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Summary

This report focuses on the economic trade-off space between effects on yield and input costs of management measures aimed at enhancing soil organic carbon (SOC) stocks to maintain soil fertility while providing important ecosystem services. An optimising farm level model, ScotFarm, is used to investigate the financial impacts of SOC management measures (e.g., cover crops, zero tillage, minimum tillage and residue management) for groups of farmers in Scotland (UK), Aragon (Spain) and Tuscany (Italy). The sensitivity of model results to effects on crop yields and costs of production is tested for each measure. The findings point to further research needs with respect to the investigated trade-off space, and have implications for agricultural policy design aimed at enhancing SOC stocks under a changing climate.

Key results are:

- Financially, tillage management is the only positive measure for Scottish farms at baseline levels of yield effects and input costs. In the case of farms in Aragon, Spain, fertiliser management, crop rotation and tillage management (in later years) are expected to improve farm margins. The model results suggest that the farm margins of farms in Tuscany, Italy benefit from cover crops (hairy vetch) as well as tillage measures.
- Residue management is expected to have a negative impact on farm margins for both Scottish and Spanish crop farms. The forgone value of straw through its incorporation into the soil and expectations of only moderate yield effects are the main factors explaining this finding.
- The projected maximum positive financial impact of any SOC management measure was highest for crop farms in Aragon, Spain (up to $\pm 20\%$), followed by crop farms in Tuscany, Italy (up to 15%) and Scotland ($< 10\%$). This reflects significant regional differences in the potential of SOC measures to be financially viable.
- Results of the sensitivity analysis in all three case study regions indicate that financial impacts of SOC management measures on farm margins are more sensitive to a change in crop yields than to changes in input costs.
- The robustness of impacts on farm margins differs across SOC management measures in the case study regions. This finding points to a need for a more detailed understanding of local environmental and farm management factors that affect yields and input costs. In the absence of such information being available to farmers, measures such as cover crops in Scotland and Aragon, for example, may be attractive to risk averse farmers. Despite lower projected positive impacts on gross margins compared to alternative SOC management measures, the impact of the cover crop measure on farm margins is relatively robust within the trade-off space between effects on yield and input costs. Given that cover crops can have a considerable impact on increasing SOC stocks, ways to encourage further uptake should be developed.

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1 Introduction

The stocks of Soil Organic Carbon (SOC) interact in a complex manner with soil properties and functions that ultimately affects the provision of ecosystem services (Robinson et al. 2013; Dominati et al. 2010). Management of SOC in arable agricultural systems can affect the productive capacity of land as a final ecosystem service by improving the growth conditions of crops and therefore yields, and by increasing nutrient use efficiency that may affect the amount of fertiliser input required for optimal plant growth (e.g., Luxhøi et al. 2007; Pan et al. 2009). These effects are related to intermediate services that are affected by soil organic matter stocks and flows, including the provision of plant available nutrients, the control of erosion/loss of topsoil, the provision of a platform for (root) growth, the provision of a moisture regime that is suitable for plant growth, levels of biological diversity influencing pest/disease control, and the provision of a habitat for soil-based pollinators (Glenk et al. 2013). Additionally, management of SOC has been associated with a wide range of potentially beneficial (co-) effects, notably the potential to contribute to climate change mitigation via soil-based carbon sequestration, to help improving water quality at catchment level, and to enhance sub-soil and above-soil biodiversity (Freibauer et al. 2004; Feng and Kling 2005; Smith et al. 2007a; Glenk and Colombo 2011).

It has been discussed elsewhere (smartSOIL Deliverable 1.3) how changes in SOC stocks and flows affect the biophysical processes that are at work in providing each of these intermediate services, and ultimately the productive capacity of land. This report focuses on the economic trade-off space related to different SOC management measures and the related nutrient availability and yield effects as two distinct outcomes of changes in the productive capacity of land that directly affect gross margins at the farm level. Both are of great relevance in the context of moving to sustainable agricultural systems that provide food security in the mid- and long term (Kahiluoto et al. 2014), where food demand is expected to increase and substitution of organic fertilisers through inorganic ones may become increasingly challenging (Cordell et al. 2009).

An optimising farm level model, ScotFarm, is used to investigate the financial impacts of SOC measures (e.g., cover crops, zero tillage, minimum tillage and residue management), which have been identified as suitable for arable farms under the conditions in three case study regions (Eastern Scotland; Aragon, Spain; Tuscany, Italy). Impacts of SOC management on nutrient availability and yield effects differ between proposed SOC management measures. Within these management measures and under given environmental conditions, there is also considerable uncertainty regarding their impact on nutrient availability, yield and other impacts on variable costs of farming including pest control and changes in farming operations which are highly dependent on spatial context and farm characteristics (Morris et al. 2010; Rickson et al. 2010). We exploit this expected variation across and within SOC management measures to investigate the sensitivity of uptake and gross margins on assumptions regarding the effectiveness on nutrient availability, yield effects, pest control and farming operations. The main aim is to better understand the farm-level impacts of trade-offs between input

costs, including nutrient availability, and yield effects of SOC management decisions. The information derived via farm-level models for the case study regions should not be used as a predictive tool for policy makers and farmers; rather, we seek to demonstrate important considerations that affect the uptake and profitability of SOC management and that should therefore be carefully evaluated by decision makers on a case-to-case basis.

2 Model structure

A profit maximising farm level model, ScotFarm (Shrestha et. al., 2014), was used on Scottish crop farms which are concentrated mainly on the eastern Scotland. The model has a generic linear programming set up such as:

$$\text{Max } z = (p - c) * x + \text{SFP};$$

subject to $A * x \leq R$ and $x \geq 0$,

where z is farm net margin; x is farm activity; p is a measure of the returns; c are the costs procured for x ; SFP is the farm payment ; A is an input-output coefficient for activity x ; and R is a limiting farm resource.

ScotFarm (Figure 1) assumes that all farmers are profit oriented and maximise farm net income within a set of limiting farm resources. The model consists of arable production which is constrained by the land and labour available to a farm. The total land available to a farm is fixed. but can choose to hire labour if required. The farm net income is comprised of the accumulated revenues collected from the final product of the farm activities and farm payments minus costs incurred for inputs under those activities.

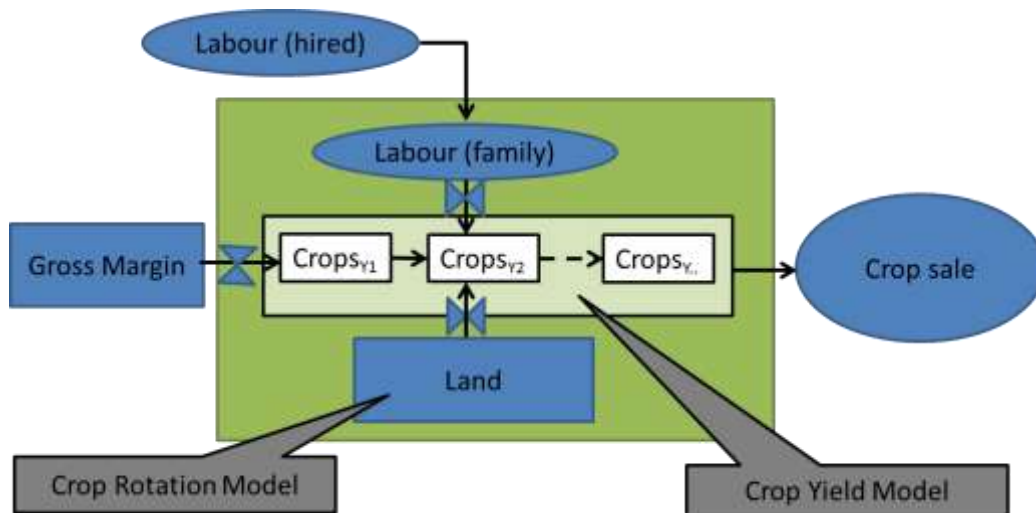


Figure 1: A schematic diagram of the crop component of ScotFarm

In the figure the green rectangle represents a farm with limiting resources of land and labour. The model has the capability to link with external crop models to generate crop yields and follow crop rotation. However, for this study, crop rotation is not used and

crop yields are based on farm survey data. The model considers all major crops in the case study regions. Allocation of land under each crop, in subsequent years, is based on what initial allocation in the first year (taken from the survey data) and gross margins of each crop.

To include the price effect in the results, price indices derived from a partial equilibrium model, FAPRI (DEFRA, 2012), were used for the time period considered in the model. The model runs for a 21 year time frame providing results for each year. Results for the first and last three years are discarded to minimise initial and terminal effects of linear programming. The results for the remaining 15 years are presented in 5-yearly averaged figures for year 2015, 2020 and 2025.

The model is run under a 'baseline' scenario where crop yields and input costs are based on farm survey data and a number of 'soil organic content management' (SOC) scenarios which are different for different case study regions and are described in section 3.1 below. The model results from the SOC management scenarios are then compared with the baseline scenario results to infer the impact of the SOC management measures on farms.

The parameters used for the changes in crop yields and input costs, under the SOC management measures are based on literature and observed data if available, and adjusted using expert knowledge to allow for estimates that better reflect the heterogeneity in environmental condition in the case study regions, and the uncertainty regarding effects of SOC management measures on yield and input costs. This resulted in three sets of parameters for changes in yield effects and input costs. The first reflects average conditions for the case study regions ('Mean'). The other two sets of parameters reflect lower; Ymin for crop yield and Cmin for input costs and upper bounds; Ymax for yield and Cmax for the input costs respectively. For yield effects, the lower bound parameters (Ymin) reflect cases where SOC management measures do not result in substantial gains in yield, or are even associated with a yield decrease. Upper bound parameters (Ymax) imply an optimistic perspective on changes in yield following the implementation of SOC management measures; that is, gains in yield can typically expected and may be substantial for some of the measures. Regarding input costs, all factors affecting costs (e.g., fertiliser requirement; weed and pest control; field operations) are assumed to be at a level that minimises costs for the lower bound parameters (Ymin). This implies, for example, that fertiliser needs and costs of weed and pest control are lower than in the representative case (Mean). The opposite applies to upper bound parameters for input costs (Ymax).

The sensitivity of changes in gross margins to using lower and upper bounds for yield effects and input costs is analysed for all four combinations of minimum and maximum changes in yield effects and input costs. The sensitivity analysis therefore comprises results of possible outcomes under the following four cases:

YmaxCmax, where yield effects and changes in input costs are both assumed to be at a maximum;

YmaxCmin, where yield effects are assumed to be at the upper bound and changes in input costs are at their minimum level;

YminCmax, where yield effects are assumed to be the low and changes in input costs considered to be the highest;

YminCmin, where both yields and input costs are assumed the be at the minimum level of change.

The results demonstrate the relative trade-offs between yield effects and changes in input costs associated with each management measure. This provides important insights into the robustness of SOC management measures to yield positive changes in gross margins.

ScotFarm is an optimising model, hence it should be noted that the results provided by the model is by achieving all farm activities and farm management to the optimal level. The results should be read as the maximum attainable target rather than projected figures for each farm groups.

