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

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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. However, there is 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, farmers would forego more than $80 in profit for every additional tonne of CO₂-e stored in soil, depending on their adoption of crop residue retention practices. This is much higher than the initial carbon price of $23.t⁻¹ in Australia’s recently legislated carbon tax. This analysis does not incorporate the possibility that greenhouse gas emissions may increase as a result of including longer pasture phases. Accounting for emissions may substantially reduce the potential for net carbon sequestration at low carbon prices.

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

1. Introduction

Agriculture contributes significantly to increased atmospheric levels of greenhouse gases—such as CO₂, CH₄ and N₂O—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). In Australia, the agricultural sector contributed 15 per cent to net national greenhouse gas emissions in 2009 (DCCEE, 2010).

¹ CO₂-equivalents are used to compare the emissions from different greenhouse gases based on their global warming potential, relative to that of carbon dioxide. For soil carbon, 1000 kg C = 3.667 tonnes CO₂-e.
Farmers can mitigate greenhouse gas (GHG) emissions by altering their management practices. One of the carbon sinks that is receiving considerable attention is the amount of soil organic carbon (SOC) that can be stored in agricultural soils (e.g. Lal et al., 2002; Ostle et al., 2009; Sanderman et al., 2010; Smith et al., 2001). Trees, grasses, shrubs, forbs and legumes fix carbon dioxide (CO$_2$) into organic carbon through the process of photosynthesis. Some of this carbon (C) becomes soil organic carbon (SOC) through above and belowground decomposition (Fynn et al., 2009). By changing agricultural practices, it is possible to increase the amount of carbon stored in the SOC pool. Changes in land-use patterns and agricultural practices can also affect the amount of C released back into the atmosphere. Typically, CO$_2$-equivalents are used to compare the global warming potential of different GHG. For soil carbon, 1000 kg C = 3.667 tonnes CO$_2$-e.

Lal (2004) estimates the global SOC pool at more than twice the size of the atmospheric pool of carbon, and 2.7 times the size of the carbon pool in vegetation. The potential of the world’s agricultural soils to offset global GHG emissions has been estimated at 5 to 15 per cent (Lal, 2004). Garnaut (2008) estimated the potential carbon removal by soils on Australian cropped land at 68 Mt CO$_2$-e per year (compared to a potential 16 Mt CO$_2$-e emission reduction by alternative livestock management). Practices that farmers can adopt to reduce SOC losses from the soil, and/or potentially reabsorb (sequester) carbon in their soil include:

- Conservation tillage;
- Increased retention of crop residues or “stubble”;
- Regrowth of native vegetation;
- Reduced frequency of fallowing;
- Conversion from annual to perennial crops or pasture;
- Grazing and livestock management: for example, intensive rotational grazing;
- Sowing improved grass species that produce more biomass.

(Campbell et al., 2005; Conant et al., 2001; Desjardins et al., 2001 and 2005; Hutchinson et al., 2007; Sanderman et al., 2010; van Caeseele, 2002).

Various policy programs support soil carbon sequestration as a strategy to offset GHG 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 additional 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).

From a biophysical perspective it is possible to store SOC in agricultural soils by changing management practices. However, it is likely that farmers will only voluntarily adopt new management practices to increase SOC stocks if those practices are economically profitable. Some SOC sequestration management may lower farm profits (e.g. when changing from a high-value annual crop to a lower-value grazed perennial), in which case incentive schemes may be needed to compensate farmers. Although it has been claimed that SOC sequestration can be achieved for payments between $8-10 (Australian dollars) through to $25 per tonne (Taylor, 2011), there is currently little research into the financial impacts of changed management on farming businesses.

Our objective is to assess the costs of changing rotations to increase SOC sequestration, under varying levels of crop residue retention. We conduct a whole-farm bio-economic analysis that quantifies the trade-offs between farm profit and potential SOC storage. Because changing the farm’s crop-pasture mix and residue retention can considerably affect SOC sequestration (Luo et al., 2010), we analyse SOC sequestration for a wide range of potential crop-pasture rotations. Our analysis is limited in scope, and does not account for the possibility that greenhouse gas emissions may increase with a change of rotations. Considering that livestock emissions from enteric fermentation play a large role in the agricultural emissions (Garnaut, 2008), a full analysis of potential profitability of carbon farming would need to account for greenhouse gas emissions as well as sequestration potential.

