A farm level approach to explore economic trade offs of soil organic carbon management in Scottish crop farms

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Abstract

This paper 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 dynamic farm level model, ScotFarm, was used to investigate the financial impacts of 4 SOC management measures (cover crops, zero tillage, minimum tillage and residue management) for three groups of Scottish crop farms. A sensitivity analysis was carried out to test the robustness of the model results on crop yields and costs of production for each measure. The results suggest that financially, tillage management is the only positive measure for Scottish farms at baseline levels of yield effects and input costs. Residue management is expected to have a negative impact on farm margins for the farms. The projected maximum positive financial impact was less than 10%. Results of the sensitivity analysis 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 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.

Keywords

Soil Organic Carbon, Farm level modeling, Scottish crop farms, SOC management measures

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 et al. 2011).

This paper 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 the SOC measures (namely cover crops, zero tillage, minimum tillage and residue management), which have been identified as suitable for arable farms under Scottish conditions. 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.

2. Data

2.1 SOC management measures

The SOC management measures for Eastern Scotland considered for the modelling include cover crops, zero and minimum tillage, and residue management, in particular incorporation of straw (see Smith et al. (2007b) for a detailed description of agricultural SOC management measures). Cover crops refer to the provision of a vegetative winter cover between crops, which is then ploughed into the soil. These cover crops add carbon to soils and may also extract plant-available N unused by the preceding crop, thereby reducing N2O emissions and possibly reducing amount of fertilizer N that needs to be added. In Scotland, cover crops in barley/oats production may require a change from winter to spring crop. 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 SOC stores and increasing emissions of greenhouse gases. Therefore, zero tillage often results in SOC gain. Minimum tillage can take many forms including ridge tillage, shallow ploughing and rotovation. All cause less soil disturbance than conventional deep tillage.

Reduced tillage increases SOC stocks and decreases greenhouse gas emissions through decreased aeration and crop residue incorporation. Adopting zero tillage may also affect emissions of N2O, but the net effects are inconsistent and not well-quantified globally. Regarding residue management, we consider the incorporation of straw when the field is tilled. This 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.

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 1 reports SOC accumulation rates for the measures identified for Scotland.

Table 1

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. Even in the absence of a direct link to an underlying SOC model, our analysis will 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.

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

This section describes expectations regarding the effect of SOC management measures on yield, nutrient availability and a range of variable costs associated with implementing the measures. Table 2 lists the yield ranges in t ha^{-1} for the main crops in Scottish arable systems, which serve as a baseline.

Table 2

We expect SOC management measures to affect yield as reported in Table 3 below. The yield changes are based on available on field experiments. However, because this literature is often applicable to very specific local conditions, the ranges were defined using expert judgment.

Table 3

SOC management measures may allow substitution of organic and/or inorganic fertiliser application due to improved nutrient availability. For example, Carvalho et al (2012) find that for an increase in SOC content from 1% to 2% under long-term minimum tillage conditions, 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. The assumed impacts on nutrient availability as reported in Table 4 refer to overall fertiliser (that is, N,P,K combined), and an average price of £0.7 kg^{-1} (SRUC 2014) is applied to derive at an estimate of the difference that fertiliser substitution would have on gross margins.

Table 4

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. The values used in the farm level model are reported in Table 5. 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 a key to suppressing weeds. Concerns have been raised that min and zero tillage would increase the need for herbicide use for weed control (Soane et al. 2012), but not necessarily the use of other pesticides (Jordan et al. 1997). Under certain conditions, cover crops may even improve pest control, but there is a need to better understand insect cycles and pest interactions over time. 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 for all SOC management practices.

Table 5

SOC management practices can result in changes in costs for field operations (McVittie 2014), 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 model are reported in Table 6. Cover crops are assumed to be associated with a slight increase related to the need for seeding and killing of the cover crop. Zero and minimum 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).

Table 6

Seed costs for establishing a cover crop vary widely depending on the type of cover crop used. We assume seed costs to be £70 ha^{-1} on average, ranging between £20 ha^{-1} for some rye grass varieties to £120 ha^{-1} for some legumes. Note that the choice of cover crop (legume or non-legume) can affect the nutrient availability effect. Given the lack of reliable information on this influence this report does not specifically weight the nutrient effect by the type of cover crop used. However, there is an implicit relationship between cheaper cover crops (typically non-legume) and lower fertilisation rates, and vice versa, in the low and high cost scenarios used for the farm level models.