2.1 Input data

Data used for this study is drawn from the National Farm Survey data for the study regions (for Scotland; NFS, 2010; for Aragon, Spain; Aragon Census (INE, 2009) and MAGRAMA 2011 and for Tuscany, Italy FADN). The data consisted of farm level data (physical as well as financial data) collected from crop farms (135 farms in Scotland, 105 in Aragon). These crop farms were separated into a number of farm groups based on farm size, farm gross margins, labour used and farm subsidies received for each of the study region. Farm variables in each of the group is averaged and used in the model as a representative farm for that farm type. These variables include land use, average crop yields, crop gross margins (derived from revenues collected minus costs of production including labour and machinery) as well as feed crops in farm types where sheep production system is available. The prices and costs are adjusted over the model time frame using FAPRI price indices.

Under the SOC management scenarios, changes in crop yields and input costs for each of the scenarios are incorporated in the model. The parameters for changes in crop yields and input costs under different measures are based on different sources and assumptions as detailed in Section 3.3. Changes in crop margin are associated with the changes in cost elements under each of SOC measures. Crop gross margins are therefore derived from the revenues collected minus costs of production such as cost of sprays (weed and pest control), seed cost, fertiliser cost and other cost related to field operations.

3 SOC management measures

3.1 Description of measures

We draw on McVittie et al. 2014 and Deliverable 2.1 (Wösten and Kuikman 2014) for identifying the SOC management measures considered in the farm-level models, also see Smith et al. (2007b) for a detailed description of agricultural SOC management measures. The selection is based on feasible SOC measures and crop combinations for each of the case study regions based on the observed cropping activities in each region. The selected SOC management measures can be characterized as follows, based on Wösten and Kuikman (2014) and Flynn et al. (2007), with specific reference to potential processes related to carbon sequestration and GHG emission reduction. Table 1 gives an overview of the SOC measures selected for each case study region.

Table 1: SOC measures selected for case study regions

SOC measures	Scotland, UK	Aragon, Spain	Tuscany, Italy
Cover crops (legume)	x	x	x
Cover crops (non-legume)	x	x	
Zero tillage	x	x	x
Minimum tillage	x	x	x
Residue management	x	x	
Fertilisation with animal manures		x	
Optimised fertiliser application		x	
Crop rotations (with legumes)		x	

3.1.1 Cover crops

The provision of temporary vegetative cover between agricultural crops, which is then ploughed into the soil is termed a catch crop or green manure, and winter cover crops are also in this category. These catch crops very efficiently add carbon to soils (Poeplau and Don 2015) and may also extract plant-available N unused by the preceding crop, thereby reducing N₂O emissions and possibly reducing amount of fertiliser N that needs to be added. Cover crops in barley/oat production (Scotland) may require a change from winter to spring crop. This related opportunity cost (see McVittie et al. 2014) has not been considered in the Scottish farm models. The vegetative cover may include legumes or not. Seed mixes with legumes (e.g., clover) have higher cost and differ in fertiliser requirements, but may result in greater SOC gains and yield effects than non-legume seed mixes, although a recent meta-analysis does not find this effect (Poeplau and Don 2015).

3.1.2 Zero tillage

Advances in weed control methods and farm machinery now allow many crops to be grown without tillage (zero tillage or no till). In general, tillage promotes decomposition, reducing soil C stores and increasing emissions of GHGs, through increased aeration, crop residue incorporation into soil, physical breakdown of

residues, and disruption of aggregates protecting SOM. Therefore zero tillage often results in SOC gains.

3.1.3 Reduced tillage

Reduced tillage or conservation tillage can take many forms including ridge tillage, shallow ploughing and rotovation, or scarification of the soil surface. All cause less soil disturbance than conventional deep tillage with a mouldboard plough. Reduced tillage decreases decomposition, increases soil carbon stocks and decreases GHG emissions via decreased aeration and crop residue incorporation. Adopting no-till may also affect emissions of N₂O, but the net effects are inconsistent and not well-quantified globally.

3.1.4 Residue management

Residue incorporation, where stubble, straw or other crop debris is left on the field, and then incorporated when the field is tilled, is used in some areas for water conservation, but also enhances carbon returns to the soil, thereby encouraging carbon sequestration. However, incorporation can increase N₂O emissions and therefore net benefits in terms of climate mitigation may be highest when residues with high N content are removed. Composting these residues and then returning them to the soil may reduce N₂O emissions in relation to incorporation untreated, while retaining benefits in terms of reduced requirements for mineral fertiliser. Therefore three main types of residue management can be distinguished, which have different effects on carbon and nitrogen:

1. Leaving crop residues on the field instead of burning or removal
2. Removal of crop residues
3. Composting of crop residues and returning them to the field

The contribution of crop residues to soil organic matter differs per crop. Crop residues with lots of carbon and little nitrogen are usually less easily broken down than crop residues with relatively less carbon.

3.1.5 Fertilisation with animal manures

Incorporating animal manures to arable land is expected to encourage carbon sequestration, because it increases organic carbon stores and enhances carbon return to the soil. However, an increase in N₂O emissions can be associated with the manure management undertaken (Freibauer et al. 2004). Manure management may imply large infrastructure requirements in terms of improved storage and handling, and add extra cost due to additional demand for labour and fuel (Smith et al. 2007a). In Spain, for example, the low availability of manure on farms and the restrictive legislative requirements for manure management, treatment and transportation (EU Nitrates Directive 91/676/EEC) may limit its use by many farmers (Sánchez et al. 2014).

3.1.6 Optimised fertiliser application

This measure can be subdivided into 3 options: changing fertiliser rates, fertiliser placement / precision farming and fertiliser timing / split application. Being more

efficient in fertiliser application (at the right time of the crop growth and under the most optimal weather and soil conditions) is associated with lower fertiliser rates. Precision farming and placement releases the right amount of fertiliser at the right time and can therefore reduce fertiliser use. A correct timing of fertiliser application, e.g. not under wet conditions which leads to a higher emission, and split applications of N will lower the emission of N_2O . Further, the optimised fertilisation stimulates the plant growth, plant and root biomass and the microbial activity, having a direct impact on SOC (López-Bellido et al. 2010). Particularly, N fertilisation should be managed by site-specific assessment of soil N availability to be able to mitigate atmospheric CO_2 enrichment (Khan et al. 2007). In Mediterranean regions, N fertilisation was found to have a long term effect on SOC dynamics depending to the management applied and the soil water content (Morell et al. 2011a; Álvaro-Fuentes et al. 2012).

3.1.7 Crop rotation (with legumes)

Using crop rotations in the same plot, increases soil carbon stores and requires reduced fertiliser use, thereby reducing nitrous oxide emissions. Inclusion of legumes in a cereal crop rotation has a positive effect on the content and the quality of SOC compared to cereal rotations. In Spain, McVittie et al. (2014) report that this was not considered an appropriate practice in arid areas with precipitation below 350 mm/year. Crop rotations have shown a positive effect over time on SOC sequestration and content in rainfed Mediterranean due to C additions as plant and root biomass, and due to better soil structure (López-Bellido et al. 2010).

3.2 Impacts on SOC content

The SOC management measures can be related with changes in SOC stocks and flows, ultimately providing useful information on effectiveness and potential for adoption/uptake of these measures under varying conditions and assumptions regarding their effect on nutrient availability and yield.

Table 2 lists SOC accumulation rates for the measures identified for the case study regions. Generally, in the literature it has been difficult to find values adjusted for the different climatic and soil conditions in the case study regions; and that are easily comparable due to different sampling depth; for arable crops, changes in SOC up to depth of $\pm 1m$ may be of relevance for plant growth. Also, recent research has found that SOC effects can differ dramatically if changes are based on deeper sampling depths, especially for tillage measures (Baker et al. 2007). Accumulation rates are also sensitive to soil type and their current SOC content. It should be noted, that the rates listed in Table 2 are based on expert knowledge guided by the referenced literature. The values are not directly derived from the literature or a sound empirical database. 'Mean' values reflect 'best estimates'. Because there is a high level of uncertainty regarding effects on SOC, both within and across case study regions and cropping systems, Table 2 also shows lower and upper bound values (Min and Max) that reflect this uncertainty. Given

that SOC accumulation rates as shown in Table 2 are not empirically robust estimates, these numbers should be treated with caution and should only be seen as indicative.

Table 2: SOC accumulation rates for measures in kgC ha⁻¹ yr⁻¹

SOC measures		Mean	Min	Max	Related references
Cover crops (legume)		400	0	800	Smith et al (2008); Lal and Bruce 1999; Steenwerth and Belina 2008; Nieto et al. 2013; Ogle et al, 2005; Poeplau and Don 2015
Cover crops (non-legume)		200	0	400	
Zero tillage		0	-100	100	Smith et al (1997, 1998); Freibauer et al (2004); see also West and Post (2002)
Minimum tillage		0	-100	100	
Residue management	yr 0-20	400	0	800	Powlson et al (2008); Freibauer et al (2004)
	yr 21-25	300	0	600	
Fertilisation with animal manures		200	0	400	Paustian et al. 1997; Smith et al. 1997; Follet 2001; Smith et al. 2008; Freibauer et al. 2004
Optimised fertiliser application		0	0	100	
Crop rotations (with legumes)		400	0	800	Lal and Bruce 1999; Follet 2001; Snyder et al. 2009
					Lal and Bruce 1999; Follet 2001; West and Post 2002; Lal 2004

A basic calculation of the amount of SOC in t ha⁻¹ for a given % SOC content can be made by multiplying % SOC with bulk density and sampling depth. For example, for a typical soil in Scottish arable system (silty clay loam), a bulk density of 1.52 Mg m³ and a sampling depth of 23 cm (although crop roots extend much deeper) this results in an estimated 70 t C ha⁻¹. Over the time frame considered in the farm level models (25 years), the rates in Table 2 imply potential changes in SOC ha⁻¹ as detailed in Table 3. Additionally, a reduction in accumulation rates over time is only assumed for residue management after 20 years. Accumulation may, however, not follow a linear path over time for other SOC measures, too.

Table 3: Potential changes in SOC content (t C ha⁻¹) after 25 years for different SOC management measures

SOC measures	Mean	Min	Max
Cover crops (legume)	10	0	20
Cover crops (non-legume)	5	0	10
Zero tillage	0	-2.5	2.5
Minimum tillage	0	-2.5	2.5
Residue management	9.5	0	19
Fertilisation with animal manures	5	0	10
Optimised fertiliser application	0	0	2.5
Crop rotations (with legumes)	10	0	20

Changes in SOC resulting from the application of the SOC management measures do not directly enter the model. Instead, we assume that SOC changes can affect yield and nutrient availability. This assumption resembles the general structure of the simple SOC model developed in smartSOIL WP1 (Deliverable 1.3; Olesen et al. 2014). Ideally, the

simple SOC model would provide predictions of changes in yield and nutrient availability over time for the management measures under given assumptions, and these outputs would then be used as inputs to the farm level model. However, at the time this report was written the direct link between the SOC model and the farm-level model was not established. In the absence of this link, our analysis will still be useful in that it demonstrates the range of potential impacts of SOC measures on gross margins. These could then be discussed in the light of the processes and conditions that govern yield response and nutrient availability as a result of a change in management practice; and in terms of their effectiveness in enhancing SOC and providing other ecosystem services.

3.3 Impacts on yield, nutrient availability and elements of variable costs

3.3.1 Scotland, UK

The assumed impacts on yield and cost elements are based on literature where possible, but are heavily informed by expert judgment. Table 4 lists the range of yield in t ha⁻¹ for the main crops in Scottish arable systems.

