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Assessing costs of soil carbon sequestration by crop-livestock farmers in Western Australia

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Research Highlights

- We estimate trade-offs between profits and soil carbon sequestration in agriculture.
- Our analysis of crop-pasture rotations is based on a bioeconomic model.
- Changing rotations to increase C-sequestration will considerably reduce profits.
- The minimum C-price would need to be over $60 to compensate farm profit losses.

Abstract

Carbon sequestration in agricultural soil has been identified as a potential strategy to offset greenhouse gas emissions. Within the public debate, it has been claimed that provision of positive incentives for farmers to change their land management will result in substantial carbon sequestration in agricultural soils at a low carbon price. There is, however, little information about the costs or benefits of carbon sequestration in agricultural soils to test these claims. In this study, the cost-effectiveness of alternative land-use and land-management practices that can increase soil carbon sequestration is analysed by integrating biophysical modelling of carbon sequestration with whole-farm economic modelling. Results suggest that, for a case study model of a crop-livestock farm in the Western Australian wheatbelt, sequestering higher levels of soil carbon by changing rotations (to include longer pasture phases) incur considerable opportunity costs. Under current commodity prices, a profit-maximising farmer would require over $60 compensation for every additional tonne of CO_2-e stored in soil, depending on their adoption of residue retention practices. Lower carbon prices are likely to generate only modest increases in soil carbon sequestration.

Keywords

APSIM; Bioeconomic Modelling; Carbon Farming; Climate Change Mitigation; MIDAS; Soil Carbon Sequestration

1. Introduction

Agriculture contributes significantly to increased atmospheric levels of greenhouse gasses—such as CO_2, CH_4 and N_2O—through, for example, direct emissions from livestock or fertiliser use; and emissions from carbon lost as a result of deforestation, changing cultivation, and arable cropping. It has been estimated that agriculture accounts for about 14 per cent of anthropogenic greenhouse gas emissions worldwide (FAO, 2001). There are various ways in which farmers can mitigate their greenhouse gas emissions. These include improved fertiliser management, conservation tillage, grazing and livestock management, biofuel production or conversion of annual to perennial crops or pasture (e.g. Cole *et al.*, 1997; Desjardins *et al.*, 2005; Smith *et al.*, 2008).

One of the strategies to mitigate greenhouse gas emissions from agriculture that is receiving increasing attention is to reverse the loss in soil organic carbon (SOC) by storing carbon in managed soils (e.g. Lal *et al.*, 2002; Ostle *et al.*, 2009; Sanderman *et al.*, 2010; Smith *et al.*, 2001). Farmers can adopt practices that reduce carbon losses from the soil, and potentially reabsorb (*sequester*) CO_2 in their soil. SOC-conserving practices (Campbell *et al.*, 2005; Conant *et al.*, 2001; Desjardins *et al.*, 2001; Hutchinson *et al.*, 2007; Sanderman *et al.*, 2010; van Caeseele, 2002) include:

- Conservation tillage;
- Increased retention of crop residues or "stubble";
- Regrowth of native vegetation;
- Continuous cropping;
- Less fallowing;
- Conversion from annual to perennial agricultural plant species: for example, by including perennial forages in crop rotations;
- Pasture and grazing management: for example, intensive rotational grazing;
- Sowing improved grass species that produce more biomass;

Soil carbon sequestration on agricultural lands is widely advocated by scientists and policy makers as a potentially cost-effective strategy to offset greenhouse gas emissions. For example, the American Clean Energy and Security Act includes provisions to establish incentive programs for agricultural activities that can sequester carbon in vegetation or soils (US Congress, 2009), while the recently proposed Australian Carbon Farming Initiative (CFI) aims to give farmers, forest growers, and other landholders, access to voluntary carbon markets (Parliament of the Commonwealth of Australia, 2011). In these voluntary markets, farmers can choose to sell carbon credits for CO_2 sequestered in vegetation or soils as a result of a change in land use or management practices. Carbon sequestration achieved under the CFI will be credited as abatement under the National Carbon Offset Standard (NCOS--Department of Climate Change, 2010).

Notwithstanding the interest in soil carbon sequestration and policy developments in this field, knowledge about the biophysical potential for soil carbon sequestration, and the economic issues associated with carbon sequestration, remains limited. Despite a great deal of (ongoing) scientific research (e.g. Collard and Zammit, 2006; Follett, 2001; Lal *et al.*, 2002; Miklos *et al.*, 2010; Ostle *et al.*, 2009; Post *et al.*, 2004; Sanderman *et al.*, 2010 and http://www.csiro.au/science/Soil-Carbon-Research-Program.html; Smith *et al.*, 2000), significant bio-physical uncertainties remain. The net effect of management practices on the potential for carbon sequestration in arable soils depends on local climatic conditions and soil characteristics (Campbell *et al.*, 2005). Regions where virgin soils had high soil carbon levels before conversion to agriculture are likely to have the highest potential for carbon storage.

Estimates for total potential SOC-sequestration vary widely across continents and practices. The greatest increase in SOC is generally found for conversion of cultivated lands to grassland, and for retirement or restoration of degraded agricultural lands (Hutchinson *et al.*, 2007; Smith *et al.*, 2008). A review of changes in management practices in North America by Hutchinson et al. (2007) showed that the amount of carbon sequestered in agricultural soils could average 60-800 kg C ha^{-1} yr^{-1} for conversion from conventional till to no-till, while reduction of summer fallow could result in a 50-185 kg C ha^{-1} yr^{-1} increase in SOC. Improvements to croplands could result in 40-500 kg C ha^{-1} yr^{-1}, and estimates for carbon sequestration ranged between 50-590 kg C ha^{-1} $yr^{-1}$for improved grassland management. A summary of field trials in Australia showed potential for additional carbon storage of 50-510 kg C ha^{-1} yr^{-1} for changes in crop rotations, and up to 770 kg C ha^{-1} yr^{-1} when moving from conventional to no-till (Sanderman *et al.*, 2010). On average, estimated SOC-sequestration potential for Australian soils was lower than potential sequestration of northern hemisphere soils due to a less favourable climate and edaphic constraints(Sanderman *et al.*, 2010).

It has been suggested that changing crop rotations will have a significant impact on potential SOC retention. For example, Lal et al. (1998) estimated that adopting winter cover crop rotation systems in the US could sequester an additional 100-300 kg C ha^{-1} yr^{-1}. Using a global dataset, West and Post (2002) concluded that enhancing rotation complexity can sequester an average 200 kg C ha^{-1} yr^{-1}. Estimating SOC changes in Australia, Luo et al. (2010) found that increasing crop diversity, frequency, and including more perennials in rotations led to significant increases in soil C. Notwithstanding this evidence, few studies have analysed the impacts of changing rotation systems on both soil carbon sequestration and farm profit (see Robertson *et al.*, 2009, for an exception).

From a biophysical perspective, it is possible to recapture at least some of the carbon that is lost from soils by changing agricultural practices. However, if we expect farmers to store carbon in soils, we need to know the impacts of changed management on farm profitability. It is likely that farmers will only adopt new management practices to increase SOC stocks if those practices are economically feasible. Although it has been claimed that carbon sequestration can be achieved for between $8-10[1] through to $25 per tonne (Taylor, 2011), there is currently little research into the financial impacts of changed management on farming businesses.