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). It is assumed that straw production is proportional to yield change. Average, minimum and maximum absolute values are defined for the different crops as shown in Table 7.

Table 7

3. Methodology

3.1 Farm level Modelling

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;

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

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

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 per ha; A is an input-output coefficient for activity x; and R is a limiting farm resource.

ScotFarm assumes that all farmers are profit oriented and maximise farm net income within a set of limiting farm resources. The model consists of two production systems; arable and sheep production (as many crop farms also keep sheep especially on permanent pasture). These systems are constrained by the land, labour, feed and stock replacement available to a farm. The total land available to a farm is fixed. Farms are allowed to buy in feeds, ewe replacements and hire labour if required. The farm net income is comprised of the accumulated revenues collected from the final product of the farm activities (crops and lambs) and farm payments minus costs incurred for inputs under those activities.

Figure 1

A schematic diagram of the crop component of ScotFarm is provided in Figure 1. In the figure the green rectangle is a farm with limiting resources of land and labour. The model has 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 consists of all the major crops in Scotland. Allocation of land under each crop, in subsequent years, is based on what they grow in the first year (taken from the survey data) and gross margin of the crop. A part of cereal crops go to livestock module as feed crop and rest are sold in the market. The amount of feed crop produced is based on the requirements of animals and prices of other feed in the market.

To include the price effect in the results, price indices derived from a partial equilibrium model, FAPRI (DEFRA, 2012), were used for the time frame in the model. The model runs for 26 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 20 years are presented in 5-yearly averaged figures for year 2010, 2015, 2020 and 2025.

The model is run under 5 scenarios; S1, the baseline scenario where crop yields and crop gross margins are based on farm survey data and the SOC measures scenarios as S2, the cover crops, S3, the zero tillage, S4, the minimum tillage and S5, the residue management scenarios where crop yields and gross margins are assumed to be under corresponding SOC measures implemented on farms. The model results from the SOC measures scenarios are then compared with the baseline scenario results to analyse the impact of those measures on farms.

The parameters used for the changes in crop yields and crop gross margins under the SOC measures are generated either from different literatures or expert knowledge. It is univocal to say that these changes would have a wide range of variability based on other external parameters such as spatial, physical, management etc. Additional model runs are carried out to explore the uncertainty of changes assumed on yields and gross margins under the SOC measure scenarios. In the SOC measure scenarios listed above, a mean of changes to crop yields and gross margins is used in the model. Because of the possible uncertainty of these changes, a range of a maximum and minimum is provided under each of the SOC measures (Table 3-5). The sensitivity analysis for this uncertainty represents all 4 possible outcomes; i) MaxMax, where yields and input costs are both assumed to be at maximum, ii) MaxMin, where yields are assumed to attend the maximum but input costs are at the minimum level, iii) MinMax, where yields are assumed to be the lowest but input costs considered to be the highest, and iv) MinMin, where both yields and input costs are assumed the be at the minimum level of change.

3.2 Input data

Data used for this study is drawn from the Scottish Farm Survey data, 2010. It consists of farm level data (physical as well as financial data) collected from 135 crop farms. These crop farms were subjected to a cluster analysis to group farms together based on farm size, farm gross margins, labour used and farm subsidies received. 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 scenarios, changes in crop yields and crop gross margins for each of the scenario are incorporated in the model. The parameters for changes in crop yields and gross margins under different measures are based on different sources and assumptions as detailed in section 2.3. 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 control and pesticide), seed cost, fertiliser cost and other cost related to field operation.

4. Results

The cluster analysis resulted in three crop farm types which are designated as Crop Large, Crop Medium and Crop Small farm groups. Some of the major characteristics of these farm groups are shown in Table 8. The scale of land and level of production is the major difference between these farm groups although all of the farms follow almost similar management practices such as the proportion of arable area under major crops.

Table 8

The model results show that all crop farm types benefit financially under both of the tillage managed measures except for first 5 years under zero tillage scenario (Figure 2). In these two tillage measures, crop yields decreases 5% and 2% respectively for first 5 years and increased by 5% in subsequent years after that. The main benefit comes from savings in input costs by reducing the costs of tillage in these measures and farms benefit the most after year 2020.