Table 4: Overview on crop yields for main crops in Scottish arable systems

Crop	Mean	Min	Max
Winter wheat	8	6	10
Winter barley	7.5	6	9
Spring barley	5.5	4	7.5
Winter oats	7.5	5	9
Spring oats	5	3.5	6.5

Source: SAC Farm Management Handbook 2013/14 (SAC 2013)

We expect SOC management measures to affect yield as reported in Table 5 below.

Table 5: Percentage (%) change in yield under different SOC measures in t C ha⁻¹ (Scotland)

SOC measures		Mean	Min	Max
Cover crops (legume)		+5	+0	+20
Cover crops (non-legume)		+0	-5	+10
Zero tillage	year 0-9	-5	-20	+5
	year 10-25	+0	-10	+10
Minimum tillage	year 0-9	-2	-10	+10
	year 10-25	+0	-10	+10
Residue management		+0	-10	+10

SOC management measures may allow substitution of organic and/or inorganic fertiliser application due to improved nutrient availability. For example, Carvalho et al (2005) find that for an increase in SOC content from 1% to 2%, up to 62 kg N ha⁻¹ could become available. Regarding effects of SOC measures on nutrient availability, we assume that in years 1-5 following the adoption of a SOC management measure, no substitution of fertiliser through increased availability of nutrients is possible due to immobilisation (Luxhøi et al. 2008); in fact, nutrient availability may temporarily decrease. For the following years, replacement potential is greatest for N fixing cover

crops (e.g., legumes). However, cover crops have also the greatest variation in N substitution possibilities.

Generally, effects on nutrient availability are likely to affect N, P and K availability. It would be interesting to consider impacts of SOC management measures on N, P and K separately. It is likely that at some point in the mid-term future P will become more expensive (i.e., it will become more scarce). This would justify a closer look at N,P,K composition of the residues for the management options and different crops. To consider the effect separately, it would be required to assess N,P,K content and mineralisation dynamics for every plant substrate and management option; and in addition, it would be necessary to differentiate differences in N,P,K content between different crops for residue management and zero/min tillage. However, this would require a series of assumptions that are not necessarily productive in that they would help to generate more accurate or reliable model outcomes, especially since reliable data from field experiments is lacking, and because such a level of detail would not be warranted given the assumptions made on yield impacts and other cost elements. The impact of increasing fertiliser (in particular P) prices could be investigated to some degree through farm level models by making assumptions about an expected increase in fertiliser costs over time.

Given the above, the assumed impacts on nutrient availability as reported in Table 6 refer to overall fertiliser (that is, N,P,K combined), and an average price of £0.7 kg⁻¹ is applied to derive an estimate of the difference that fertiliser substitution would have on gross margins. The value of £0.7 kg⁻¹ results from recommended fertiliser requirements divided by the variable fertiliser costs per ha listed in the SAC Farm Management Handbook 2013/14 (SAC 2013) for the 'mean' yield scenarios. This includes the cost of applying the fertiliser (e.g., in terms of field operations). Of course, there is a possibility that a certain level of replacement due to SOC management measures could result in less operations necessary, but thresholds for this are likely to vary across crop types and farm types and are therefore difficult to establish. For completeness, Table 6 also reports typical N requirements for the different crops, and applications of total N,P,K to crop types related to mean yields as reported in the SAC Farm Management Handbook 2013/14 (SAC 2013).

With respect to weed control and pesticide/fungicide use, we define changes as percentage changes of the different SOC management practices from the mean expenditure on weed control as reported in the SAC Farm Management Handbook 2013/14 (SAC 2013). The values used in the farm level models are reported in Table 7. The impact of SOC management practices on the need for weed control and spraying will depend on environmental factors and management (e.g., crop rotations, presence of and support for antagonist species; allelopathic effects of e.g. rye and vetch). Regarding min or zero tillage, for example, ploughing is supposed to be key to suppressing weeds. Concerns have been raised that min and zero tillage would increase the need for herbicide use (Soane et al. 2012), but not necessarily the use of other pesticides (Jordan et al. 1997). Under certain conditions, cover crops may improve pest control and hence

reduce the need for pest and weed control, but there is a need to better understand insect cycles and pest interactions over time, as well as to understand the impact of different herbicides and pesticides on any potential natural pest control benefits. Our assumption regarding changes in weed control and spraying are relatively conservative. We expect on average a moderate increase for min and zero tillage, but define a 'best' case where cover crops see a small reduction in costs associated with spraying while no change is assumed in the 'best' case for all other SOC management practices.

Table 6: Fertiliser substitution effects (kg ha^{-1}) for SOC measures (upper part) and N requirements and NPK application rates for crop types (lower part) (Scotland)

SOC measures		Mean	Min	Max
Cover crops (legume)		30	50	10
Cover crops (non-legume)		+0	15	-5
Zero tillage	year 1-5	-10	5	-15
	year 6-25	+0	40	-10
Minimum tillage	year 1-5	+0	5	-5
	year 6-25	+0	20	-5
Residue management	year 1-5	-10	5	-15
	year 6-25	5	40	-10
N requirements (TN 651) kg ha^{-1}		Application of total NPK in kg ha^{-1} according to SAC (2013)		
Winter wheat	200	350		
Winter barley	150	330		
Spring barley	110	253		
Winter oats	140	297		
Spring oats	100	257		

Note: Negative values for fertiliser substitution effects reflect an increase in fertiliser needs, which in turn implies a decrease in gross margins entering the farm level model. N requirements for barley assume that $\sim 1/2$ of the crop is produced for malting (i.e., meeting C:N ratio expected by maltsters)

SOC management practices can result in changes in costs for field operations (see e.g. Morris et al. 2010), that is, use of machinery and associated time and fuel costs for ploughing, tillage, seeding and, in case of residue management, bailing of straw. The values used in the farm level models are reported in Table 8, developed using expert judgment and baseline figures for field operations from SAC (2013). Cover crops are assumed to be associated with a slight increase related to the need for seeding and killing of the cover crop (e.g., Pratt et al. 2014). Zero and min tillage are assumed to result in lower costs of ploughing and tillage operations (Morris et al. 2010), and a slight decrease is assumed for residue management (no need for bailing of straw).

Seed costs for establishing a cover crop vary widely depending on the type of cover crop used. We assume seed costs to be $\text{£}80 \text{ ha}^{-1}$ on average if they entail legumes, and $\text{£}80 \text{ ha}^{-1}$ on average if they don't. Seed costs may be as low as $\text{£}20 \text{ ha}^{-1}$ for some rye grass varieties but may be up to $\text{£}120 \text{ ha}^{-1}$ for some legumes. Note that the choice of cover crop (legume or non-legume) can affect the nutrient availability effect (see Table 6 above on fertiliser substitution effects).

Table 7: Percentage (%) changes in weed control and spraying costs for SOC management practices (upper part) and related absolute changes in costs (£ ha⁻¹) for different crops (lower part) (Scotland)

SOC measures	Mean	Min	Max
Cover crops (legume and non-legume)	+ -0	-20	20
Zero tillage	30	+ -0	60
Minimum tillage	20	+ -0	40
Residue management	10	+ -0	20
Spring barley cover crops	0	-11.6	11.6
Spring oats cover crops	0	-10.4	10.4
Winter wheat zero till	38.4	0	76.8
Winter barley zero till	26.4	0	52.8
Spring barley zero till	17.4	0	34.8
Winter oats zero till	18	0	36
Spring oats zero till	15.6	0	31.2
Winter wheat min till	25.6	0	51.2
Winter barley min till	17.6	0	35.2
Spring barley min till	11.6	0	23.2
Winter oats min till	12	0	24
Spring oats min till	10.4	0	20.8
Winter wheat residue management	12.8	0	25.6
Winter barley residue management	8.8	0	17.6
Spring barley residue management	5.8	0	11.6
Winter oats residue management	6	0	12
Spring oats residue management	2	0	10.4

Note: Changes relative to baseline as reported in SAC (2013): winter wheat £128 ha⁻¹; winter barley £88 ha⁻¹; spring barley £58 ha⁻¹; winter oats £60 ha⁻¹; spring oats £52 ha⁻¹

Table 8: Changes in field operation costs (£ ha⁻¹) for SOC management practices (Scotland)

SOC measures	Mean	Min	Max
Cover crops (legume and non-legume)	30	10	50
Zero tillage	-100	-120	-80
Minimum tillage	-80	-100	-60
Residue management	-20	-40	-10

As a final cost element specifically related to residue management is the forgone production value of straw. How straw is used after it is being bailed and hauled depends on local demand for straw within the same farm or as a commodity sold to other users (e.g. livestock farms or biomass plants). We assume that changes in straw production are proportional to yield change. Table 9 reports baseline straw yields, which are multiplied by the expected yield change (equal to 1 if there is no change in yield) and the value of straw in £ t⁻¹ to derive the annual value of the forgone production of straw used in the farm models. The average, minimum and maximum straw yield for the reference case (no SOC measure applied) and values of straw are guided by the SAC Farm Management Handbook 2013/14 (SAC 2013) for the different crops. Values of straw vary from 15 £ t⁻¹ to 65 £ t⁻¹ with an average value of 40 £ t⁻¹.

Table 9: Baseline straw yields (t ha⁻¹) (Scotland)

Crop	Mean	Min	Max
Winter wheat	4.2	3.2	5.2
Winter barley	4.1	3.3	5
Spring barley	2.9	2.1	3.9
Winter oats	4.7	3.2	5.7
Spring oats	3	2.1	3.9

Source: SAC Farm Management Handbook 2013/14 (SAC 2013)

3.3.2 Aragon, Spain

Table 10 lists the range of yield in t ha⁻¹ for the main crops used in the analysis for arable systems in Aragon (Spain).

Table 10: Overview on crop yields for crops in arable systems in Aragon, Spain

Crop	Mean	Min	Max
Wheat (rainfed)	2	1.2	2.7
Wheat (irrigated)	4	3.2	4.5
Barley (rainfed)	2.3	1.1	3.4
Barley (irrigated)	3.7	2.8	4.4
Maize (irrigated)	9.5	8.2	11.9
Alfalfa (irrigated)	15.2	12.1	18.3
Almond (rainfed)	0.5	0.1	0.8
Vineyard (rainfed)	3.3	2.2	4.4
Olives (rainfed)	0.8	0.3	1.1

Source: Spanish Agricultural Census 1999/2011

The expected effects of SOC management measures on yield are reported in Table 11. For cover crop effects, see Gabriel and Quemada (2011). Yield changes due to tillage regime changes draw on Morell et al. (2011b) and Soane et al. (2012). Meijide et al. (2007), Van Alphen and Stoorvogel (2000) and Díaz-Ambrona and Mínguez (2001) were used to guide assumptions on yield effects for fertilisation with animal manures, optimised fertiliser applications and crop rotations, respectively.

Table 11: Percentage (%) change in yield under different SOC measures in t C ha⁻¹ (Aragon)

SOC measures	Mean	Min	Max
Cover crops (legume)	+10	-10	+30
Cover crops (non-legume)	+5	-5	+10
Zero tillage	year 0-9 year 10-25	-5 +40	-20 +20
Minimum tillage	year 0-9 year 10-25	-5 +40	-20 +20
Residue management		-10	+10
Fertilisation with animal manures		+10	+40
Optimised fertiliser application		+3	-30
Crop rotations (with legumes)		+30	+20

Regarding the fertiliser substitution effect of applying SOC measures, Table 12 reports assumptions regarding changes in fertiliser needs and N requirements for the SOC measures and crops in the Aragon, Spain, case study.