Economic studies of agriculture and carbon sequestration tend to focus on tree plantings, rather than soil carbon (e.g. Antle *et al.*, 2007; Flugge and Abadi, 2006; Kingwell, 2009; Plantinga *et al.*, 1999; Plantinga and Wu, 2003; Polglase *et al.*, 2011). Only a few studies are available that have assessed soil carbon sequestration in agriculture. For a case study in Montana, Antle et al. (2001) found that the marginal costs for converting cropland to permanent grass ranged from US$50 to over US$500 per tonne of soil carbon sequestered, while the marginal costs to adopt continuous cropping ranged from US$12 to US$140 per tonne of soil carbon. Tschakert (2004) and Diagana et al. (2007) simulated the carbon sequestration potential of a selected set of management and land-use options for small-scale farmers in Senegal. Results showed that some SOC-sequestering actions (e.g. tree planting or carbon contracts) would generate a net benefit for landholders, while other management changes may lead to significant net costs to farmers. More recently, Robertson et al. (2009) investigated the relationship between crop rotations, farm profits, and environmental conditions. Changes in four indicators of natural resource quality (including soil carbon) were analysed for a selected mix of crop rotations in two Australian case study areas: Murrumbidgee and the wheatbelt of Western Australia. The results showed significant differences between impacts on the four indicators and between case study areas. In particular, substantial improvements in natural resource conditions were found to come at a quantifiable cost to farm profits. This study did not consider changes in soil carbon over varying time frames and different depths in soil profile. Other economic studies on soil carbon have focused on the potential and the costs of carbon sequestration resulting from conservation tillage (Kurkalova *et al.*, 2006; Manley *et al.*, 2005; Pendell *et al.*, 2007). For a study in south-eastern Australia, Grace et al. (2010) estimated the potential for carbon sequestration for different tillage scenarios using the IPCC Greenhouse Gas Inventories (IPCC, 2006). The opportunity costs of changing from conventional tillage to minimum or no-till (net of fixed and transaction costs) were assessed using a statistical model. Results indicated that, even at carbon

[1] Unless indicated otherwise, all dollar amounts are expressed in AU$.

prices as high as $200 per tonne C, only 11 to 16 per cent of farmers in the Southern Region would participate in carbon contracts. This is largely due to the large proportion of farmers that have already adopted conservation tillage practices in Australia, even without carbon incentives.

Most broad-acre mixed farmers have already adopted reduced or no-tillage practices in Australia (Kearns and Umbers, 2010). Analyses of changing from conventional tillage to minimum or no-till therefore have limited relevance for Australian broad-acre farm systems. Our study will instead focus on the other main tools available to farmers to manipulate soil carbon; changing crop-pasture rotations and stubble (crop residue) retention rates. Stubble (crop residue) management practices vary widely (Anderson, 2009; Llewellyn and D'Emden, 2010), with potential consequences for soil carbon sequestration rates (Chan and Heenan, 2005). Different levels of stubble retention can affect carbon sequestration rates, and the effectiveness of residue management on carbon storage will vary between soils (Lal *et al.*, 1998).

Only one study was identified that has estimated the costs of carbon sequestration for different stubble retention levels. Choi and Sohngen (2010) used a dynamic programming model to estimate the costs of carbon sequestration for corn and soybean cropping in the Midwest US under three residue-management scenarios. The relation between residue inputs and carbon accumulation rates was assumed to be linear. Results indicate that some carbon gains (0.12–0.26 Mt C/yr) can be achieved in the 19.9 million hectares of cropland in the study region at relatively low carbon prices of US$2 to US$10/tonne C. The region could sequester significantly more carbon (up to 2 Mt C/yr) if carbon prices were US$100-US$150/tonne C. The authors conclude that carbon payment schemes will be more efficient if they include minimum residue requirements.

Our objective in this study is to further assess the costs of changing rotations to increase soil carbon sequestration. We conduct a bio-economic analysis that quantifies the trade-offs between farm profit and potential carbon storage. Because changing the farm’s crop-pasture mix and residue retention can significantly affect SOC sequestration (Luo *et al.*, 2010), we analyse carbon sequestration for varying rotations and residue retention rates. Choi and Sohngen (2010) analysed only soybean and corn cropping options, whereas we investigate a wide range of potential crop-pasture rotations. The next section presents the biophysical and farm-business models used to estimate carbon sequestration and farm profit, and outlines the different management scenarios analysed. In Section 3 and 4, we present results of the analyses, which are discussed in the concluding Section 5.

2. Methods

The study reported in the present paper builds on the bio-economic modelling approach demonstrated by Robertson et al. (2009). We use a process-based biophysical model to estimate SOC sequestration under different crop rotations and to assess how sequestration varies with stubble retention rates. These estimates are linked to a whole-farm bio-economic model of a representative farming system in a major cropping region in Australia, to jointly assess the impacts of changed crop rotations and stubble management on farm profit and carbon sequestration.

2.1 Case study area

The bio-economic model was developed for a typical 2000 hectare farm in the central wheatbelt of Western Australia (Cunderdin—Fig. 1).

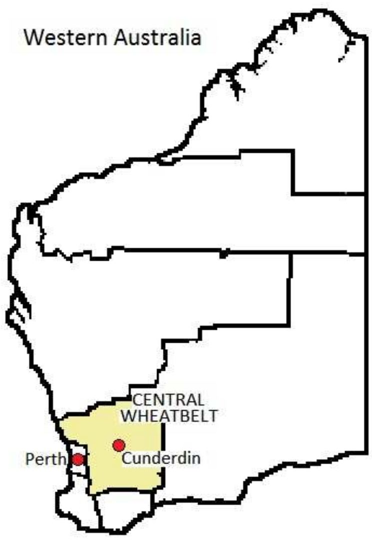

Fig. 1. Location of case study area in the central wheatbelt of Western Australia

The region receives an average of 350-400 mm annually, with the majority of rainfall falling between May and October. The weather is characteristic of the Mediterranean climate in south-western Australia with long, hot and dry summers and cool, wet winters[2]. In the model the break of season in the region occurs, on average, on the 10th of May. A typical farm in the central wheatbelt engages in a mixture of cropping and livestock enterprises. In the farm model, the crops options include wheat (*Triticum aestivum*), barley (*Hordeum vulgare*), oats (*Avena sativa*), chick peas (*Cicer arietinum*), lupins (*Lupinus angustifolius*), canola (*Brassica napus*), field peas (*Pisum sativum*), and faba beans (*Vicia faba*). These can be grown in rotation with lucerne and a variety of pasture species. Sheep on the farm are produced for wool and meat and are mostly Merino breeds. The soil types and areas included in the model are listed in Table 1.

Table 1. Soil types and areas included in the bio-economic model (adapted from Kingwell, 2009)

[2] Note that the current analysis is based on the current climatic conditions in the Central Wheatbelt and does thus not incorporate any potential future climate change.