2. Background

Despite a great deal of scientific research (e.g. Follett, 2001; Lal et al., 2002; 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), substantial bio-physical uncertainties about the achievable rates of SOC sequestration remain. Accurate measurement of soil organic matter and statistically verifying changes in SOC stock is complex because of the many, and heterogeneous factors affecting SOC-sequestration (such as temporal variability in vegetation coverage and spatial heterogeneity in soil environments—Sanderman et al., 2010).
Estimates for total potential SOC-sequestration vary widely with the greatest increase 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). Using a global dataset, West and Post (2002) concluded that enhancing rotation complexity can sequester an average 200 kg C ha\(^{-1}\) yr\(^{-1}\). Agricultural soils in Australia can potentially store additional SOC by changing crop rotations (estimated 50-510 kg C ha\(^{-1}\) yr\(^{-1}\)) or by moving from conventional to no-till (up to 770 kg C ha\(^{-1}\) yr\(^{-1}\)) (Sanderman et al., 2010; Luo et al., 2010). The estimated SOC-sequestration potential for Australian soils is, on average, lower than potential sequestration of northern hemisphere soils due to a less favourable climate and edaphic constraints (Sanderman et al., 2010).

Most studies that have assessed the impacts of carbon farming on whole-farm profitability have tended to focus on tree plantings (e.g. Antle et al., 2007; Flugge and Abadi, 2006; Kingwell, 2009; Plantinga et al., 1999; Plantinga and Wu, 2003; Polglase et al., 2011) and a minority on SOC (Antle et al., 2001, Robertson et al. 2009). In general, the studies showed that any substantial improvements in SOC would come at a significant cost to farm profits.

A number of authors assessed the potential and the costs of reduced-tille sequestration (Kurkalova et al., 2006; Manley et al., 2005; Pendell et al., 2007). Grace et al. (2010) estimated how many farmers would adopt carbon-sequestering practices under varying carbon contracts, in the Southeast Region of Australia. At a carbon price of $200 per tonne of C, contract participation rates for minimum and no-tillage were only 11 and 16% respectively. These low participation rates were not a result of carbon prices per se, but rather due to the large proportion of farmers that has already adopted reduced or no-tillage practices in Australia, even without carbon incentives (Kearns and Umbers, 2010). Because of additionality requirements in the CFI (see Section 6), analyses of changing to conservation tillage therefore have limited relevance for Australian broad-acre mixed farm systems. Our study will instead focus on the other main tools available to farmers to manipulate SOC; 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 SOC sequestration rates (Chan and Heenan, 2005). Different levels of residue retention can affect SOC sequestration rates, and the effectiveness of residue management on SOC storage will vary between soils (Lal et al., 1998). Only one study has estimated the costs of SOC sequestration from residue retention. For corn-soybean systems in the Mid-West of the USA, Choi and Sohngen (2010) found that modest SOC gains can be achieved at relatively low carbon prices of US$2 to US$10 per tonne C. More SOC sequestration would require higher carbon payments.
The study described in this paper builds on the bio-economic modelling approach demonstrated by Robertson et al. (2009) by linking a process-based biophysical model to a whole-farm economic model, to jointly assess the impacts of changed crop rotations and residue management on farm profit and SOC sequestration. We extend their study by considering changes in SOC over varying time frames and estimate the potential costs of SOC sequestration in terms of reductions in farm profit.

3. Methods

We use the APSIM biophysical model to estimate SOC sequestration under different crop rotations and varying residue retention rates (results are available online as ancillary material to this paper). These estimates are linked to the MIDAS whole-farm bio-economic model for a representative farming system in Western Australia. The setups for the APSIM and MIDAS models used for this analysis are available upon contacting the first author.