Table 12: Fertiliser substitution effects (kg ha⁻¹) for SOC measures (upper part) and N requirements and NPK application rates for crop types (lower part) (Aragon)

SOC measures		Mean	Min	Max
Cover crops (legume)		30	50	10
Cover crops (non-legume)		+0	15	-5
Zero tillage	year 1-5	-5	5	-15
	year 6-25	13	40	-10
Minimum tillage	year 1-5	-5	5	-5
	year 6-25	13	20	-5
Residue management	year 1-5	-10	5	-15
	year 6-25	15	40	-10
Fertilisation with animal manures		+0	+0	+0
Optimised fertiliser application	year 1-5	+0	+0	+0
	year 6-25	28	62	-6
	year 1-5	+0	+0	+0
Crop rotations (with legumes)	year 1-5	+0	+0	+0
	year 6-25	62	74	25
		N requirements kg ha ⁻¹		
		Application of total NPK in kg ha ⁻¹ according to Ministry of Agriculture, Food and Environment, Spain		
Wheat (rainfed)	150	350		
Wheat (irrigated)	200	550		
Barley (rainfed)	100	300		
Barley (irrigated)	150	500		
Maize (irrigated)	300	800		
Alfalfa (irrigated)	30	400		
Almond (rainfed)	80	230		
Vineyard (rainfed)	52	400		
Olives (rainfed)	50	250		

Note: Negative values for fertiliser substitution effects reflect an increase in fertiliser needs, which in turn implies a decrease in gross margins entering the farm level model.

More details on the general mechanism of fertiliser effects following the application of SOC measures are given in section 3.3.1. Regarding SOC measures not considered in the Scottish case study, fertiliser needs for *fertilisation with animal manures* are assumed to remain the same, but if manure is applied to some types of cereals, mineral fertiliser could almost fully be replaced by organic fertiliser (for maize, some mineral fertiliser would need to be added to the organic application). Assumed reductions in fertiliser needs of 23% of the baseline on average for *optimising fertiliser application* draw on Van Alphen and Stoortvogel (2000). For crop rotations (with legumes), it is assumed that fertiliser needs will be reduced by 50% for the average case based on expert judgment. The average price of £0.7 (€0.82) kg⁻¹ fertiliser assumed is the same as in the Scottish case study.

Percentage changes in costs associated with weed and pest control, and implied absolute changes in costs, are reported in Table 13. Percentages are assumed to be

similar to Scottish values, except for min and zero tillage, where the average percentage increase in costs is assumed to be 25% for both measures. For more details regarding impacts of SOC measures on weed control and pesticide/fungicide use, see section 3.3.1.

Table 13: Percentage (%) changes in weed control and spraying costs for SOC management practices (upper part) and related absolute changes in costs (€ ha⁻¹) for different crops (lower part) (Aragon)

SOC measures	Mean	Min	Max
Cover crops (legume and non-legume)	+0	-20	20
Zero tillage	25	+0	50
Minimum tillage	25	+0	50
Residue management	10	+0	20
Fertilisation with animal manures	+0	+0	+0
Optimised fertiliser application	+0	+0	+0
Crop rotations (with legumes)	+0	+0	+0
Cover crop Wheat (rainfed)	+0	-2.8	2.8
Cover crop Wheat (irrigated)	+0	-5.2	5.2
Cover crop Barley (rainfed)	+0	-4	4
Cover crop Barley (irrigated)	+0	-6.4	6.4
Cover crop Maize (irrigated)	+0	-15.6	15.6
Cover crop Almond (rainfed)	+0	-10	10
Cover crop Vineyard (rainfed)	+0	-27.6	27.6
Cover crop Olives (rainfed)	+0	-3.8	3.8
Zero/min till Wheat (rainfed)	3.5	+0	7
Zero/min till Wheat (irrigated)	6.5	+0	13
Zero/min till Barley (rainfed)	5	+0	10
Zero/min till Barley (irrigated)	8	+0	16
Zero/min till Maize (irrigated)	19.5	+0	39
Zero/min till Alfalfa (irrigated)	9	+0	18
Zero/min till Almond (rainfed)	12.5	+0	25
Zero/min till Vineyard (rainfed)	34.5	+0	69
Zero/min till Olives (rainfed)	4.75	+0	9.5
Straw/residue mgmt Wheat (rainfed)	1.4	+0	2.8
Straw/residue mgmt Wheat (irrigated)	2.6	+0	5.2
Straw/residue mgmt Barley (rainfed)	2	+0	4
Straw/residue mgmt Barley (irrigated)	3.2	+0	6.4

Note: Changes relative to baseline: wheat (rainfed) €14 ha⁻¹; wheat (irrigated) €26 ha⁻¹; barley (rainfed) €20 ha⁻¹; barley (irrigated) €32 ha⁻¹; maize (irrigated) €78 ha⁻¹; alfalfa (irrigated) €36 ha⁻¹; almond (rainfed) €50 ha⁻¹; vineyard (rainfed) €138 ha⁻¹; olives (rainfed) €19 ha⁻¹

Changes in field operation costs (including use of machinery and associated time and fuel costs for ploughing, tillage, seeding etc.) for the Aragon, Spain case study are listed in Table 14. In the case of optimised fertiliser application, the cost refers to the cost of performing soil analysis.

Table 14: Changes in field operation costs (€ ha⁻¹) for SOC management practices (Aragon)

SOC measures	Mean	Min	Max
Cover crops (legume and non-legume)	30	10	50
Zero tillage	-10	0	-20
Minimum tillage	-20	-10	-40
Residue management	140	75	200
Fertilisation with animal manures	6	3	10
Optimised fertiliser application	0	0	0
Crop rotations (with legumes)	30	10	50

Costs of procuring seeds for cover crops are assumed to be € 70 ha⁻¹ on average for legumes or legume mixes, and € 30 ha⁻¹ on average for e.g. ryegrass mixes. Seed costs vary between a minimum of € 20 ha⁻¹ and a maximum of € 120 ha⁻¹.

Opportunity costs associated with applying residue management include the income forgone from straw. For Aragon, Spain, baseline straw yields are listed in Table 15. The value of straw is € 35 t⁻¹ on average, ranging from € 25 t⁻¹ to € 45 t⁻¹. Baseline straw yields are multiplied by the expected yield change (Table 11; equal to 1 if there is no change in yield) and the value of straw in € t⁻¹ to derive the annual value of the forgone production of straw used in the farm models.

Table 15: Baseline straw yields (t ha⁻¹) (Aragon)

Crop	Mean	Min	Max
Wheat (rainfed)	4.9	3.9	5.9
Wheat (irrigated)	6.6	5.6	7.6
Barley (rainfed)	5.8	4.8	6.8
Barley (irrigated)	6.2	5.2	7.2

Source: Moragues et al. 2006; Urbano 2002; Francia et al., 2006; Pordesimo et al. 2004; Note: minimum and maximum values are assumed to be ± 1 t ha⁻¹ compared to mean

3.3.3 Tuscany, Italy

To define the inputs for the farm level model for the Tuscany (Italy) case study, information from farm data is used in addition to available agricultural statistics and expert judgment. In particular, field data about yield and SOC content variations, change in costs for fertilisers, pesticides, field operations, and seeds have been collected from a farm located in Ceppaiano (Pisa), which performs conservation measures on arable land for 20 years. In Tuscany, residues are typically either left on the ground or incorporated onto the field. They are not collected for sale (no market) or alternative uses. In this context, costs associated with residue management (i.e., no costs or very low costs) are indirectly included in the cost assumptions of the other practices. Table 16 reports yield in t ha⁻¹ for the main crops in arable systems in Tuscany, Italy.

Table 16: Overview on crop yields for crops in arable systems in Tuscany (Italy)

Crop	Mean	Min	Max
Durum wheat (spring)*	3.29	2.2	4.3
Sunflower	2.01	1	3
Maize	7.64	3.2	9.5
Common wheat **	3.58	2.2	4.5
Barley	3.15	2.4	4.5

Source: ISTAT (http://agri.istat.it/sag_is_pdwout/jsp/NewDownload.jsp?id=15A), average 2007-2011; Note: Mean values averaged over 5 years (2007-2011); * In Italy, all cultivated varieties are spring varieties (i.e. now vernalisation requirements). Nevertheless, they are usually sown in autumn; ** In Italy, both spring and winter varieties are cultivated, but both are usually sown in autumn. Thus, measures are suitable for both winter and spring wheat varieties.

Table 17 summarises expected changes in yield as a result of applying SOC management measures. The cover crop SOC measure focuses on applications of hairy vetch, which is a legume.

Table 17: Percentage (%) change in yield under different SOC measures in t C ha⁻¹ (Tuscany)

SOC measures	Mean	Min	Max
Cover crops (Hairy vetch)	+0	-15	+15
Zero tillage	+13	-2	+28
Minimum tillage	+16	+1	+31

Note: min and max based on expert judgment, +/- 15 % deviation from average

Information on the effect of applying SOC management measures on the N requirements for Tuscany are shown in Table 18. As for Scotland and Aragon, a value of £0.7 (€0.82) kg⁻¹ fertiliser is assumed.

Table 18: Fertiliser substitution effects (kg ha⁻¹) for SOC measures (Tuscany)

SOC measures		Mean	Min	Max
Cover crops (Hairy vetch)		0	0	0
Zero tillage	year 1-5	80.5	92	69
	year 6-25	0	0	0
Minimum tillage	year 1-5	34.25	137	0
	year 6-25	0	0	0

Note: Based on own expertise; Positive values for fertiliser substitution effects reflect decrease in fertiliser needs, which in turn implies an increase in gross margins entering the farm level model.

Table 19: Percentage (%) changes in weed control and spraying costs for SOC management practices (upper part) and associated changes in costs (€ ha⁻¹) for different crops (lower part) (Tuscany)

SOC measures	Mean	Min	Max
Cover crops (Hairy vetch)	-75	-76	-74
Zero tillage	36	-6	54
Minimum tillage	-24	-74	100
Durum wheat Cover Crops	-86.25	-87.4	-85.1
Sunflower Cover Crops	-35.25	-35.72	-34.78
Maize Cover Crops	-22.5	-22.8	-22.2
Common wheat Cover Crops	-86.25	-87.4	-85.1
Barley Cover Crops	-86.25	-87.4	-85.1
Durum wheat Zero till	41.4	-6.9	62.1
Sunflower Zero till	16.92	-2.82	25.38
Maize Zero till	10.8	-1.8	16.2
Common wheat Zero till	41.4	-6.9	62.1
Barley Zero till	41.4	-6.9	62.1
Durum wheat Min till	-27.6	-85.1	115
Sunflower Min till	-11.28	-34.78	47
Maize Min till	-7.2	-22.2	30
Common wheat Min till	-27.6	-85.1	115
Barley Min till	-27.6	-85.1	115

Note: Changes relative to baseline: durum wheat € 115 ha⁻¹; sunflower € 47 ha⁻¹; maize € 30 ha⁻¹; common wheat € 115 ha⁻¹; barley € 115 ha⁻¹ (no data was available to support the baseline pest control cost of barley; the same cost as for common wheat is applied)

Percentage changes in the cost associated with weed and pest control are reported in Table 19. For cover crops, less herbicide sprays are needed due to the presence of the dead mulch of hairy vetch on the soil surface. Regarding zero tillage, glyphosate is necessary for pre-sowing weed control in the absence of tillage. Early post-emergence herbicide cannot be used effectively under zero-till, due to the presence of thick dead mulch on the soil surface. Therefore, a post-emergence herbicide is applied late in the season. Due to the higher weed pressure, two applications of herbicides are needed under minimum tillage.