Dominant soil type	*Soil categories in the biophysical model*	*Land management unit in the farm model*	*Farm area (ha)*
Deep pale sand	Poor sand	Poor sands	140
Deep yellow sand	Deep sand	Average sandplain	210
Yellow gradational loamy sand	Loamy sand	Good sandplain	350
Sandy loam over clay	Loamy sand	Shallow duplex soils	210
Rocky red/brown loamy sand/sandy loam; Brownish grey granatic loamy sand	Loamy sand	Medium heavy	200
Red/brown sandy loam over clay; Red and grey clay valley floor	Loamy sand	Heavy valley floors	200
Deep sandy surfaced valley; Shallow sandy-surfaced valley floor	Loamy sand	Sandy surfaced valley	300
Loamy sand over clay	Loamy sand	Deep duplex soils	390

2.2 Biophysical modelling

Although some Australian monitoring data is available on potential rates of carbon sequestration (e.g. Sanderman *et al.*, 2010), field measurements are highly variable and confounded by soil types and climatic conditions of the study site. Simulation models provide a valuable tool for dissecting the separate and interacting effects of management actions, soil type and climate in agronomic research and complement field studies. Soil carbon sequestration rates were predicted using the process-based model APSIM (Agricultural Production Systems Simulator—Keating *et al.*, 2003). APSIM is comprised of individual modules that simulate components such as soil water balance, soil nitrogen and carbon balance, surface residues, crop production, pasture production, and livestock production. The model is widely used to predict the impacts of management on, for example, crop yield, soil nutrients, and soil organic matter (Connolly *et al.*, 2001; Meinke *et al.*, 2002). The APSIM model accounts for the interactions between increasing SOC levels, changes to the C/N cycle, and impacts on production, but does not incorporate other effects, such as changes in soil structure. APSIM predictions generally provide a satisfactory representation of observed SOC changes (Probert *et al.*, 1998; Ranatunga *et al.*, 2005).

APSIM was configured to produce annual output for crop grain yields and forage production, and soil organic carbon content for the upper 30 cm of soil. A depth of 30 cm was used conform the IPCC guidelines for C-accounting (IPCC, 2006). The simulations were conducted using a 120-year historical climate record for the case-study region (i.e. potential changes in future climatic conditions were not accounted for in the present analysis). Short-term and long-term trends in SOC were estimated by linear regression[3] through the annual output for 10, 30, 50 and 120 years. This approach avoids instability in results for soil carbon change induced by year-to-year and seasonal variability and is an improvement upon the approach of Robertson et al. (2009) who looked at single year changes in SOC.

The APSIM model was used to estimate soil carbon sequestration rate under a range of crop-pasture rotations. A total of 64 crop rotations were analysed, on three representative soil types (Table 1). These three soil types covered the eight land management units used in the farm model. Predicted rates of SOC changes will depend on the initial levels of carbon in the soil. The initial SOC levels in each soil type are typical of sandy soils subjected to continuous annual cropping and pastures since clearing for agriculture: 0.9 per cent in the 0–10 cm surface layer, 0.3 per cent in the 10–20 cm layer, and 0.1 per cent in the deeper soil to 250cm. The crops and pastures included in each rotation were simulated with representative fertiliser inputs so that long-term mean yields and forage produced were comparable to those assumed in the farm economic model for each land management unit.

Farmers in the Western Australian wheatbelt may graze, burn, or bale crop residues to varying degrees following harvest. This can lead to different rates of SOC sequestration and different future steady-state levels of soil carbon (Chan and Heenan, 2005; Lal *et al.*, 1998). Most studies to date have ignored the effects of stubble retention on carbon sequestration (Choi and Sohngen, 2010). To investigate how alternative rotations affect SOC-sequestration potential under varying crop residue retention levels, we ran the APSIM simulations for three different rates of crop residue retention to represent no-, medium-, and full-stubble retention. In these scenarios, a set fraction of crop residues (0, 50 and 100 per cent) were removed at the end of each year, after the cropping season has finished.

2.3 Farm modelling

The farm economic analysis was based on the whole-farm bio-economic model MIDAS (Model of an Integrated Dryland Agricultural System - Kingwell and Pannell 1987). MIDAS is a steady-state mathematical programming model that aims to maximise annual net returns. Net return is attained by deducting all operating costs, overhead costs, depreciation and opportunity costs associated with farm assets (exclusive of land) from production receipts. The several hundred activities in MIDAS include alternative rotations on each of eight land management units (Table 1), crop sowing opportunities, feed supply and feed utilisation by different livestock classes, yield penalties for

[3] Of the various models that were estimated, a simple linear regression provided a good model fit (minimum R^2 was 0.87).

delays to sowing, cash flow recording, machinery and overhead expenditures (Kingwell, 2009). Constraints on the availability of land, labour and capital are also included in the model.

MIDAS has been widely used in Australia to determine profit-maximising strategies for grazing vegetative wheat crops (Doole *et al.*, 2009); for including herbicide-resistant weeds (Gibson *et al.*, 2008); or to determine the value of saltland pastures in mixed crop and livestock farming systems (O'Connell *et al.*, 2006). MIDAS has also been used to analyse the relationship between farm profit and natural resource outcomes such as environmental benefits of including perennial forage shrubs (Monjardino *et al.*, 2010); greenhouse gas abatement policies for different farming enterprises (Flugge and Schilizzi, 2005); or to assess the benefits of perennials for on-farm salinity prevention (Bathgate and Pannell, 2002).

One of the major strengths of MIDAS is its ability to incorporate a range of costs and benefits at a whole-farm scale. The model accounts for the impacts of any productivity gains and losses that may result from changing the farm rotation system on profit, including impacts such as changes in weed control costs, fertilizer requirements, machinery usage requirement, hired labour costs, nitrogen fixation by legumes and crop disease effects. It should be noted that the possibility of greater productivity due to increased SOC levels are not accounted for in MIDAS i.e. the model does not ascribe any benefits due to the level of SOC *per se*.

The model was run using the same set of rotation scenarios included in APSIM to analyse farm profits under alternative crop-pasture rotations. All scenarios were run for five different sets of commodity prices. The gross commodity prices in each scenario were based on Robertson et al. (2010) and are summarised in Table 2. The MIDAS model selects the combinations of rotations that maximise farm profit on each land management unit and thus provides information about the maximum annual farm profits that can be achieved for different enterprise mixes. In calculating farm profit, payments for carbon sequestration are not included. We aim to quantify the trade-offs between profit and carbon sequestration, to estimate the likely sequestration response of farmers under different carbon prices.

In each set of model solutions, the level of stubble retention was specified in advance at 0, 50 or 100 per cent. The model thus identified financially optimal rotations endogenously, while setting the level of stubble retention exogenously. This strategy was adopted for several reasons. Firstly, stubble retention is "best-practice" conservation strategy that is widely adopted in Australia, and is therefore unlikely to satisfy the additionality requirements[4] for carbon payments. However, it is not

[4] The currently proposed criterion for judging additionality—and thus eligibility as a genuine offset—is that the practice must not be common practice in the region (Parliament of the Commonwealth of Australia, 2011).

practised universally. According to Llewellyn and D'Emden (2010), around 22 per cent of farmers remove (a proportion of) their cereal stubbles through burning and grazing. It is therefore important to examine partial retention in the analysis. Secondly, even if farmers do practise full stubble retention, there is variability and uncertainty about the level of carbon storage in different soil types. One could interpret the low- and medium-stubble retention scenarios as representing less effective outcomes from full stubble retention.