Figure 2

The residue management measure shows the largest negative impact on all three farm types. The crop yields remain the same under this measure but a substantial loss to straw revenues led to a decrease up to 8% in farm gross margins for farms. There is a slight improvement in farm margins after 2015 when the effect of substituting inorganic fertilizer comes into act and reduces costs to some extent. The cover crop measure has a very small but negative impact on all farm types with small and medium crop farms having slightly more reductions compared to the large crop farms. As under residue management scenario, farms also improve their margins slightly when inorganic fertiliser substitution effect lowers the costs of production after 2015. The results in general show similar impact of SOC measures on all three crop farm groups suggesting that there is not a large variability in management practices between farm groups under these SOC measures.

Figure 3

Under the sensitivity analysis, four combinations of maximum and minimum changes for each of the SOC measures are considered and results are presented in Figure 3 below. The graphs shown in the figure suggest that the SOC measures are sensitive to changes in yields and gross margin. The MaxMin option is the most optimistic option used in this analysis and all SOC measures show improvement to the farm gross margins as is expected. The cover crop scenario provides the highest improvement of up to 18% increase after 2015 when the yields are at maximum and costs at the minimum. On the other hand, MinMax is the most pessimistic option under this analysis where all SOC measures show a reduction in farm gross margins. Zero tillage and Minimum tillage show the highest reduction in farm margin under this option. Although these low tillage measures still save costs of tillage under this option, the reduction in yield is the highest (up to 20% reduction) under these measures which affected overall farm gross margins.

5. Discussion and conclusions

The model result show the zero tillage SOC measure can be the most beneficial for the Scottish crop farms as it improves the farms financially especially after a small reduction in first five years. Under this measure, both of the positive aspects (increase in crop yields and decrease in costs of production) suggest it to be suitable under Scottish conditions. With regards to SOC, this measure is also on par to the cover crops measure in accumulating SOC over next 25 years. On the other hand, the residue management measure is associated with the largest change in SOC but leads to the highest decrease in farm margins. However, the sensitivity analysis shows that the cover crop measure is the most robust SOC measure as it shows potential for considerable benefits under the optimistic option of high yield and low costs, but also has the lowest reduction under the pessimistic option of low yield and high costs. Zero tillage, the best performer under the baseline scenario, has the highest decrease in farm margins when the low yield and high input costs are assumed.

Before concluding, it is necessary to point to some important limitations in the analysis presented in this paper. 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.

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 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.

The results also show that there is no variability in impacts of SOC measures except for the scale of impact between different farm types. All of the crop farms are concentrated in the eastern coast of Scotland, hence 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 assumption for each farm type would most probably bring out some variability on the impacts of these measures on different farm types.

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. 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.

The results 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.

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Table 1: SOC accumulation rates for measures in kgC ha^{-1} yr^{-1}

SOC measures		Mean	Min	Max	Relevant references (selection)
Cover crops		300	-200	1000	Some seed mix with legumes or clover; follows Smith et al (2008)
Zero tillage		300	100	600	Smith et al (1997): 0.73% yearly increase in SOC; Freibauer et al. (2004) 0.3+-0.1 tC ha^{-1} yr^{-1}; see also West and Post (2002)
Minimum tillage		100	-100	300	Ball et al. (1994) for Scotland: 510 kgC ha^{-1} yr^{-1}; Arrouyays et al (2002) 0.21 t C ha^{-1} yr^{-1} for France; Bhogal et al (2007) 340 kg C ha^{-1} yr^{-1} for England (top 30cm); Sun et al. (2010) (Scotland) zero for top 60 cm
Residue management	year 0-20	460	115 (-75%)	805 (+75%)	Powlson et al (2008): addition of cereal straw containing 1.7 t C ha^{-1} yr^{-1}, sampling depth 23cm, calculated with RothC; Min and Max as 75% (indicated as >50% uncertainty in Freibauer et al (2004))
	year 21-25	180	45 (-75%)	315 (+75%)	

Table 2: 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: SRUC Farm Management Handbook 2013/14 (SRUC 2014)