Changes in costs for field operations used in the farm level models are reported in Table 20. This includes costs related to slug pellets (for cover crop only) and fuel costs.

Seed costs for establishing a hairy vetch cover crop vary from € 50 ha⁻¹ to € 90 ha⁻¹ with an average of € 70 ha⁻¹.

Table 20: Changes in field operation costs (€ ha⁻¹) for SOC management practices (Tuscany)

SOC measures	Mean	Min	Max
Cover crops (Hairy vetch)	-48	-49	-47
Zero tillage	-68	-68	-68
Minimum tillage	-23	-25	-15

3.4 Farm data

3.4.1 Scotland, UK

For Scotland, a cluster analysis based on farm area, family labour and farm payments resulted in three farm clusters or groups; Crop Large, Crop Medium and Crop Small. Farm characteristics of each of the group are shown in Table 21 below. There are four main crops produced on these farms. The average land allocation for these crops in each of the farm groups is also provided in the table.

Table 21: Farm characteristics (Scotland)

Farm type	Grass- land (ha)	Rough grazing land (ha)	Arable land (ha)				Family labour (MU)	Single Farm Payments (£)
			Wheat	Barley	Oats	Oilseed		
Crop Large	178.3	0	104.4	106.1	0	16	7.5	77,258
Crop Medium	86.3	6.9	50.3	130.7	7.4	23.1	2.7	80,350
Crop Small	46.6	5.1	17.6	61.9	3.6	4.2	1.5	34,023

3.4.2 Aragon, Spain

In the Aragon region of Spain, crop farms were separated in three farm groups based on agriculture area and number of holdings. The groups are (similar to Scottish farms); Crop Large (maximum size), Crop Medium (mean size) and Crop Small (minimum size). The characteristics of farms in each of the groups are presented in Table 22 below.

There is a wide variety of crops produced in this region. Land allocated to crops on farms in the different groups is also provided in the table.

Table 22: Farm characteristics (Aragon, Spain)

Farm type	Grass Land	Rough grazing land	Arable land (ha)											Single farm payments (€)
			Total	WR	WI	BR	BI	M	A	AM	V	O	F	
Crop Large	245.4	302.1	254.5	30.3	8.3	49.0	11.2	10.3	10.6	8.5	4.2	5.2	71.2	25,451
Crop Medium	209.8	246.3	172.4	20.5	5.6	33.2	7.6	7.0	7.2	5.8	2.8	3.5	48.2	17,245
Crop Small	10.9	10.2	12.8	1.5	0.4	2.5	0.6	0.5	0.5	0.4	0.2	0.3	3.6	1,278

Note: WR: Wheat (rainfed); WI: Wheat (irrigated); BR: Barley (rainfed); BI: Barley (irrigated); M: Maize; A: Alfalfa; AM: Almond; V: Vineyard; O: Olives; F: Fallow

3.4.3 Tuscany, Italy

In the Tuscany region of Italy, the crop farms were separated in four farm groups based on the economic size of an agricultural holding measured as the total Standard Output (SO) of the holding expressed in Euro. The Standard Output (SO) is the average monetary value of the agricultural output at farm-gate price of each agricultural product (crop or livestock) in a given region. The groups are named as follows; Crop Small (<€25000), Crop Small-Medium (€25000 - €50000), Crop Medium (€50000 - €100000) and Crop Medium-Large (> €100000). The characteristic of farms in each of the group is presented in Table 23 below. There is a wide variety of crops produced in this region (including durum and bread wheat, maize, sunflower, barley, grassland and permanent pastureland, barley, tick-beans). Land allocated to crops on farms in the different groups is also shown in the table.

Table 23: Farm characteristics (Tuscany, Italy)

Farm type	Grass-land (ha)	Arable area (ha)													Family labour (MU)	Single farm payment (€)
		O	DW	BW	M	B	TB	SF	A	T	CP	RS	SP	SO		
Crop Small	9.0	5.4	6.9	4.7	3.2	3.3	3.1	5.5	3.9	0	0	0	0	0	0.96	4,383
Crop Small-Medium	18.1	5.8	14.2	3.4	5.0	3.8	5.5	10.0	7.5	0	0	0	0	0	1.38	23,090
Crop medium	22.0	9.1	23.5	8.2	12.2	7.7	8.3	13.4	10.8	0	0	0	0	0	1.65	48,426
Crop medium-Large	44.2	11.1	33.1	14.7	20.4	9.0	19.1	25.9	13.2	7.2	5.8	18.5	7.4	8.2	1.86	99,127

Note: O: Oats; DW: Durum wheat; BW: Bread wheat; M: Maize; B: Barley; TB: Tick-Bean; SF: Sunflower; A: Alfalfa; T: Triticale; CP: Chickpea; RS: Rapeseed; SP: Spelt; SO: Sorghum

4 Results

4.1 Scotland, UK

As presented in Figure 2, the model results show that all crop farm types benefit financially from both min and zero tillage measures in the long term. For these two measures that crop yields decrease by 5% and 2% respectively for the first 5 years, and increase by 5% in subsequent years. The main benefit arises from savings in input costs associated with tillage. The residue management measure shows the largest negative impact on gross margins (up to -6%) in all three farm groups. Crop yields remain the same under this measure but a substantial loss in straw revenues reduces farm gross margins. Both of the cover crop measures have a small but negative impact (< -3%) across all farm groups.

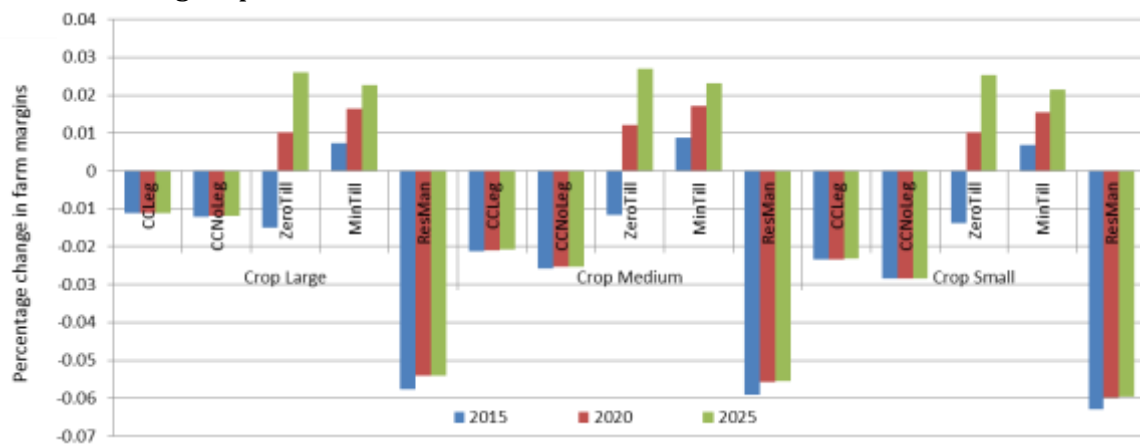


Figure 2: Change in farm gross margin under different SOC options compared to the baseline for Scottish farm groups

The sensitivity analysis (Figure 3) shows that for the Scottish context and most of the SOC management measures assumptions on crop yields affect farm gross margins more than variation in input costs. An exception to this is residue management, where farm gross margins are equally sensitive to assumptions regarding yield effects and changes in input costs (associated in particular with the forgone value of straw). Residue management only achieves a positive impact for upper bound yield effects and lower bound assumptions on input costs. Also, residue management has the potential for considerable reductions in farm gross margins (up to -30%).

There are only small differences between the two cover crop measures across all four scenarios arising mainly from legume cover crops having greater positive yield effects, especially at the upper bound (Ymax), while at the same time seed costs can be considerably higher, reflected in lower farm gross margins than non-legume cover crops in the YminCmax case. The cover crop SOC management measures are overall quite robust to changes in assumptions; i.e., impacts on farm gross margins are in the range of -5% to +5% across the four sensitivity analysis cases. However, cover crop measures lack the potential for substantial positive impacts that are particularly apparent for zero and minimum tillage measures in the YmaxCmin cases (up to 14% increase after 2015).

Minimum tillage performs always better or at least equally well as zero tillage across all time periods, and yield effects are key to both tillage measures to arrive at positive impacts on farm gross margins. Additionally, zero tillage appears to be particularly sensitive to yield effects in earlier years. If zero tillage was to be promoted as a SOC management measure in Scotland, the factors determining yield in early years of implementation need to be understood to increase the probability of less adverse yield effects in the first years. Without this understanding, risk averse farmers aiming to adopt SOC measures would likely opt for minimum tillage. Figure 3 also shows that the patterns of sensitivity found do not differ much across farm types.

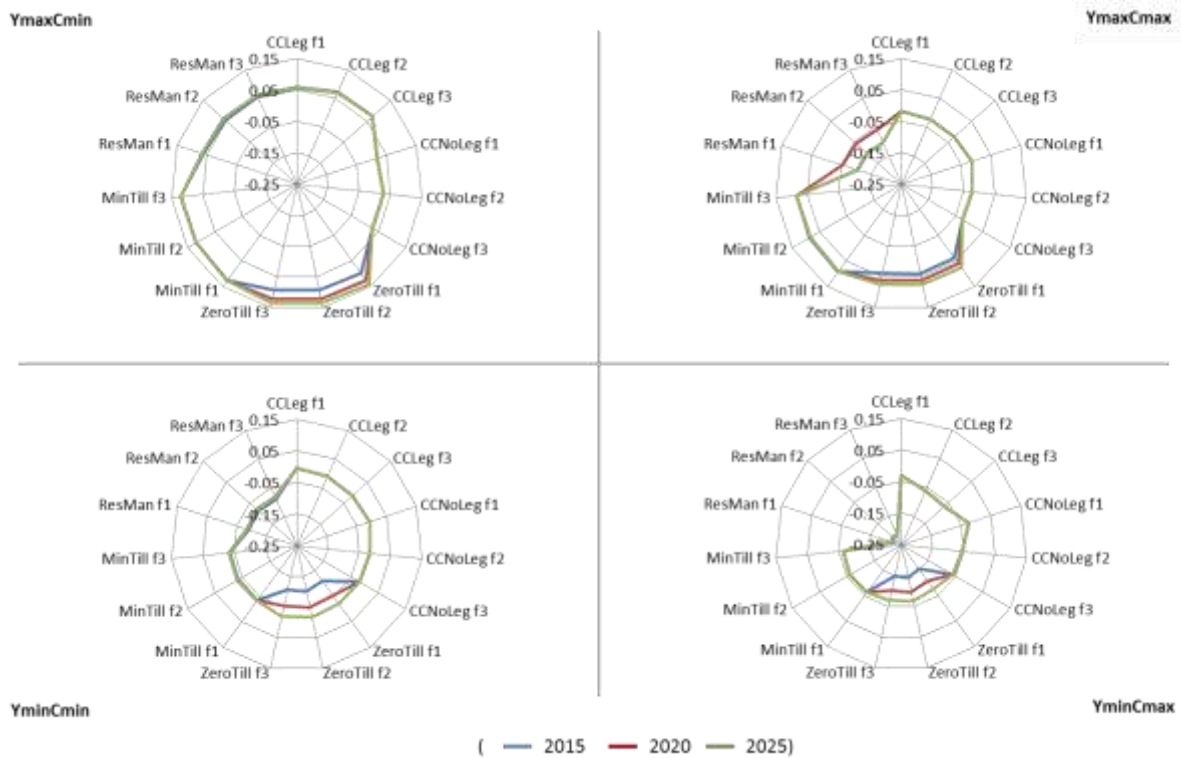


Figure 3: Changes in far gross margin compared to the baseline under sensitivity analysis of crop yield and crop gross margins

4.2 Aragon, Spain

For the Spanish results, it should be mentioned that due to lack of variability between crop yields and corresponding input costs for different SOC management scenarios (except for tillage and residue management scenarios), the model results show only negligible variability between farm types. Therefore, results displayed in Figure 4 and in the following sensitivity analysis apply across all farm types. Since farm gross margins at the baseline differ across farm types in absolute terms, the impact on farm types in absolute terms is discussed below following the sensitivity analysis.