Table 2. Price scenarios used in the farm modelling (FOB price)

	Price scenario				
Commodity	***Base prices***	***Low crop***	***High crop***	***Low sheep***	***High sheep***
Wheat ($/t)	300	200	400	300	300
Feed wheat ($/t)	250	150	340	250	250
Barley ($/t)	300	200	400	300	300
Feed barley ($/t)	250	150	340	250	250
Oat ($/t)	180	120	240	180	180
Lupin ($/t)	280	190	380	280	280
Canola ($/t)	460	300	620	460	460
Field Peas ($/t)	300	200	400	300	300
Faba Beans ($/t)	300	200	400	300	300
Chick Peas ($/t)	350	200	500	350	350
Wool (WMI, c/kg)	720	720	720	450	1000
Lamb ($/kg DW)	3	3	3	2.25	3.75
Ewes ($/hd)	40	40	40	30	50
Wethers ($/hd)	50	50	50	37.5	62.5

3. Results

Following the methodology outlined in Robertson et al. (2009), APSIM predictions of carbon storage were linked to MIDAS output, to evaluate the trade-offs between profit maximisation and the carbon storage potential under different rotation and stubble management scenarios.

3.1 Base case—carbon sequestration rates and farm profit

In the base case scenario, SOC sequestration rates are simulated at 50 per cent crop residue retention and base commodity prices. The results for our typical Central Wheatbelt farm are shown in Figure 2, at varying constrained proportions of farm land allocated to cropping. The bar-graphs in Figure 2 show the potential rates of carbon sequestration for the profit-maximising combinations of crop-pasture rotations. Three different simulation periods are shown (10, 30 and 120 years).

Sequestration rates are highest when approximately 10–20 per cent of the farm's arable area is allocated to cropping, while the rest is devoted to pastures for sheep production. The predominant rotations in this enterprise mix are continuous pastures, pasture-wheat rotations or lucerne-wheat rotations (Appendix). The perennial pastures contribute to high soil carbon sequestration rates. Over a 10 year simulation period, a maximum of approximately 241 kg of carbon could be sequestered per hectare per year if a farmer were to use 10–20 per cent of his arable land for cropping activities. The predicted annual rates of carbon sequestration decrease over longer simulation periods; to an average of 118 kg C ha^{-1} yr^{-1} over 30 years and 84 kg C ha^{-1} yr^{-1} over a 120 year simulation period. These model predictions are in line with previous empirical measurements (e.g Luo *et al.*, 2010; West and Post, 2002). The predicted decline shows that carbon sequestration rates are highest in the first few years after a change in management, and decrease as the carbon stock increases.

When more land is used for annual cropping—wheat, barley, or lupin-based rotations—soil carbon sequestration rates decline because much of the carbon-containing plant mass is removed (van Caeseele, 2002). For example, if 60–80 per cent of the farm was cropped, the average SOC sequestration rates over a 30 year period range between 85 and 72 kg C ha^{-1} yr^{-1} for the profit-maximising mix of rotations (Fig. 2).

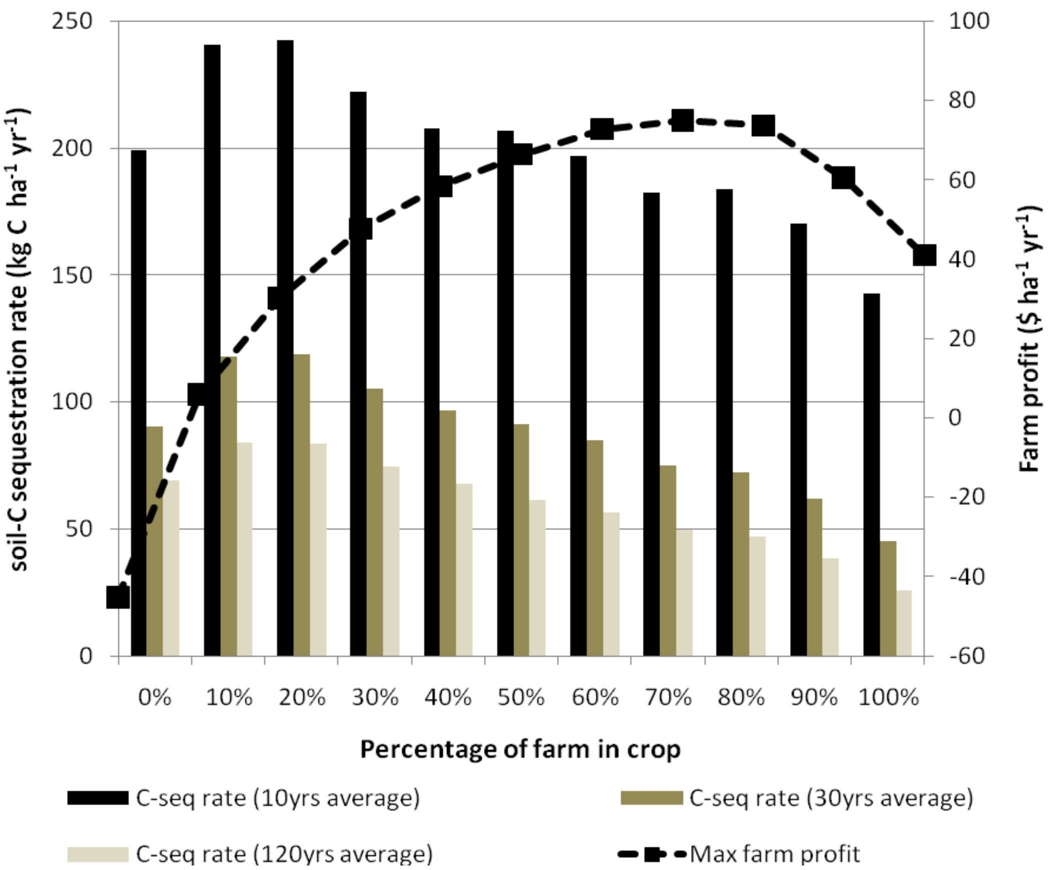

Fig. 2. Maximum attainable profits ($ ha^{-1} yr^{-1}) and average SOC-sequestration rates in 0-30cm soil over 10, 30 and 120 yr simulation periods (kg C ha^{-1} yr^{-1}) for profit-maximising enterprise mixes

The MIDAS model provides information about the maximum attainable annual farm profits under optimal crop-pasture rotations. Under a base-case scenario, a farmer can maximise profit at about $75 ha^{-1} yr^{-1} by using approximately 70 per cent of the available land for cropping activities (Fig. 2). The enterprise mix then includes various rotations, including some dominated by annual or perennial pastures and some that involve rotations between cereal crops and grain legumes (see Appendix). Note that the representative farm comprises eight different land management units and that the selected cropping and pasture activities are selected for each soil types simultaneously to provide the most profitable farming system overall. Figure 2 illustrates that carbon sequestration rates decline, while profit increases, when more than 20 per cent of the land is committed to cropping (up to a maximum profit at about 70 per cent cropping). This highlights that there is a tension between the optimal enterprise mix for farmers and policy objectives to increase soil carbon.

