrier identified is the lack of skills and the need for training and capacity building for delivering specific fertilizer recommendations at farm level, this has been noted in other studies (Robert 2002).

(f) Cover crops in rainfed vineyards and olives might provide about 0.07MtCO_2e at a positive cost of about 50€/tCO_2e $ha^{-1}yr^{-1}$. Pellerin et al. (2013) estimated similar costs for farmers in France (14€/tCO_2e $ha^{-1}yr^{-1}$). Recent experiments have demonstrated the potential for SOC gains and erosion reduction of cover crops in orchards under semiarid conditions (Marquez-Garcia et al. 2013). Conversely, cover crops can increase costs to the farmer when applied in rainfed systems due to possible water and nutrient competition (Pellerin et al. 2013). Experts also identified this competition between crops as an agronomic and economic barrier, together with the risk of decrease in soil moisture and the cost of increased maintenance and management required.

(g) Cover crops in rainfed almonds might provide abatement of about 0.06MtCO_2e at a positive cost of 238€/tCO_2e $ha^{-1}yr^{-1}$. The favourable impact of the practice on SOC could make the system more profitable in the long term and an early cover crop removal would minimize possible yield losses (Ramos et al. 2010). In almonds, the maintenance of cover crops by mowing instead of repeated disking can be less costly, reduce insect and mite problems, cause less soil compaction, increase water penetration, and require less management time (Elmore 1989). However, selecting the proper species and management according to the specific conditions of the farming system (e.g., soil type, water availability and cultural practices to control weeds) can be critical to maximize the benefits (Ingels et al. 1994; Connell et al. 2001). In Aragón, the almond is grown in severe low rainfall areas where traditional management is widespread and where farmers are less keen to adopt cover crops, than occurs in rainfed vineyards and olives, due to the potential competition for water and nutrients.

(h) Residue management in barley and wheat could provide abatement of about 0.12MtCO_2e at higher positive cost. Higher costs are mainly due to loss of revenue from selling straw for animal feed as a by-product. Wang et al. (2014) found that returning straw or residue back to wheat and maize fields in China, improved soil fertility at a negative cost. Incorporating residues from crops into the soil, where stubble, straw or other crop debris are left on the field, may enhance carbon returns and SOC sequestration (Smith et al. 2008). The expert group reported that there are still some farmers practicing pruning debris burning in the region who do not recognise the need for implementing residue management.

Our analysis focuses on a relatively small aspect of GHG mitigation within the agriculture sector as we are considering only measures that impact on SOC levels. Far greater GHG abatement can be achieved cost-effectively through measures that directly target methane emissions from enteric fermentation and nitrous oxide from nutrient management (see for example Moran et al., 2011a,b). Ultimately, SOC increases are relatively small on a per hectare basis, therefore the cost (or benefit) per tonne abated appears to be excessively high. Further studies have analysed the cost of carbon sequestration to evaluate the cost-effectiveness of the agricultural and forestry strategies (Povellato et al. 2007), however the difference in carbon accounting complicates comparison between cost estimates (e.g., different use of terms, geographic scope, assumptions or methods; Richards and Stokes 2004). Recently, De Cara and Jayet (2011) estimated the shadow price of carbon in the EU agriculture sector to range from 32 to 42€ per tonne of carbon. The analysis of the role of other sectors shows also potential for a cost-effective GHG mitigation by different strategies. For instance, the bio-energy options and the contribution of energy efficiency might provide significant abatements saving up to €198 per tonne of CO_2e by replacing the "business as usual" systems based on fossil resources with ones based on biogas (Rehl and Müller 2013).

3.3. SOC abatement wedges

In terms of the effect of the practices, we show the low, mean and high values for the estimated abatement potentials using SOC abatement wedges. In Figure 5 we idealize the SOC improvement as a "ramp" trajectory from the present time – equal to no implementation - to the future – equal to full implementation of practices. The trajectory creates a "potential SOC abatement triangle", located between the flat trajectory and the projected SOC trajectory. To keep the focus on practices that have the potential to reduce emissions by improving SOC rather than monetary terms, we plot the SOC triangle into "wedges" that represent the SOC potential of the practices in the case study region. The results show that both the upper (optimistic) and the lower (pessimistic) levels of estimated mitigation by practices implementation in the region could provide significant abatements. SOC abatement wedges can illustrate the potential role that have SOC sequestration by sustainable agricultural management to mitigate emissions (Grosso and Cavigelli 2012; Lassaletta and Aguilera 2015).