3.1 Case study area

The bio-economic model was developed for a representative farm in the Central Wheatbelt of Western Australia (Cunderdin—Fig. 1). The area is one of Australia’s main grain growing regions, producing nearly one-third of Australia’s total bulk wheat exports (ABS, 2012). Recent grain yields for the Central Wheatbelt region average 1.6t.ha$^{-1}$, compared to 1.4 and 1.3t.ha$^{-1}$ for Western Australia and the whole of Australia respectively (Hooper et al., 2011).

The region receives an average of 350-400 mm annually, with the majority of rainfall falling between May and October, during which time crops and pastures are grown. The weather is characteristic of the Mediterranean climate in south-western Australia with long, hot and dry summers and cool, wet winters. Farm size in the Central Wheatbelt varies from 1500 to 4000 hectare (average 2000 ha) comprising multiple soil types (Table 1). Typically, 20 to 70 per cent of arable land is sown to crops, which can be grown in rotation with lucerne and various annual pasture species (see Appendix). Nearly
90% of growers in the region have adopted some form of no-till or minimum tillage sowing techniques (Llewellyn and D’Emden, 2010). Sheep (mostly the Merino breed) are the dominant livestock enterprise, producing wool and meat.

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

<table>
<thead>
<tr>
<th>Soil categories in the biophysical model</th>
<th>Land management unit in the farm model</th>
<th>Farm area (ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poor sand</td>
<td>Poor sands</td>
<td>140</td>
</tr>
<tr>
<td>Deep sand</td>
<td>Average sandplain</td>
<td>210</td>
</tr>
<tr>
<td>Loamy sand</td>
<td>Good sandplain</td>
<td>350</td>
</tr>
<tr>
<td>Loamy sand</td>
<td>Shallow duplex soils</td>
<td>210</td>
</tr>
<tr>
<td>Loamy sand</td>
<td>Medium heavy</td>
<td>200</td>
</tr>
<tr>
<td>Loamy sand</td>
<td>Heavy valley floors</td>
<td>200</td>
</tr>
<tr>
<td>Loamy sand</td>
<td>Sandy surfaced valley</td>
<td>300</td>
</tr>
<tr>
<td>Loamy sand</td>
<td>Deep duplex soils</td>
<td>390</td>
</tr>
</tbody>
</table>

* Soil categories were defined as follows: Poor sand = 55mm of plant available water capacity to 250cm; Deep sand = 93mm plant available water capacity for wheat to 150cm; Loamy sand = 130mm plant available water capacity to 250cm.

3.2 Biophysical modelling

Although some Australian monitoring data is available on potential rates of SOC sequestration (e.g. Sanderman et al., 2010), field measurements are highly variable and confounded by soil types and climatic conditions of the study site. We therefore used simulation modelling, which can dissect the separate and interacting effects of management, soil type and climate, to estimate rates of SOC sequestration. The process-based model, APSIM (Agricultural Production Systems Simulator—Keating et al., 2003), is comprised of individual modules that simulate components such as soil water balance, soil nitrogen and SOC balance, surface residues, crop production, pasture production, and livestock production. It accounts for the interactions between increasing SOC levels and nutrient cycling through changes to the C/N balance, 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; Luo et al. 2011).

APSIM was configured to produce annual output for crop grain yields and forage production, and SOC content (to a depth of 30 cm so as to conform with IPCC guidelines for C-accounting (IPCC, 2006)). The simulations were conducted using the 120-year historical climate record for Cunderdin and so
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 through the annual output for 10, 30, 50 and 120 years. This approach reduces fluctuations in results for SOC change induced by year-to-year, and seasonal variability associated with crop-pasture sequences. It is also an improvement upon the approach of Robertson et al. (2009) who looked at single year changes in SOC.

A number of different regression models were estimated to determine the appropriate average carbon sequestration rates over time. Of these models, a simple linear regression provided a good model fit (minimum $R^2$ across crop-pasture sequences was 0.87).