3.2 Profit - SOC trade-offs

The carbon sequestration rates predicted by APSIM were combined with the profit-maximising rotations selected by MIDAS. This results in a 'production possibility frontier' of the maximised carbon storage and farm profit potential under different crop-pasture rotations (Fig. 3). All results are based on the 30-year simulation results (approximately one generation). Although this may be considered a short-term time period in a carbon sequestration context (where planning periods of more than 100 years are used—Parliament of the Commonwealth of Australia, 2011), a 30-year period is more appropriate from the perspective of long term farm management planning. The curves in Figure 3 show the trade-offs between potential carbon sequestration and maximum profits at 50 per cent residue retention and three price scenarios. Similar figures were generated for other simulation periods and price scenarios.

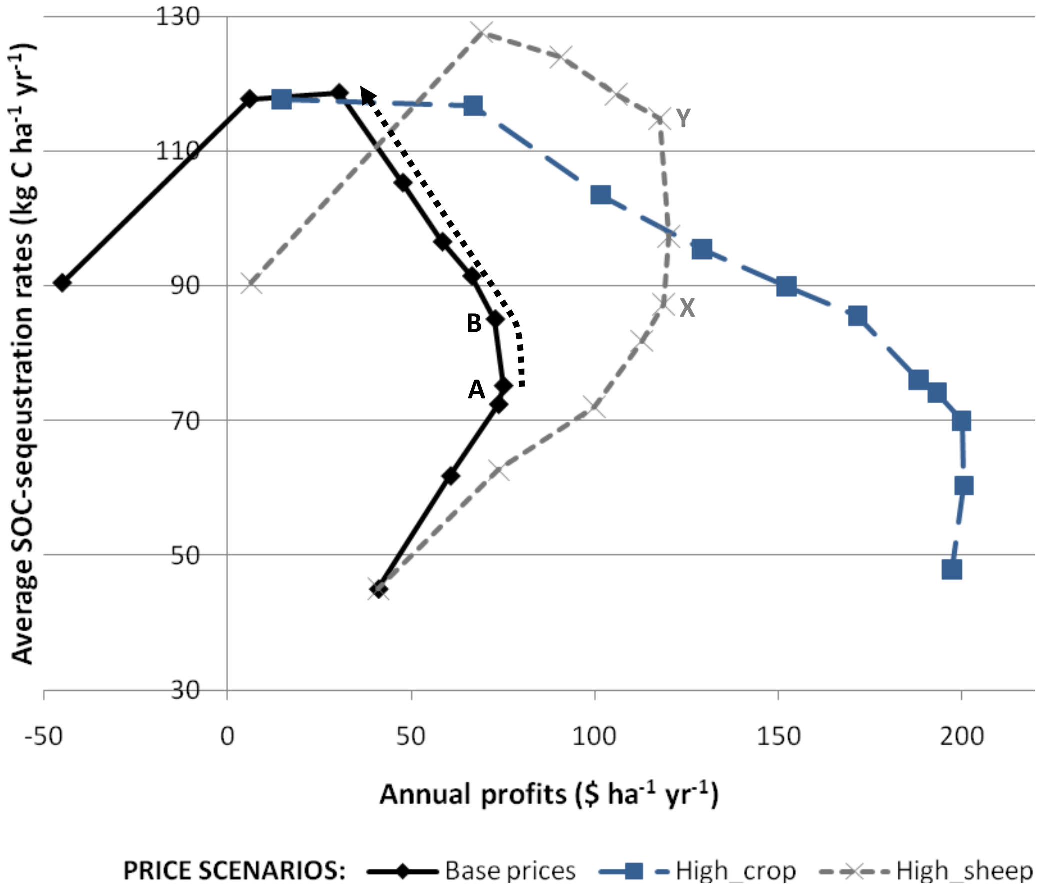

Fig. 3. Trade-offs between annual profit and average SOC-sequestration rates in 0—30cm soil layer

Results indicate that a change in enterprise mix to achieve higher rates of SOC-sequestration will reduce farm profits. In Figure 3, this movement along the base-case production possibility frontier is indicated by the black dotted arrow.

These results show that that different levels of sequestration require different levels of economic sacrifice, with the opportunity cost (in terms of reduced profits) tending to increase at higher rates of sequestration. Relatively small increases in carbon sequestration may be achieved at relatively low costs. For example, under a base-case price scenario, a profit-maximising mix of rotations would yield an annual farm profit of approximately $75 per hectare. Reducing crop area by 10 per cent below the profit maximising area (a movement from A to B in Fig. 3) would reduce annual profits by only \$2.2 ha^{-1}—as would be expected given the flat payoff curve around the point of profit maximisation (see, also, Pannell, 2006)—while increasing the average SOC sequestration rate by nearly 10 kg C ha^{-1} yr^{-1} (= 0.036 tCO_2-e)[5]. This means that the extra sequestration will cost the farmer approximately $62 per tonne of CO_2 (as average reduced profits over 30 years). More substantial increases in carbon sequestration (moving up along the curves in Figure 3) come at much higher cost. For example, a change in rotations from maximum profits to maximum SOC-sequestration rates (top of the curve) would reduce the annual farm profit by around \$45 ha^{-1} under the base-case commodity price scenario. Carbon sequestration rates would increase from 75 kg C ha^{-1} yr^{-1} to nearly 120 kg C ha^{-1} yr^{-1}, implying a cost per tonne of CO_2 sequestered of at least $280. Given limitations of the model and data, these carbon sequestration costs should be considered to be broadly indicative, illustrating the limited potential for low carbon prices to drive sequestration of SOC in this farming system.

Prevailing commodity prices and costs will determine how much land is allocated to cropping to maximise farm profits. Increasing SOC sequestration rates requires the farmer to include more pasture-based rotations in their enterprise mix, and the costs of increased carbon sequestration will thus depend on a range of factors including commodity prices.

In a high crop-price scenario, a larger proportion of farmland will be allocated to growing crops, and the maximum attainable profit predicted by MIDAS, assuming average seasonal conditions, may be as high as $200 per hectare per year. Under this price scenario, changing the mix of rotations to maximise carbon sequestration (i.e. limiting the amount of land under crop) would considerably reduce farm profits—from \$200 to approximately \$70 ha^{-1} yr^{-1}—while SOC sequestration rates increase by about 56 kg C ha^{-1} yr^{-1} (over 600 \$ t^{-1} CO_2-e).

On the other hand, when sheep prices are high, it will be profitable to commit more land to grazing. With more farm land devoted to pastures or lucerne rotations, the farmer can increase sequestration rates at a lesser reduction in profit. But even under high prices for livestock products, attempting to achieve sequestration rates over about 115 kg C ha^{-1} yr^{-1} would cost more than \$40 t^{-1} CO_2-e (see Section 6).

[5] 1000 kg C = 3.667 tonnes CO_2-equivalents.

3.3 Impacts of stubble retention

The above analysis shows the trade-offs between profit and carbon sequestration potential for different farm enterprise mixes and commodity price scenarios. These results assume a base-case scenario of 50 per cent stubble retention. As noted earlier, varying levels of crop and pasture residues retention are observed in Australia (Anderson, 2009; Llewellyn and D'Emden, 2010). The level of residue retention may alter the cost-effectiveness of changing rotations as a strategy to increase carbon sequestration. We therefore analysed the trade-offs between profit and carbon storage potential under different stubble retention scenarios.