Table 3: Percentage (%) change in yield under different SOC measures

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

Table 4: Fertiliser substitution effects (kg ha^{-1}) for SOC measures (upper part) and N requirements

SOC measures		Mean	Min	Max
Cover crops	year 1-5	0	0	0
	year 6-25	70	20	120
Zero tillage	year 1-5	0	0	0
	year 6-25	30	10	50
Minimum tillage	year 1-5	0	0	0
	year 6-25	20	10	30
Residue management	year 1-5	0	0	0
	year 6-25	30	10	60

Table 5: Percentage (%) changes in weed control and spraying costs for SOC management practices (upper part)

SOC measures	Mean	Min	Max
Cover crops	0	-20	20
Zero tillage	30	0	60
Minimum tillage	20	0	40
Residue management	0	0	20

Table 6: Changes in field operation costs (£ ha^{-1}) for SOC management practices

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

Table 7: Reference values to estimate value of straw for residue management (£ ha^{-1})

Crop	Mean	Min	Max
Winter wheat	208	160	260
Winter barley	207	165	248
Spring barley	143	104	195
Winter oats	237	158	284
Spring oats	150	105	195

Source: SRUC Farm Management Handbook 2013/14 (SRUC 2014) with straw valued £50 t^{-1}

Table 8: Some of the main characteristics of three crop farm groups

Farm Type	Arable land	Grass land	Family labour	Farm payments	Barely		Wheat		Others
	ha	ha	LU	£	Area (ha)	Yield (t/ha)	Area (ha)	Yield (t/ha)	Area (ha)
Crop Large	230	179	7.5	86,974	107	6.4	105	9.2	18
Crop Medium	218	87	2.7	81,131	130	6.5	50	8.5	38
Crop Small	89	47	1.5	34,322	62	5.8	18	8.1	9