The APSIM model was used to estimate SOC sequestration rate under a range of crop-pasture rotations. A total of 64 crop rotations were analysed, comprising combinations of wheat, barley, oats, canola, lupins, field pea, chickpea, faba bean, annual pasture and lucerne. Three representative soil types were simulated (Table 1). These three soil types corresponded to the eight land management units used in the farm model. The crops and pastures included in each rotation were simulated with representative fertiliser inputs at sowing so that long-term mean yields and forage produced were comparable to those assumed in the farm economic model for each land management unit. A number of the sequences included lucerne phases of lengths varying between 2 and 4 years. Lucerne leys were sown between May and June and removed in November. Annual pastures and lucerne were grazed whenever above-ground biomass exceeded 2000 kg/ha.

Predicted rates of SOC changes will depend on the initial levels of SOC 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 250 cm.

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 SOC (Chan and Heenan, 2005; Lal et al., 1998). To investigate how alternative rotations affect SOC-sequestration potential under varying crop residue retention levels, we ran the APSIM simulations for each rotation with a base-case for crop residue retention, and a ‘full-residue retention’ scenario which is expected to increase SOC sequestration. In the base case, 50 per cent of crop residues were removed at the end of each year, after the cropping season has finished, while no residues were removed in the full-residue retention scenario.

3.3 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 profits. Profits are defined as farm income remaining after deducting all overhead and variable costs, plus depreciation and opportunity costs associated with farm assets (apart from land). The almost 2000 activities in MIDAS include crop-pasture 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 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.

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 takes into account the effect of changes in the farming system by considering its integrated impact on various factors affecting farm profitability such as weed control costs, fertilizer requirements, machinery requirements, labour costs, nitrogen fixation by legumes, and crop disease effects. Because of the limited biophysical evidence and biochemical uncertainties about the relationships between soil organic matter and crop production (Baldock and Nelson 2000), the model does not quantify possible changes in crop productivity due to increased SOC levels i.e. the model does not ascribe any production benefits due to the level of SOC per se.

The model was run to analyse farm profits at base commodity prices plus four additional scenarios (Table 2). We constrained the percentage of pastures in the enterprise mix as a way to perturb this mixed farming system. This approach represents the current practical focus of Australian Carbon Farming policies which aim to stimulate management changes (rather than achieving some target level of abatement). Crop-percentage curves are also commonly used as a sensitivity analysis in MIDAS modelling. 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 crop-pasture mixes. These estimates are linked to the predicted soil carbon sequestration rates for the MIDAS-selected crop-pasture mixes to show the trade-offs between profit at varying cropping percentages and soil carbon sequestration. In calculating farm profit, payments for SOC sequestration are not included. We aim to quantify the trade-offs between profit and SOC sequestration, to estimate the likely sequestration response of farmers under different carbon prices.

The base case scenario assumes 50 per cent crop residue retention. A second scenario was run with the level of crop residue retention specified at 100 per cent. The model thus identified financially optimal rotations endogenously, while setting the level of residue retention exogenously. This strategy was adopted because residue retention is a “best-practice” management strategy that is widely adopted by farmers in Australia, and is therefore unlikely to satisfy the additionality requirements for...
carbon payments (see below for definition and discussion of “additionality”). However, it is not practised universally. According to Llewellyn and D’Emden (2010), around 22 per cent of farmers remove (a proportion of) their cereal residues through burning and grazing. It is therefore important to examine partial retention in the analysis, and to assess the SOC benefits of increasing retention rates.