Significant differences in were found in carbon sequestration rates between no-, medium-, and full-stubble retention (Fig. 4.). A profit-maximising farmer who currently does not retain any stubble would lose soil carbon at an average rate of 27 kg C ha^{-1} yr^{-1} over a 30 year period (indicated by C_0 in Fig. 4). If this farmer were to increase stubble retention rates to 50 per cent, average SOC-sequestration rates would increase to 75 kg C ha^{-1} yr^{-1} (C_{50}). Moving to full stubble retention (C_{100}), under the same set of rotations, could increase SOC-sequestration rates further to more than 170 kg C ha^{-1} yr^{-1}. This indicates that, if stubble retention were not already widely adopted, policies aimed at promoting stubble retention could achieve higher rates of carbon sequestration without changing farm enterprise mix.

The combinations of rotations at which a farmer can maximise profits are indicated by points C_0 to C_{100} in Figure 4. If the farmer were to increase the area of pastures to maximise soil carbon sequestration (to the points indicated by D_0 to D_{100}), profit would reduce by approximately \$45 ha^{-1} yr^{-1}. The increase in SOC sequestration rates is distinctly different between rates of residue retention. Under a no-retention scenario, moving from 70 to 20 per cent cropping (C_0 to D_0) would increase the annual rate of carbon sequestration by nearly 73 kg C ha^{-1} yr^{-1}. The same reduction in crop area would increase annual SOC-sequestration rates by only 17 kg C ha^{-1} yr^{-1} under a full-retention scenario (C_{100} to D_{100}). Thus, at full retention, there is less potential to increase carbon sequestration rates through a change in the crop-pasture mix.

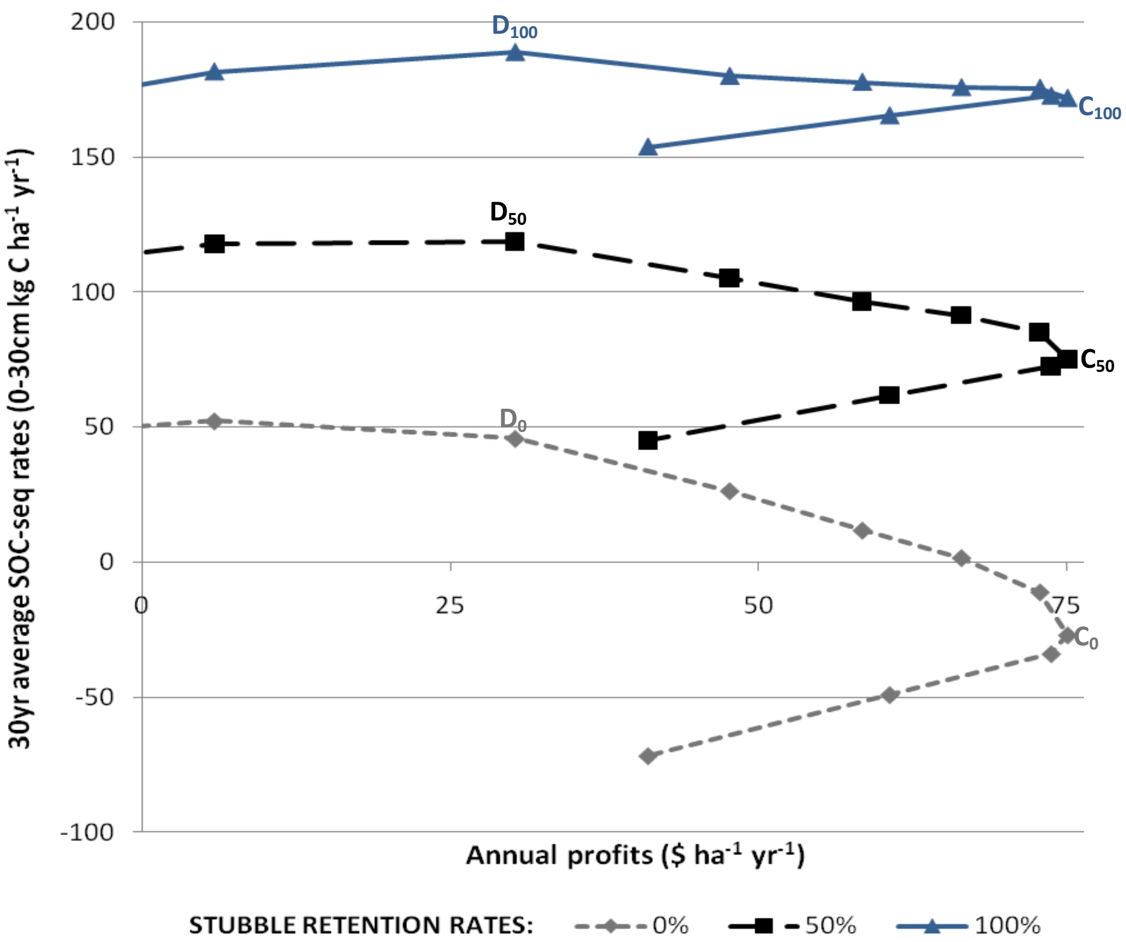

Fig. 4. Trade-offs between annual profit and SOC-sequestration (top 30cm soil, averaged over 30yr period) at varying rates of residue retention. The points on each curve represent varying proportions of farm in crop.

4. Compensatory payments

Given the trade-offs between increasing profit and increasing SOC sequestration, a profit maximising farmer is unlikely to change the enterprise mix to increase carbon sequestration unless compensatory payments are available. A voluntary carbon offset market could provide such payments.

We calculated the annual incentive payments required to stimulate profit-maximising farmers to change their enterprise mix for increased SOC-sequestration rates. The changes in profit and average carbon sequestration were calculated for a step-wise, 10 per cent, reduction in the proportion of farm land allocated to cropping. It is assumed that the farmer will initially operate under a profit-maximising mix of rotations (ignoring carbon payments). The annual payment p_{comp} required to compensate for the reduction in profits as calculated as: $p_{comp} = (\Delta\pi / \Delta SOC) \cdot 3.667 \;\; 10^{-3}$,

where $\Delta\pi$ is the change in annual profits, and ΔSOC is the average annual carbon sequestered in the top 30cm of soil in the first 30 years[6] after a change in farm rotations (in tonnes per hectare). Since carbon prices are typically expressed in \$ per tonne of CO_2-equivalents, results are multiplied by 0.003667 to convert sequestration from SOC to CO_2-equivalents.