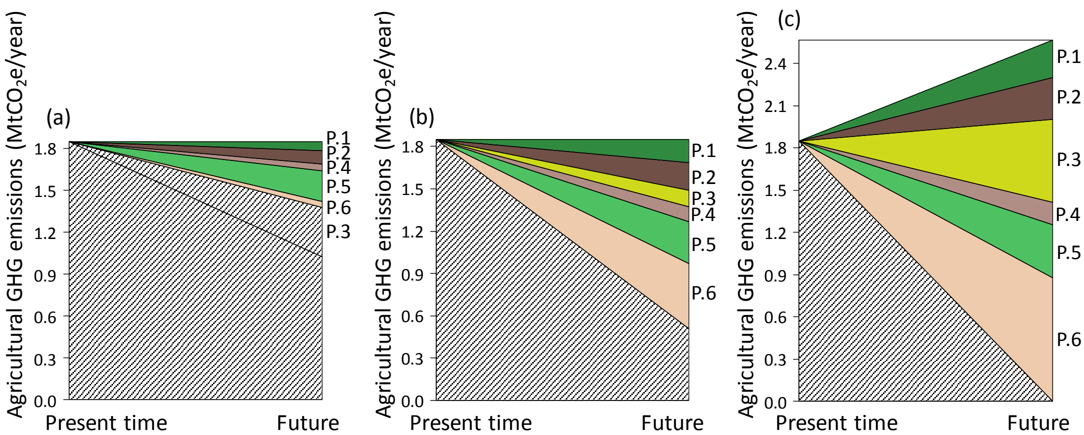

Figure 5. Low, mean and high SOC abatement wedges for the mitigation practices in NE Spain (Aragón region). (a) Low SOC abatement potential; (b) Mean SOC abatement potential; (c) High SOC abatement potential; P1 Cover crops; P2 Minimum tillage; P3 Residue management; P4 Animal manure fertilization; P5 Optimized fertilization; P6

Crop rotations (with legumes). The barred area shows the agricultural GHG emissions released from crop cultivation in Aragón region.

There is a need to establish priorities to simultaneously reduce emissions and maximize social benefits with a given budget and target commitments (Glenk and Colombo 2011). According to the barriers revealed by the experts in our case study, even when cost effectiveness and abatement are optimal, agronomic and social factors are likely to constrain implementation of promising practices. Some of these constraints may be addressed by policy interventions (Pannell 2008); for example, training and advisory support can address lack of farmer skills in fertilisation, and capital grants and support can address farmers' need for machinery and additional weed control for minimum tillage. However constraints such as the farmers established traditions of conventional tillage in older communities, poor availability of livestock manure, and unfavourable market conditions for legume crops are more entrenched and beyond the scope of some policy measures.

4. Conclusions

Mitigation policies to abate GHG emissions from agriculture need to be renegotiated periodically to take into account the revised results of research. This study provides multi-disciplinary research on linkages between climate change mitigation and economics of sustainable farm management. Here we use a marginal abatement cost curve and a wedge approach to illustrate the cost and abatement potential of agricultural practices to support practitioners and mitigation policy choices. MACC analysis is particularly useful to prioritize mitigation practices and highlight the trade-offs and synergies between economic and environmental effects. However, cost values may be underestimated and abatement potential can be overestimated due to omission of ancillary costs or benefits and current uncertainty on GHG estimations (Kesicki and Strachan 2011; Ward 2014). Therefore, it is important to communicate the underlying assumptions of MACC for their use in mitigation policy development (Kesicki and Ekins 2012). SOC stabilization wedges are useful to understand that each of the wedges represents an effort beyond what would occur under a no-implementation scenario (Pacala and Socolow, 2004). Information on the barriers to adoption is also provided to contribute to potential policy interventions that encourage the implementation. Our estimates advance the regional understanding on the cost and the abatement that might be achieved by small changes in crop and soil management. It is the first attempt to approach the abatement potential for the cropland sector in a region of Spain (i.e., 1.34MtCO_2e in the Aragon region in NE Spain), and also may be of international interest since it exemplifies a semi-arid region in the Mediterranean that can be generalized to other semi-arid areas with similar conditions. Despite the shortcomings associated to the analysis, we provide an initial indication of potential farming and policy choices to contribute to mitigation policy at European regional level.

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