Model results of the Spanish data suggest that all of the SOC measures projected to increase yields of the main crops except for tillage management in earlier time periods and residue management. Tillage management has a slight decrease in yield (5%) in the

first 10 years, but yield increases substantially (40% relative to business as usual) after that. This shows in a 22% and 5% reduction in farm gross margins in first 10 years, but an increase in farm gross margins of 10% by 2025 (Figure 4). There is no change in yields expected for the residue management measure in the baseline scenario, but due to forgone revenue from straw farm gross margins are projected to decrease by up to 4%. There is no substantial change in farm gross margins under both of the cover crop options. The increase in crop yields and increases in input costs almost balance each other out under these management measures. The fertiliser management and the crop rotation measures are projected to improve farm gross margins. Crop yields increase by up to 30% under these measures, largely explaining improved farm gross margins.

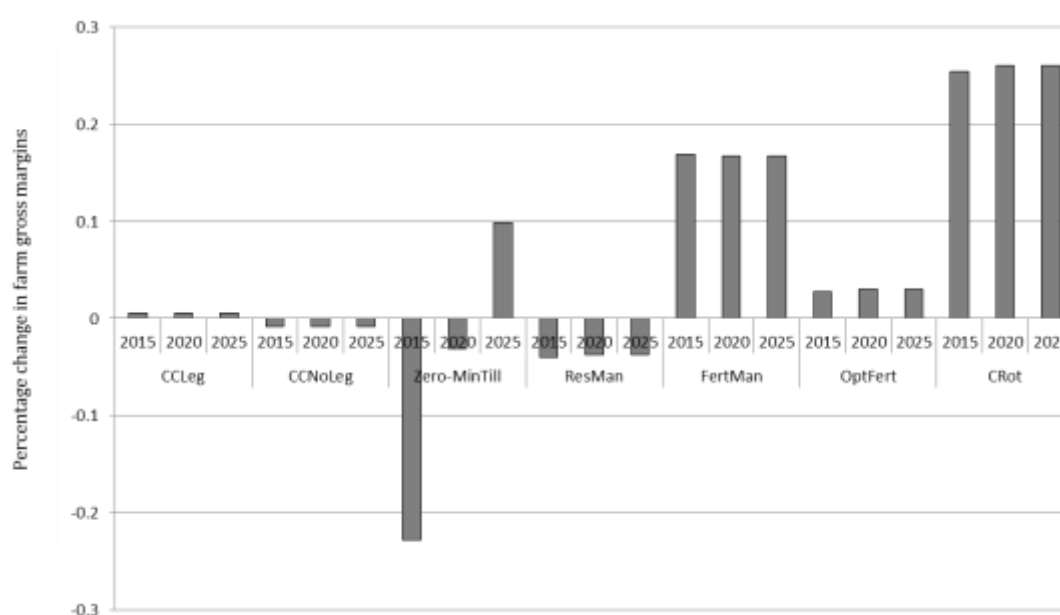


Figure 4: Change in farm gross margin under different SOC options compared to the baseline for on farm in Aragon region of Spain

The sensitivity analysis shows that for the Spanish context, results are more sensitive to changes in crop yields than to changes in input costs, as illustrated in Figure 5 below. All the SOC management measures have a positive impact for the case of upper bound crop yields except for cover crop (non-legume), tillage (by 2015) and residue management measures. Residue management does not show a positive impact in all four sensitivity analysis cases, whereas cover crop (non-legume) and tillage management measures improve farm gross margins when input costs are at the minimum. Fertilisation with animal manures and crop rotation (with legumes) are relatively robust across all four combinations of upper and lower bound estimates for crop yield effects and input costs. This is in contrast with optimised fertiliser application, which in the Ymax cases is only exceeded by the crop rotations measure in its positive impact on farm gross margins of approximately 30%, but which shows the largest negative impact on farm gross margins by 2025 (minus 25%) if yield effects are assumed to be at the lower bound (Ymin).

As stated earlier, the percentage change in farm gross margin is almost similar across all farm types considered in the model. Figure 6 presents the variability in the impact between three farm types in absolute terms. The extent of the impact very much represents the size of the farm: the larger the size of the farm, the greater the absolute change in farm gross margins.

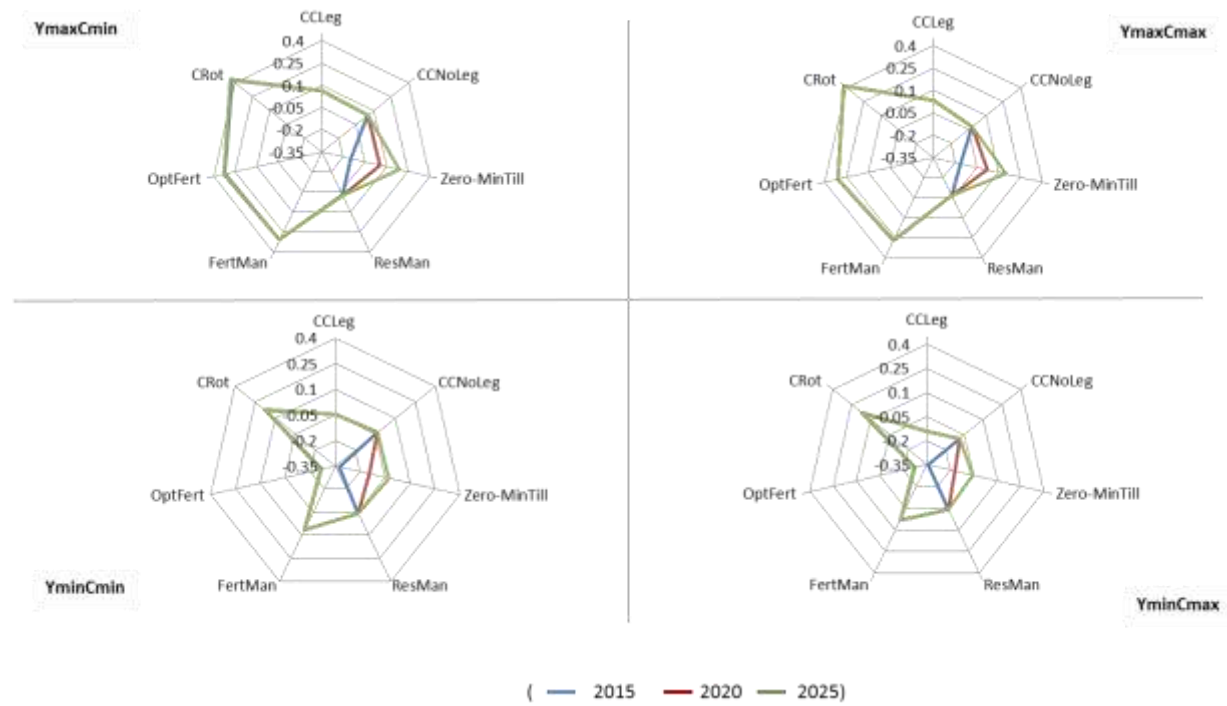


Figure 5: Changes in farm gross margin compared to the baseline under sensitivity analysis of crop yield and crop gross margins on farms in Aragon region of Spain

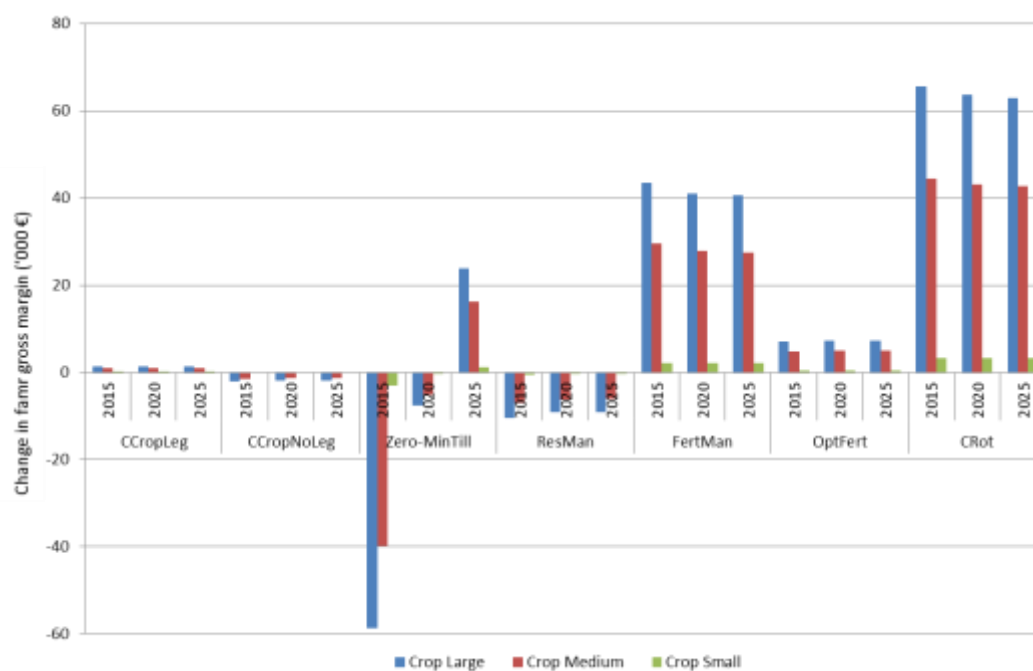


Figure 6: Absolute changes in farm gross margins (GM) compared to the baseline GM for farm groups in Aragon region of Spain

4.3 Tuscany, Italy

The crop farms in Tuscany are projected to improve on farm margins under all three SOC management options considered for this study (Figure 7). The cover crop measure is expected to yield a very small but positive change in farm gross margins, but the tillage management measures are expected to increase their farm gross margins by 12%-17%. There is an increase in crop yields as well as savings on fertiliser, seed and spray under these management measures, all of which have a beneficial impact. There is some variability on relative impact across farm types; however, the differences are very small.