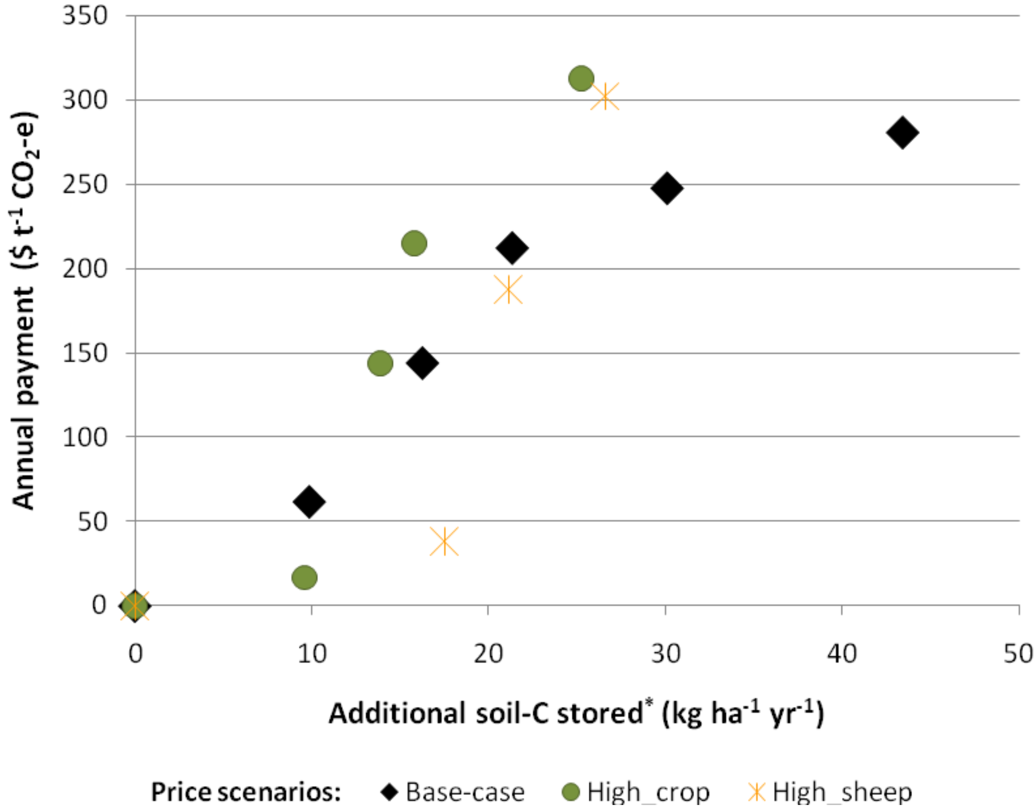

Fig. 5. Carbon offset payments required to compensate for costs of additional soil-C stored under varying commodity price scenarios (at 50 per cent stubble retention)

* Compared to carbon sequestration rate under a profit-maximising mix of crop-pasture rotations

Figure 5 shows the payments required to compensate for reductions in farm profit at three commodity price scenarios. The compensatory payments depend on the target level of carbon sequestration. For example, under a base-case scenario (Section 3.1), the offset payment required to achieve a maximum increase in SOC sequestration of an additional 43.5 kg C per hectare per year would be over \$280 t^{-1} CO_2-e. In the same base-case scenario, smaller increases in SOC-

[6] One reviewer commented on the requirement in the Australian CFI to maintain SOC levels for a period of 100 years after sequestration has occurred. We did not analyse the implications of this (CFI-specific) maintenance requirement in the current paper, but discuss its potential impacts in Section 5.

sequestration are feasible at a lower reduction in profit. Nevertheless, even a small increase in carbon sequestration of about 10 kg C ha^{-1} yr^{-1} would still require payments of over \$60 t^{-1} CO_2-e (at base-case prices).

The 'flat' areas along the production possibility frontiers in Figure 3 (e.g. the move from crop-pasture mix X to mix Y) might suggest that large increases in SOC sequestration are achievable at low costs. However, the results indicate that the increase of approximately 17.5 kg C ha^{-1} yr^{-1} would still reduce farm profits by about \$2.5 ha^{-1} yr^{-1}. This equates to a compensation of about \$38 t^{-1} CO_2-e (Fig. 5).

The costs of sequestration could vary between farmers practising different rates of residue retention (Fig. 6). The compensatory payments depicted in Figure 6 are for the base-case commodity prices, at no-, medium, and full-stubble retention. If a farmer is currently removing all stubble from the land (triangles), increasing SOC-sequestration through a change in rotations can be achieved at relatively low payments. In this scenario, sequestering approximately 16 kg C per hectare per year would cost about \$40 per t CO_2-e. However, if a farmer has adopted conservation practices and is retaining 50 or 100 per cent of crop residues, higher payments are required to compensate for reductions in profit (Fig. 6). A similar increase in SOC sequestration of 16 kg C would cost farmers about \$144 per t CO_2-e under medium residue retention. A farmer who practises full stubble retention would require more than \$160 t^{-1} CO_2-e, to increase annual SOC sequestration rates by only 3.8 kg C per hectare.

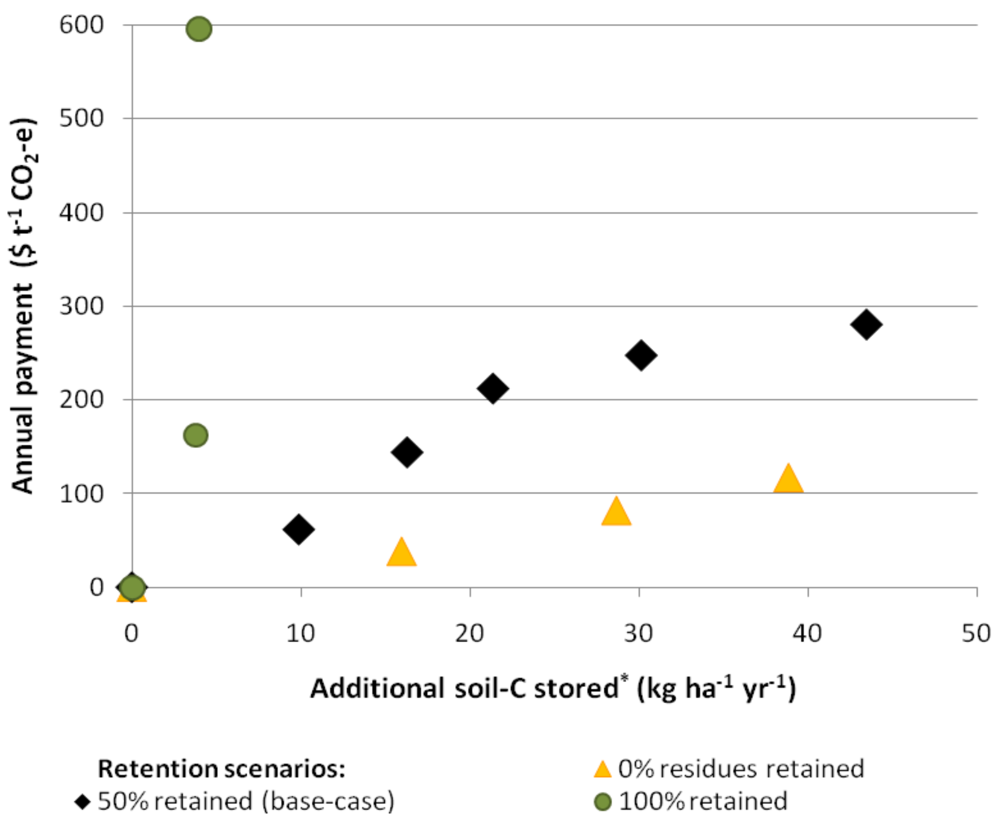

Fig. 6. Carbon offset payments under varying residue retention rates
* Compared to a carbon sequestration rate under a profit-maximising mix of crop-pasture rotations

5. Discussion

In this study, we analysed the trade-offs between profits and soil carbon sequestration for a crop-pasture farming system in the Western Australian wheatbelt. The results consistently show that increasing SOC-sequestration by changing crop-pasture rotations will reduce farm profit. The relative increase in soil carbon as a result of changing farm enterprise mix is affected by residue retention rates. SOC-sequestration rates increase at higher rates of residue retention. When we consider a farmer who has not adopted stubble retention practices (or when stubble retention practices are highly ineffective in storing soil carbon), gains in SOC-sequestration may be achievable at relatively low costs. But if a farmer has adopted conservation practices (such as retaining a high proportion of crop residues), increasing SOC-sequestration rates will become very costly.