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

<table>
<thead>
<tr>
<th>Commodity</th>
<th>Price scenario</th>
<th>Base prices*</th>
<th>Low crop</th>
<th>High crop</th>
<th>Low sheep</th>
<th>High sheep</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheat ($/t)</td>
<td></td>
<td>314</td>
<td>235</td>
<td>392</td>
<td>314</td>
<td>314</td>
</tr>
<tr>
<td>Barley ($/t)</td>
<td></td>
<td>348</td>
<td>261</td>
<td>435</td>
<td>348</td>
<td>348</td>
</tr>
<tr>
<td>Oat ($/t)</td>
<td></td>
<td>307</td>
<td>230</td>
<td>384</td>
<td>307</td>
<td>307</td>
</tr>
<tr>
<td>Lupin ($/t)</td>
<td></td>
<td>297</td>
<td>223</td>
<td>371</td>
<td>297</td>
<td>297</td>
</tr>
<tr>
<td>Canola ($/t)</td>
<td></td>
<td>582</td>
<td>437</td>
<td>728</td>
<td>582</td>
<td>582</td>
</tr>
<tr>
<td>Field Peas ($/t)</td>
<td></td>
<td>317</td>
<td>238</td>
<td>396</td>
<td>317</td>
<td>317</td>
</tr>
<tr>
<td>Faba Beans ($/t)</td>
<td></td>
<td>275</td>
<td>206</td>
<td>344</td>
<td>275</td>
<td>275</td>
</tr>
<tr>
<td>Chick Peas ($/t)</td>
<td></td>
<td>543</td>
<td>407</td>
<td>679</td>
<td>543</td>
<td>543</td>
</tr>
<tr>
<td>Wool (WMI, c/kg)</td>
<td></td>
<td>974</td>
<td>974</td>
<td>974</td>
<td>730</td>
<td>1218</td>
</tr>
<tr>
<td>Lamb ($/kg DW)</td>
<td></td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>Ewes ($/hd)</td>
<td></td>
<td>54</td>
<td>54</td>
<td>54</td>
<td>41</td>
<td>68</td>
</tr>
<tr>
<td>Wethers ($/hd)</td>
<td></td>
<td>77</td>
<td>77</td>
<td>77</td>
<td>58</td>
<td>96</td>
</tr>
</tbody>
</table>

* 2006-2011 average real commodity prices

4. Results

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

4.1 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 SOC sequestration for the profit-maximising combinations of crop-pasture rotations. Three different simulation periods are shown (10, 30 and 120 years).

When varying the area of the farm devoted to cropping, sequestration rates are highest when approximately 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-barley rotations (Appendix I). Perennial pastures contribute to high SOC sequestration rates. Over a 10 year timeframe, an average of approximately 217 kg of carbon could be sequestered per hectare per year. The predicted annual rates of SOC sequestration decrease over longer timeframes; to an average of 103 kg C.ha\(^{-1}\).yr\(^{-1}\) over 30 years and 76 kg C.ha\(^{-1}\).yr\(^{-1}\) over a 120 year period. These model predictions are in line with previous empirical measurements (e.g. Luo et al., 2010; West and Post, 2002). The decline shows that SOC 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, canola, barley, or lupin-based rotations—SOC sequestration rates decline because much of the carbon-containing plant mass is removed via grain harvest (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 57 and 44 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 0-30 cm 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 profit under optimal crop-pasture rotations. Under a base-case scenario, a farmer can maximise profit at about $48 ha^{-1} by using approximately 70 per cent of the available land for cropping activities (Fig. 2). The various profit-maximising rotations include annual or perennial pastures, cereal crops, and grain legumes (Appendix I). Note that the representative farm comprises eight different land management units and that the selected cropping and pasture activities are selected for each soil type simultaneously to provide the most profitable farming system overall. Figure 2 illustrates that SOC sequestration rates decline when more than 20 per cent of the land is committed to cropping, while profit increases up to a maximum at about 70 per cent cropping. This highlights a potential tension between the optimal enterprise mix for farmers and policy objectives to increase SOC.

4.2 Profit - SOC trade-offs

The SOC sequestration rates predicted by APSIM were combined with the profit-maximising rotations selected by MIDAS to show the relationship between potential SOC storage and farm profit, varying the area of the farm constrained to growing crops (Fig. 3). These results are based on the 30-year simulated average SOC sequestration rates. Although 30 years 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 generation-long farm management planning. The curves in Figure 3 show the trade-offs between potential SOC 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 0-30 cm soil layer