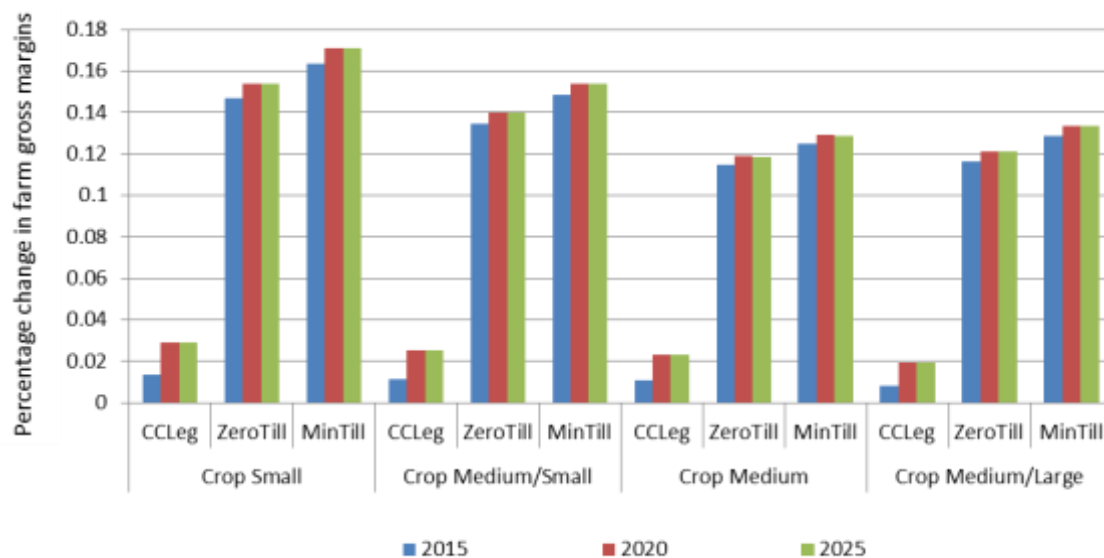


Figure 7: Change in farm gross margin under different SOC options compared to the baseline for Italian farm groups in Tuscany region

Similar to Aragon and Scotland, the sensitivity analysis for the Tuscany case study suggests that crop yields have a larger impact on farm gross margins than changes in assumptions about input costs (Figure 8). The upper bound scenario for crop yield ($Y_{maxCmax}$ and $Y_{maxCmin}$) result in an up to 25% increase in farm margins, while lower bound assumed changes in crop yields ($Y_{minCmax}$ and $Y_{minCmin}$) reduce farm margins by -15%. The impact of changes in input costs on the other hand is small. The overall changes in farm gross margins between $Y_{maxCmin}$ and $Y_{maxCmax}$, as well as between $Y_{minCmin}$ and $Y_{minCmax}$, are less than 5%. While differences are of considerable magnitude when assumptions on yield effects change, changes in farm gross margins remain positive for all management measures except cover crops. This indicates that particular attention should be paid to supporting farmers to prevent negative yield effects resulting from cover crops in order to facilitate and encourage more widespread uptake of this measure.

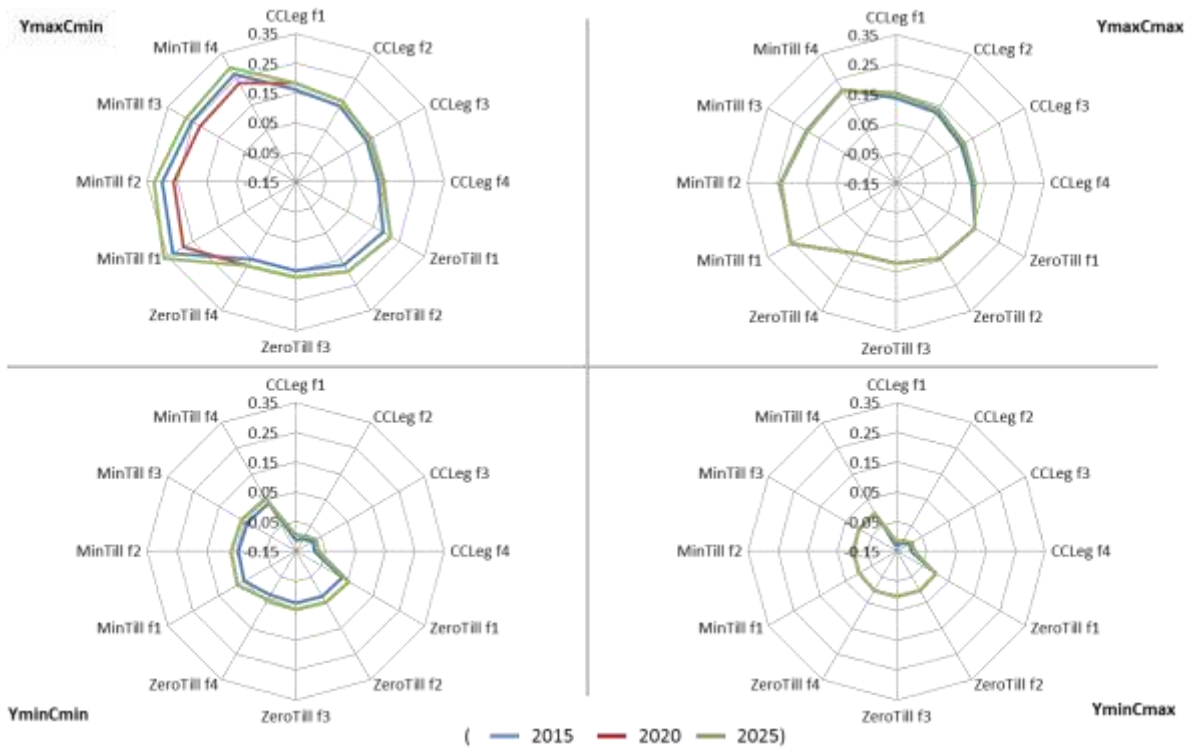


Figure 8: Changes in farm gross margin compared to the baseline under sensitivity analysis of crop yield and crop gross margins on farms in Tuscany region of Italy

5 Conclusions

The projected maximum positive financial impact of any SOC management measure was highest for crop farms in Aragon, Spain (up to $\pm 20\%$), followed by crop farms in Tuscany, Italy (up to 15%) and Scotland ($< 10\%$). This reflects significant regional differences in the potential of SOC measures to be financially viable.

Tillage management is expected to have a positive impact on farm gross margins in all three case study regions. However, there are differences in impact between zero and minimum tillage measures. In Scotland, zero tillage shows positive impacts only in later years (due to a delay in yield effects), whereas initially farm margins decrease. Both zero and minimum tillage are projected to increase farm margins by more than 10% under baseline assumptions for Tuscany, Italy.

Residue management is expected to have a negative impact on farm margins for both Scottish and Spanish crop farms. The forgone value of straw through its incorporation into the soil and expectations of only moderate yield effects are the main factors explaining this finding. In the Aragon, Spain, case study, fertilisation with animal manures and crop rotation (with legumes) are found to have large positive impacts.

The results show that there is limited variability in impacts of SOC measures between different farm types. All of the crop farms are assumed to be on similar soil type and have very similar management practices. The only major difference between the farms is size of farm and scale of production. Our assumption behind the changes in crop

yields and costs of production is generalised across all farm types. A more detailed set of assumptions for each farm type would most probably bring out some variability in the impacts of the SOC management measures on different farm types.

The results of the sensitivity analysis demonstrate the relative robustness of SOC management measures from a financial perspective at the farm level. The information derived from this study should not be used as a predictive tool for policy makers and farmers; rather, we seek to demonstrate important considerations that affect the uptake and profitability of SOC management measures. While these considerations need to be carefully evaluated by decision makers on a case-to-case basis, the results presented in this paper help to identify SOC measures that are most robust to changes in underlying assumptions regarding yield and nutrient availability effects.

Results of the sensitivity analysis in all three case study regions indicate that financial impacts of SOC management measures on farm margins are more sensitive to a change in crop yields than to changes in input costs. Therefore, it may be concluded that effects of SOC management measures on fertiliser requirements (and associated changes in cost) are not making a large difference to farm margins. However, such a conclusion may be premature. It may be important to take a careful look at fertilisation effects (e.g. for cover crops), and to better understand the biophysical relationships that underpin them.

The robustness of impacts on farm margins differs across SOC management measures in the case study regions. This finding points to a need for a more detailed understanding of local environmental and farm management factors that affect yields and input costs. In the absence of such information being available to farmers, measures such as cover crops in Scotland and Aragon, for example, may be attractive to risk averse farmers. Despite lower projected positive impacts on gross margins compared to alternative SOC management measures, the impact of the cover crop measure on farm margins is relatively robust within the trade-off space between effects on yield and input costs. Given that cover crops can have a considerable impact on increasing SOC stocks, ways to encourage further uptake should be developed. Fertilisation with animal manures and crop rotation (with legumes) are found to be promising SOC measures in the Aragon, Spain, case study. Both measures are reported to have considerable potential to increase SOC stocks, and positive impacts on farm margins are found to be relatively robust across all four combinations of upper and lower bound estimates for crop yield effects and input costs. This is in contrast with optimised fertiliser application, which can yield considerable positive estimates, but which is also found to decrease gross margins if yield effects are at their lower bound, therefore making it relatively unattractive to risk averse farmers.

Some important limitations in the analysis presented in this report should be mentioned. SOC management measures may not only affect yields and input costs, for example through fertilisation effects, but also other aspects that affect farm level

economics that were not covered in this study. Anecdotal evidence points to impacts of SOC management measures on, for example, soil structure and workability.

The results do not consider interaction effects between SOC measures, and do not consider the effect of crop rotations. For example, cover crops may be combined with a changed tillage system. Because we consider only variable cost, potential synergies related to, for example, machinery use across various SOC management practices are not considered. It is assumed that a farmer can easily implement the management practices and does not face barriers regarding access to capital and technology (machinery) required for their implementation. This assumption was necessary due to the widely unknown reference conditions in Scottish arable farms. McVittie et al. (2014) report findings from a series of workshops with farm consultants on barriers for uptake of the 4 management measures included in this study. Access to capital or machinery was not identified as a barrier. Sánchez et al. (2014) identify barriers for uptake of agricultural practices, including measures that enhance SOC, based on an econometric analysis of farm surveys in Aragon, Spain. Farmers' environmental concerns, financial incentives and access to technical advice are found to be the main factors defining farmers' barriers to implementation.

The optimisation model is based on farm level data collected for only one year. Therefore, the outcomes rely heavily on the performance of farms in that particular year. This model assumes profit maximising behaviour of farmers. Especially in relation to soil management, farmers' behaviour may also be motivated by other factors such as perceived workability of the soil, or soil health for future generations. The salience of such motivations for improved soil management is, however, unclear and remains an area that needs further investigation. Our results demonstrate the sensitivity of financial gains of SOC management on the farm level to assumptions regarding yield effects and input costs. To some degree, these can be influenced at the farm level, for example through careful weed and pest management following the switch to zero or minimum tillage. Nevertheless, from the farmers' perspective, the actual financial impacts of implementing the SOC management measures is unknown and at least partially dependent on external factors such as weather conditions and market prices. This makes investment into changes in management practices a risky choice. An extension of the model should therefore incorporate an element of risk, for example through the development of probabilistic outcomes for yield effects and costs over the years. This aspect is of interest, because SOC management measures may contribute to yield reliability (that is, to reducing variability in yield) over time, for example by improving the water holding capacity of the soil and therefore the capacity to overcome longer periods of drought. This may become increasingly important in the context of climate change adaptation.