Based on this analysis, one could argue that policy makers should simply stimulate farmers to retain a higher proportion of residues to achieve higher carbon sequestration rates. However, previous studies show that a large proportion of farmers have already adopted stubble retention systems (Kearns and Umbers, 2010; Llewellyn and D'Emden, 2010), and that the relevant costs to farmers are those predicted under the medium- or full-stubble retention rates scenarios. Paying farmers who have currently adopted low rates of residue retention would seem to be inconsistent with the current proposed criterion for “additionality” in Australia (see Section 2.3), and may result in a debate about equity because early adopters of conservation practices would ‘miss out’ on carbon payments. This would also mean that the ‘cheap’ sequestration under a no-retention scenario would not be eligible for compensation. Carbon payments would need to be over \$60 per tCO_2-e to achieve increased carbon sequestration rates from changes in rotations (assuming base-case prices and 50 per cent residue retention).

A number of issues should be considered when interpreting the results of our model. First of all, the current analysis does not incorporate how different crop-pasture mixes affect agricultural greenhouse gas emissions. For example, reducing annual cropping in the enterprise mix may increase carbon sequestration in soils, but the subsequent increase in the number of sheep on a (profit-maximising) farm will significantly increase greenhouse gas emissions generated through enteric fermentation and animal waste (Kingwell, 2009). Such an increase in emissions is likely to be classed as ‘leakage’ under the current Australian policy proposal—and accordingly be deducted from any sequestration gains. This thus has the potential to further increase the cost of sequestration. A full analysis of potential profitability of carbon farming would need to account for greenhouse gas emissions as well as sequestration potential.

Readers should bear in mind that the estimated carbon sequestration potential depends largely on assumptions about soil types and climatic conditions. The analysis presented in this paper is based on a bio-economic model for the central wheatbelt of Western Australia, and results are representative for this area. Different starting values of soil carbon or climatic conditions in other cropping regions in Australia will affect the predicted SOC-sequestration rates. Moreover, Western Australia is predicted to experience adverse impacts of future climate change (Ludwig and Asseng, 2006). Negative effects on plant production can reduce inputs of organic matter in the soil, and thus reduce SOC sequestration potential. Further work is required to assess the impacts of possible adverse climate change on soil carbon and the changes in farm profitability under such conditions.

Changing farm management to increase SOC-sequestration will only be eligible for offset payments if activities represent permanent abatement. The proposed Australian Carbon Farming Initiative stipulates that a farmer who participates in a carbon offset market will be obliged to maintain the higher level of soil carbon for 100 years (after the last year that credits were claimed—Parliament of the Commonwealth of Australia, 2011). These long planning periods are likely to increase the level of risk and uncertainty to participants in a carbon offset scheme. Commodity prices are likely to vary considerably over a 100-year period, which means that the potential reduction in farm profit is highly uncertain. This, combined with the irreversibility that participation may involve, will generate an option value from delaying participation. While uncertainties in costs and prices can be challenging for farmers, additional factors that may impose a risk on the farmer who has entered into a carbon contract include: climate change or natural disasters that could reduce or re-release soil carbon in the atmosphere; possible changes of the policy program sometime in the future; and future technology developments that could either mitigate climate change effects more cost-efficiently than soil carbon sequestration or that could raise the opportunity cost to farmers of participating in SOC enhancement. It is not unrealistic that the combination of the 100 year maintenance period and these uncertainties will reduce the preparedness of farmers to adopt activities that enhance SOC, such that greater incentives may be required to achieve SOC sequestration on farms. To design an effective and cost-efficient carbon offset scheme, research is needed into the farmer's evaluation of the risks involved with participation in an offset market and the potential losses in option values, in light of a variable climate, changing commodity prices, and different carbon offset payments.

The current analysis considers the impacts of changed management on farm profits through changes in production costs and revenues. It is likely that participation in a carbon offset scheme will yield additional costs that are not directly associated with agricultural production, such as learning, transaction, monitoring, and reporting costs. Such additional costs are not included in the current model.

6. Conclusion

In this study, results from a biophysical model were combined with whole-farm economic modelling to assess the trade-offs between farm profit and soil carbon sequestration under different crop rotations (altering the crop-pasture mix) at a range of residue retention levels.

Results from the whole-farm model show that annual farm profits are maximised if approximately 70 per cent of the farm's available land is allocated to annual cropping. Under a base-case scenario, a profit-maximising farmer in the Western Australian wheatbelt could gain a profit of approximately \$75 ha^{-1} yr^{-1}, and would sequester about 75 kg C ha^{-1} yr^{-1} over 30 years in the top 30 cm of soil.

Enterprise mixes with a larger proportion of pastures are associated with higher carbon sequestration rates, but generate lower agricultural profits than annual cropping. A farm with approximately 80 per cent of the available land under pasture could potentially sequester over 118 kg C ha^{-1} yr^{-1}, but would have a profit of about \$30 ha^{-1} yr^{-1} (compared to \$75 ha^{-1} yr^{-1} under a profit-maximising scenario). This indicates that changing crop rotations to increase the level of carbon in agricultural soils will result in reduced profits to farmers in the study region.

The reduction in profit relative to carbon gains depends on prevailing commodity prices, input costs, and the target level of soil carbon to be sequestered. Under a base-case price scenario and 50% residue retention, increasing SOC sequestration rates by about 10 kg C ha^{-1} yr^{-1} (compared to C-storage under the profit-maximising rotation mix) would cost the farmer approximately \$62 per t CO_2-e. Under a scenario that favours a high percentage of the farm being in pasture—such as high commodity prices for livestock products—an increase in soil carbon sequestration may cost farmers less, but would still require a compensation of \$38 per t CO_2-e, to store an additional 17.5 kg C ha^{-1} yr^{-1}. This is indicative of the limited extent of carbon sequestration likely to be achieved in this farming system if payments would be as low as discussed in the 2010/2011 Australian public debate.

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Appendix. Profit-maximising crop-pasture rotations selected in MIDAS

Proportion of farm-land in crop	*Most profitable rotations (allocation proportions varying per soil-type)*
0%	PPPP
10%	PPPP, PPPW, 4UW
20%	PPPP, PPPW, 3UWB, 4UW, WWF
30%	PPPP, PPPW, 3UWB, 4UW, WWF, WBL
40%	PPPP, PPPW, 3UWB, 4UW, WWF, WBL
50%	PPPP, PPPW, 4UW, WWF, WBL
60%	PPPP, PPPW, 4UW, WWF, WBL
70%	PPPP, PPPW, 4UW, WWF, WBL
80%	PPPW, 4UW, 4UAW, WWF, WBL
90%	4UW, 4UAW, WWF, WBL, WNBF
100%	WWF, WBL, WNBF, WWLD

3U = 3 years lucerne; 4U = 4 years lucerne; A = faba beans; B = barley; F = field pea; L = lupin; LD = dry sown lupin; N = canola; P = annual pasture; W = wheat.