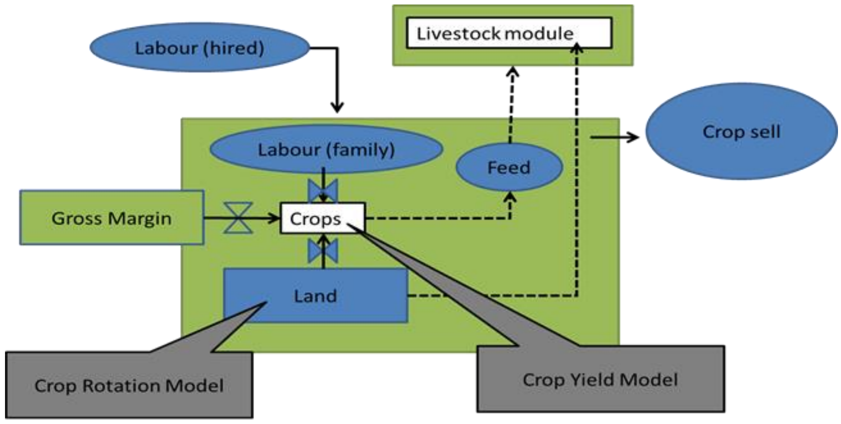

Figure 1: A schematic diagram of crop component of ScotFarm

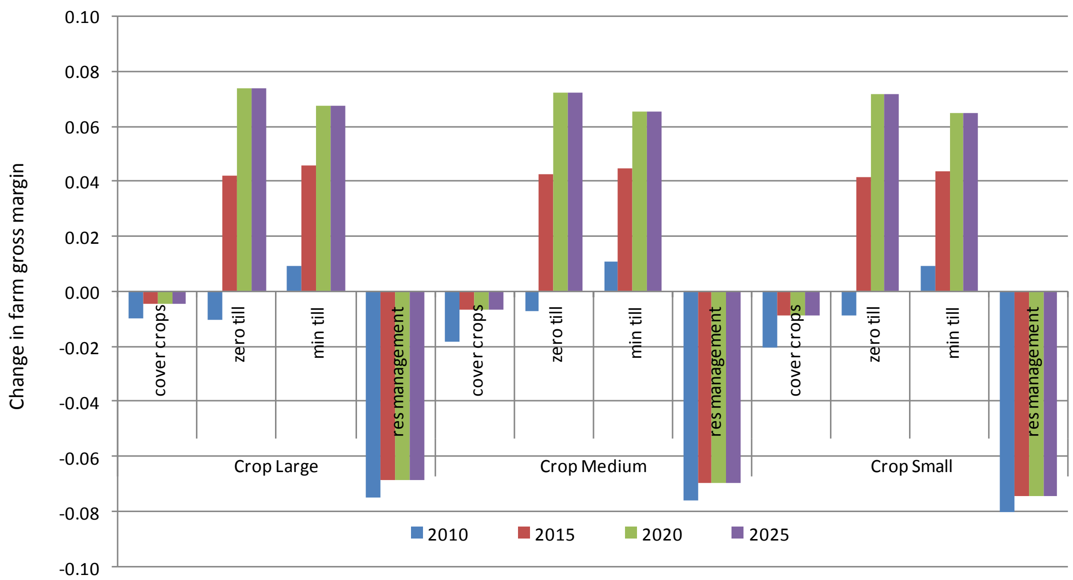

Figure 2: Change in farm gross margins in different farm types under SOC measures scenarios compared to the baseline scenario

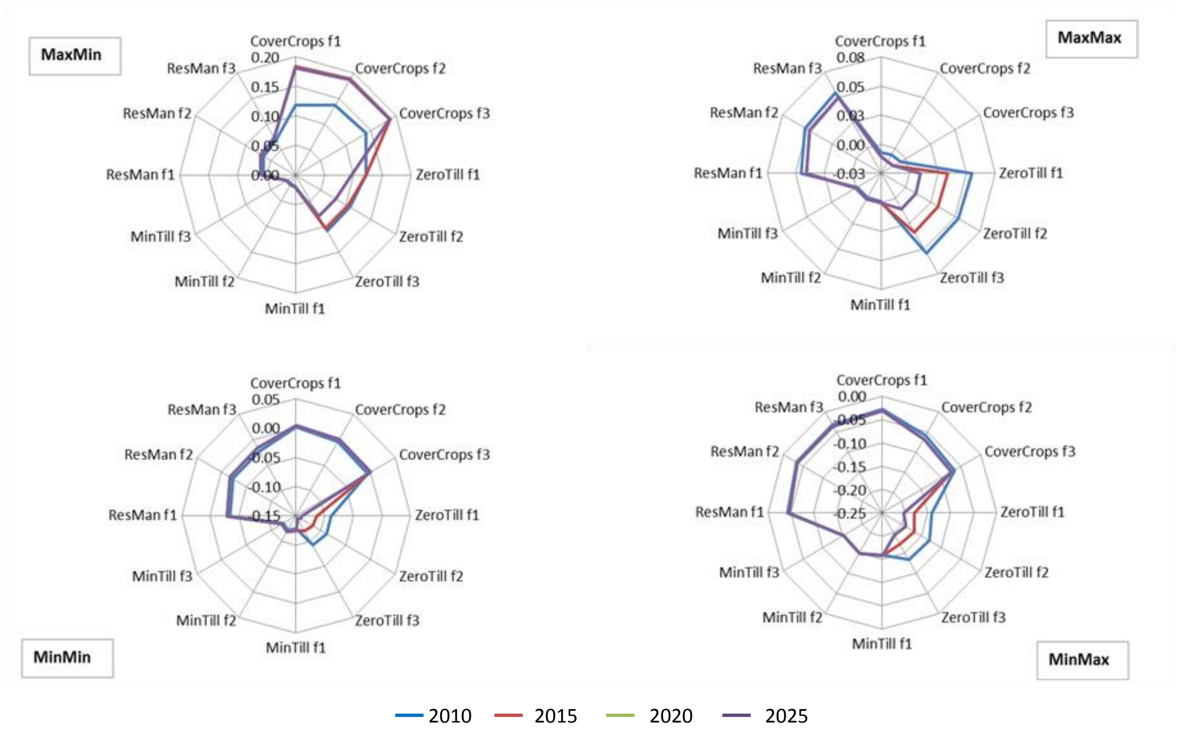

Figure 3: Changes in farm gross margins under 4 combination of maximum and minimum yields and costs under each SOC measures for three farm groups (f1- Crop Large; f2 - Crop Medium; f3 - Crop Small)