A change in enterprise mix to achieve higher rates of SOC-sequestration is likely to reduce farm profits. In Figure 3, this movement along the base-case tradeoff curve is indicated by the black dotted arrow. 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 SOC 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 $48 ha\(^{-1}\). 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 $3.4 ha\(^{-1}\)—as would be expected given the flat payoff curve around the point of profit maximisation (Pannell, 2006)—while increasing the average SOC sequestration rate by about 10.7 kg C ha\(^{-1}\).yr\(^{-1}\) (= 0.034 tCO\(_2\)-e). This means that the extra sequestration will cost the farmer approximately $87 per tonne of CO\(_2\) (as average reduced profits over 30 years). More substantial increases in SOC sequestration (moving further 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 more than $50 ha$^{-1}$ under the base-case commodity price scenario. SOC sequestration rates would increase from 47 to 103 kg C.ha$^{-1}$yr$^{-1}$, implying a cost per tonne of CO$_2$ sequestered of more than $240. Our estimates should be considered as indicative values, given limitations of the model and data. Nevertheless, these SOC sequestration costs illustrate 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 SOC sequestration will thus depend on a range of factors including commodity prices. We therefore analysed the sensitivity of our results to changing commodity prices, of which the high-price scenarios are presented here.

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, may be as high as $166 per hectare per year. Under this price scenario, changing the mix of rotations to maximise SOC sequestration (i.e. limiting the amount of land under crop from 100 to 20 per cent) would considerably reduce farm profits—from $166 to approximately $22 ha$^{-1}$yr$^{-1}$ at 50 per cent residue retention—while SOC sequestration rates increase by about 94 kg C.ha$^{-1}$yr$^{-1}$ (= over 400 $.t^{-1}$ 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 with a smaller reduction in profit. However, even under high prices for livestock products, attempting to achieve sequestration rates over about 35 kg C.ha$^{-1}$yr$^{-1}$ would cost more than $190 t^{-1}$ CO$_2$-e (Section 5, Figure 5).

4.3 Impacts of residue retention

The above analysis shows the trade-offs between profit and SOC sequestration potential for different farm enterprise mixes and commodity price scenarios with the base-case scenario of 50 per cent residue 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 SOC sequestration. Therefore, we also analysed a scenario where none of the crop stubble could be grazed or removed.

From a biophysical perspective, 100 per cent residue retention generally increased the amount of sequestration, because more organic material remained in the system where it could contribute to SOC. However, it also saw profits of the mixed-cropping livestock farm decrease because the crop
stubbles—which represent a significant source of summer feed—were no longer available (Fig. 4.). The combinations of rotations at which a farmer can maximise profits are indicated by points $C_{50}$ and $C_{100}$ in Figure 4. A profit-maximising farmer who currently retains 50 per cent residue would store SOC at an average rate of 47 kg C.ha$^{-1}$.yr$^{-1}$ over a 30 year period ($C_{50}$ in Fig. 4). If this farmer were to move to full residue retention ($C_{100}$), SOC-sequestration rates could increase to more than 130 kg C.ha$^{-1}$.yr$^{-1}$. This indicates that, if residue retention were not already widely adopted, policies aimed at promoting residue retention could achieve significantly higher rates of SOC sequestration.

![Figure 4](image.png)

**Fig. 4.** Trade-offs between annual profit and SOC-sequestration (top 30 cm soil, averaged over 30 year period) at 50% and 100% residue retention.

* The points on each curve represent varying proportions of farm in crop. C = profit maximising mix of rotations, D = SOC-maximising mix of rotations

Consider a situation where a farmer has already adopted full residue retention practices, and is operating at point $C_{100}$. If this farmer were to increase the area of pastures to increase SOC sequestration close to maximum attainable rates (to the point indicated by $D_{100}$), profit would reduce by nearly $51 ha^{-1}.yr^{-1}$. Although this reduction is similar to a farmer who would move from $C_{50}$ to $D_{50}$, the increase in SOC sequestration rates is distinctly lower. Under the base-case retention scenario, moving from 70 to 20 per cent cropping ($C_{50}$ to $D_{50}$) would increase the annual rate of SOC sequestration.
sequestration by nearly 57 kg C.ha\(^{-1}\).yr\(^{-1}\). The same reduction in crop area would increase annual SOC-sequestration rates by only 31 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 SOC sequestration rates through a change in the crop-pasture mix.