In order to evaluate the SOC management measures from a broader policy perspective, it is important to consider how they perform in terms of changes SOC stocks, especially in areas with low SOC stocks and a high risk of further decline in SOC under the current management regime. This study focused on farm level impacts of SOC management

measures, and related financial performance assessed through farm level modelling to impacts on SOC derived through literature review and expert judgment. Further research should consider linking farm level models with a more detailed SOC model, or the development of regional that optimise the allocation of management measures according to economic and soil management (SOC stocks) objectives.

Further, impacts on greenhouse gas emissions and other co-effects including improvements in water quality and water retention on the field, or biodiversity, should be assessed (Glenk and Colombo 2011). These benefits to the public can play an important role in justifying government support for improved SOC management, for example in the form of financial incentives for farmers. The welfare impacts associated with co-effects can be considerable in magnitude, and may in some cases even provide the primary reason for government intervention.

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7 Appendix

Table A 1: Change in farm gross margin under different SOC options compared to the baseline for Scottish farm groups

	2015						2020					
	Baseline (£)	Percentage change compared to baseline					Baseline (£)	Percentage change compared to baseline				
		CCLeg	CCNoLeg	ZeroTill	MinTill	ResMan		CCLeg	CCNoLeg	ZeroTill	MinTill	ResMan
Crop Large	375,367	- 0.011	-0.012	-0.015	0.007	-0.058	357,016	-0.021	-0.026	-0.012	0.009	-0.059
Crop Medium	294,391	- 0.021	-0.026	-0.012	0.009	-0.059	281,625	-0.021	-0.025	0.012	0.017	-0.056
Crop Small	132,512	- 0.023	-0.028	-0.014	0.007	-0.063	126,684	-0.021	-0.025	0.027	0.023	-0.056

	2025					
	Baseline (£)	Percentage change compared to baseline				
		CCLeg	CCNoLeg	ZeroTill	MinTill	ResMan
Crop Large	354,922	- 0.023	-0.028	-0.014	0.007	-0.063
Crop Medium	280,065	- 0.023	-0.028	0.010	0.015	-0.060
Crop Small	125,968	- 0.023	-0.028	0.025	0.021	-0.060

Table A 2: Changes in far gross margin compared to the baseline under sensitivity analysis of crop yield and crop gross margins

Scenarios	Farm types	Sensitivity analysis cases											
		YmaxCmax			YmaxCmin			YminCmax			YminCmin		
		2015	2020	2025	2015	2020	2025	2015	2020	2025	2015	2020	2025
CCLeg	Crop Large	-0.017	-0.017	-0.016	0.057	0.060	0.059	-0.030	-0.030	-0.030	-0.004	-0.004	-0.004
	Crop Medium	-0.024	-0.024	-0.023	0.070	0.071	0.070	-0.062	-0.062	-0.062	-0.009	-0.009	-0.009
	Crop Small	-0.024	-0.024	-0.024	0.074	0.075	0.074	-0.066	-0.066	-0.066	-0.011	-0.012	-0.012
CCNoLeg	Crop Large	-0.014	-0.014	-0.014	0.019	0.019	0.018	-0.025	-0.025	-0.025	-0.006	-0.006	-0.006
	Crop Medium	-0.024	-0.024	-0.024	0.029	0.029	0.028	-0.055	-0.055	-0.055	-0.016	-0.016	-0.016
	Crop Small	-0.026	-0.026	-0.025	0.029	0.029	0.028	-0.059	-0.060	-0.059	-0.019	-0.019	-0.019
ZeroTill	Crop Large	0.037	0.060	0.075	0.097	0.126	0.142	-0.155	-0.106	-0.076	-0.109	-0.054	-0.021
	Crop Medium	0.039	0.061	0.075	0.092	0.120	0.135	-0.142	-0.097	-0.068	-0.102	-0.049	-0.018
	Crop Small	0.038	0.060	0.075	0.092	0.120	0.136	-0.147	-0.100	-0.071	-0.106	-0.053	-0.021
MinTill	Crop Large	0.092	0.091	0.091	0.126	0.127	0.127	-0.064	-0.063	-0.063	-0.036	-0.033	-0.033
	Crop Medium	0.086	0.084	0.084	0.120	0.121	0.120	-0.061	-0.060	-0.060	-0.033	-0.030	-0.030
	Crop Small	0.085	0.084	0.084	0.120	0.121	0.120	-0.064	-0.064	-0.064	-0.036	-0.033	-0.033
ResMan	Crop Large	-0.104	-0.054	-0.101	0.062	0.068	0.068	-0.225	-0.220	-0.220	-0.089	-0.082	-0.082
	Crop Medium	-0.104	-0.056	-0.103	0.056	0.062	0.062	-0.216	-0.213	-0.213	-0.085	-0.078	-0.078
	Crop Small	-0.105	-0.060	-0.104	0.055	0.061	0.061	-0.220	-0.218	-0.217	-0.089	-0.082	-0.082

Table A 3: Change in farm gross margin under different SOC options compared to the baseline for on farm in Aragon region of Spain

Scenarios	Percentage change compared to baseline		
	2015	2020	2025
CCLeg	0.005	0.005	0.005
CCNoLeg	-0.008	-0.008	-0.008
Zero-MinTill	-0.227	-0.031	0.099
ResMan	-0.040	-0.038	-0.038
FertMan	0.169	0.168	0.167
OptFert	0.027	0.030	0.030
CRot	0.254	0.260	0.260

Table A 4: Change in farm gross margin compared to the baseline under sensitivity analysis of crop yield and crop gross margins on farms in Aragon region of Spain

Scenarios	Sensitivity analysis cases											
	YmaxCmax			YmaxCmin			YminCmax			YminCmin		
	2015	2020	2025	2015	2020	2025	2015	2020	2025	2015	2020	2025
CCLeg	0.035	0.035	0.035	0.064	0.064	0.064	-0.142	-0.141	-0.141	-0.045	-0.045	-0.045
CCNoLeg	-0.017	-0.017	-0.017	0.049	0.049	0.049	-0.088	-0.087	-0.087	-0.031	-0.031	-0.031
Zero-MinTill	-0.165	0.024	0.151	-0.146	0.056	0.187	-0.341	-0.171	-0.058	-0.326	-0.146	-0.029
ResMan	-0.064	-0.063	-0.063	-0.029	-0.025	-0.025	-0.043	-0.042	-0.042	-0.042	-0.039	-0.039
FertMan	0.270	0.268	0.268	0.309	0.307	0.307	0.034	0.034	0.034	0.065	0.064	0.064
OptFert	0.312	0.309	0.309	0.320	0.326	0.325	-0.272	-0.271	-0.271	-0.268	-0.262	-0.262
CRot	0.422	0.424	0.423	0.427	0.437	0.437	0.168	0.170	0.170	0.171	0.179	0.179

Table A 5: Farm gross margins (GM) in the baseline and SOC scenarios for farm groups in the Aragon region of Spain

Farm type	Baseline			CoverCropLegume			CoverCropNoLegume			Till		
	2015	2020	2025	2015	2020	2025	2015	2020	2025	2015	2020	2025
Crop Large	258,189	244,422	242,377	259,582	245,737	243,679	256,071	242,433	240,406	199,457	236,879	266,255
Crop Medium	174,938	165,610	164,225	175,882	166,502	165,107	173,504	164,263	162,890	135,144	160,500	180,404
Crop Small	12,964	12,272	12,170	13,034	12,338	12,235	12,857	12,172	12,071	10,015	11,894	13,369

	ResidueMan			FertMan			OptFert			Rotation		
	2015	2020	2025	2015	2020	2025	2015	2020	2025	2015	2020	2025
Crop Large	247,783	235,235	233,271	301,699	285,375	282,942	265,258	251,750	249,638	323,771	308,015	305,379
Crop Medium	167,888	159,386	158,055	204,419	193,359	191,710	179,728	170,576	169,145	219,374	208,699	206,913
Crop Small	12,441	11,811	11,712	15,148	14,329	14,206	13,319	12,640	12,534	16,256	15,465	15,333

Table A 6: Change in farm gross margin under different SOC options compared to the baseline for Italian farm groups in the Tuscany region

	2015				2020				2025			
	Baseline (£)	Percentage change compared to baseline			Baseline (£)	Percentage change compared to baseline			Baseline (£)	Percentage change compared to baseline		
		CCLeg	ZeroTill	MinTill		CCLeg	ZeroTill	MinTill		CCLeg	ZeroTill	MinTill
Crop Small	86,935	0.014	0.147	0.164	82,055	0.029	0.154	0.171	81,329	0.029	0.154	0.171
Crop Medium/Small	160,271	0.012	0.135	0.149	152,173	0.025	0.140	0.154	150,962	0.025	0.140	0.154
Crop Medium	179,675	0.011	0.115	0.125	171,920	0.023	0.119	0.129	170,764	0.023	0.119	0.129
Crop Medium/Large	470,130	0.008	0.117	0.129	448,244	0.020	0.121	0.134	444,964	0.020	0.121	0.133

Table A 7: Changes in farm gross margin compared to the baseline under sensitivity analysis of crop yield and crop gross margins on farms in Tuscany, Italy

		Sensitivity analysis cases											
Scenarios	Farm types	YmaxCmax			YmaxCmin			YminCmax			YminCmin		
		2010	2015	2020	2010	2015	2020	2010	2015	2020	2010	2015	2020
CCLeg	Crop Small	0.136	0.151	0.151	0.161	0.181	0.181	-0.131	-0.119	-0.119	-0.112	-0.096	-0.096
	Crop Medium/Small	0.124	0.136	0.136	0.147	0.164	0.163	-0.120	-0.109	-0.109	-0.104	-0.089	-0.089
	Crop Medium	0.104	0.115	0.114	0.125	0.139	0.139	-0.101	-0.090	-0.090	-0.085	-0.072	-0.072
	Crop Medium/Large	0.104	0.116	0.116	0.126	0.142	0.142	-0.101	-0.091	-0.091	-0.087	-0.075	-0.075
ZeroTill	Crop Small	0.157	0.156	0.156	0.188	0.218	0.218	0.002	0.002	0.002	0.030	0.055	0.055
	Crop Medium/Small	0.144	0.143	0.142	0.172	0.198	0.197	0.003	0.003	0.003	0.026	0.049	0.049
	Crop Medium	0.122	0.120	0.120	0.147	0.170	0.169	0.003	0.003	0.003	0.025	0.046	0.045
	Crop Medium/Large	0.125	0.123	0.123	0.151	0.176	0.175	0.002	0.002	0.002	0.021	0.040	0.040
MinTill	Crop Small	0.259	0.259	0.258	0.329	0.286	0.363	-0.003	-0.003	-0.003	0.051	0.077	0.077
	Crop Medium/Small	0.239	0.237	0.237	0.300	0.261	0.328	-0.002	-0.001	-0.001	0.045	0.069	0.069
	Crop Medium	0.200	0.196	0.196	0.255	0.223	0.278	-0.002	-0.002	-0.002	0.041	0.061	0.061
	Crop Medium/Large	0.212	0.209	0.209	0.269	0.235	0.294	0.000	0.000	0.000	0.036	0.056	0.056