5. 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 SOC 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. Given the discrete nature of our analysis (based on constraining the proportion of farm land allocated to cropping), the changes in profit and average SOC sequestration were calculated for a step-wise, 10 per cent, reduction in proportion of crop land. It is assumed that the farmer will initially operate under a profit-maximising mix of rotations (ignoring carbon payments). The annual payment \(p_{\text{comp}}\) required to compensate for the reduction in profits as calculated as:

\[
p_{\text{comp}} = (\Delta \pi / \Delta SOC) \cdot 3.667 \times 10^{-3},
\]

where \(\Delta \pi\) is the change in annual profits, and \(\Delta SOC\) is the average annual SOC sequestered in the top 30 cm of soil in the first 30 years 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.
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 SOC 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 extra 60 kg C per hectare per year would be over $240 t^{-1} CO_{2}-e. In the same base-case scenario, smaller increases in SOC-sequestration are feasible at a lower reduction in profit. Nevertheless, even a small increase in SOC sequestration of about 10 kg C.ha^{-1}.yr^{-1} would still require payments of $87 t^{-1} CO_{2}-e (at base-case prices). This is considerably more than the initial carbon price of $23 per tonne proposed in Australia climate policies (Garnaut, 2011).

The ‘flat’ areas along the curves in Figure 3 (e.g. the move from crop-pasture mix X to mix Y in the high-sheep price scenario) might suggest that large increases in SOC sequestration are achievable at low costs. However, the results indicate that the increase of approximately 20 kg C.ha^{-1}.yr^{-1} would still reduce farm profits by about $5 ha^{-1}.yr^{-1}. This equates to a compensation of about 35 $ t^{-1} CO_{2}-e (asterisk in 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...
As discussed in Section 4.3, moving from 50 per cent to 100 per cent residue retention may reduce farm profit (by about $12 ha^{−1}.yr^{−1}$) but can increase SOC-sequestration rates (by about 86 kg C ha^{−1}.yr^{−1}). This implies that $38 t^{−1} CO_2-e$ would be needed to compensate this farmer for reductions in profit (Fig. 6). However, there are notable differences in the sequestration rates that can be achieved by changing crop-pasture rotations given a certain level of residue retention. If profit losses would be compensated, less than $100 t^{−1} CO_2-e$ could achieve up to about 27 kg C-sequestration per hectare under both the 50 per cent and 100 per cent residue retention scenarios. But increasing sequestration further (by changing rotations) will come at a considerably higher profit loss for the farmer who has already adopted residue retention.

**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

### 6. Discussion and 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 SOC 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. 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 make approximately $48 ha\(^{-1}\) yr\(^{-1}\), and would sequester about 47 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 SOC sequestration rates, but generate lower farm profits than annual cropping. A farm with approximately 80 per cent of the available land under pasture could potentially sequester over 103 kg C ha\(^{-1}\) yr\(^{-1}\), but would make a loss of about $3 ha\(^{-1}\) yr\(^{-1}\). This indicates that changing crop rotations to increase the level of SOC 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 SOC 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 $87 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 SOC sequestration may cost farmers less, but would still require a compensation of more than $340 per t CO\(_2\)-e, to store an additional 17.5 kg C ha\(^{-1}\) yr\(^{-1}\). Given carbon prices discussed in the 2010/2011 Australian public debate never exceeded $30 per t CO\(_2\)-e this suggests that the potential to mitigate emissions through SOC sequestration is likely to be limited in this farming system.

The relative increase in SOC as a result of changing farm enterprise mix is affected by residue retention rates. SOC-sequestration rates are greater at higher rates of residue retention. Based on this analysis, one could argue that policy makers should stimulate farmers to retain a higher proportion of residues to achieve higher SOC sequestration rates. However, paying farmers to adopt residue retention may be inconsistent with the current proposed criterion for “additionality” in Australia. Additionality is a key feature of most carbon policies, and involves a requirement that the activity creates additional sequestration / reductions in emissions than would have occurred under a ‘business-as-usual’ scenario. Previous studies have shown that a large proportion of farmers have already adopted residue retention systems (Kearns and Umbers, 2010; Llewellyn and D’Emden, 2010). Therefore, increasing residue retention rates may not satisfy the “additionality” criterion.

A similar point could be made regarding increased proportions of pastures or perennials in the farm enterprise mix. To be eligible as a genuine offset, the activity must not be common practice in the region (Parliament of the Commonwealth of Australia, 2011). Given the variation in crop-pasture mixes between farms and regions, it is still uncertain (at the time of writing) under what conditions increasing pastures would be recognised as an additional practice under the CFI.
A number of issues should be considered when interpreting our results. First of all, the current analysis does not incorporate how different crop-pasture mixes affect agricultural GHG emissions. It has been estimated that current livestock production contributes nearly 42 per cent of Australia’s total rural GHG emissions (Sparkes et al. 2011). Although increasing annual pastures in the enterprise mix will enhance SOC sequestration, the subsequent increase in the number of sheep on a (profit-maximising) farm will significantly increase GHG 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 should accordingly be deducted from any sequestration gains. Further work is needed to compare the emissions associated with agricultural production against soil carbon sequestration potential. GHG emissions would include those generated by livestock through enteric fermentation and animal waste; fertiliser emissions; nitrogen fixing crop emissions; crop residue emissions; and fuel emissions produced during crop establishment, harvest, chemical and fertiliser application (Kingwell, 2009). A second important issue is that soil carbon sequestration may require application of additional nutrients (e.g. nitrogen and sulphur) to allow the carbon to be stored in a stable form (Kirkby et al., 2011). Nutrient application in the form of fertiliser would involve additional cost that would further reduce the economic attractiveness of the sequestration activities.

Readers should bear in mind that the estimated sequestration potential depends largely on assumptions about soil types and climatic conditions. The analysis presented in this paper is based on a representative bio-economic farm model for the Central Wheatbelt of Western Australia; a crop dominant and fairly dry Mediterranean agricultural zone, with low SOC soils. Different soil types, farming systems, 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 SOC 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 SOC 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 SOC 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 SOC 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 than those estimated here. 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 and are likely to present additional barriers to adopting carbon farming practices.

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References


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Kragt et al. (2012) Assessing costs of soil carbon sequestration by crop-livestock farmers


### Appendix i. Profit-maximising crop-pasture rotations selected in MIDAS in the base price scenario

<table>
<thead>
<tr>
<th>Proportion of farm-land in crop</th>
<th>Most profitable rotations (allocation proportions varying per soil-type)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td>No feasible solutions</td>
</tr>
<tr>
<td>10%</td>
<td>PPPP, PPPW, 3UWB</td>
</tr>
<tr>
<td>20%</td>
<td>PPPP, PPPW, 3UWB, WWF</td>
</tr>
<tr>
<td>30%</td>
<td>PPPP, PPPW, 3UWB, WNWL, WWF</td>
</tr>
<tr>
<td>40%</td>
<td>PPPP, PPPW, 3UWB, WBL, WNWL, WBL</td>
</tr>
<tr>
<td>50%</td>
<td>PPPP, PPPW, 3UWB, WNWL, WWBK</td>
</tr>
<tr>
<td>60%</td>
<td>PPPP, PPPW, 3UWB, WBL, WNWL, WWBK</td>
</tr>
<tr>
<td>70%</td>
<td>PPPP, PPPW, 3UWB, NWBLD, WBL, WNWL, WWBK</td>
</tr>
<tr>
<td>80%</td>
<td>PPPP, 3UWB, NWBLD, WBL, WNBK, WNBL, WNWL, WWBK</td>
</tr>
<tr>
<td>90%</td>
<td>PPPP, 3UWB, NWBLD, WBL, WNBK, WNBL, WNWL, WWLD</td>
</tr>
<tr>
<td>100%</td>
<td>NWBLD, WBL, WNBK, WNBL, WNWL, WWLD</td>
</tr>
</tbody>
</table>

3U = 3 years lucerne; B = barley (*Hordeum vulgare*); F = field pea (*Pisum sativum*); K = chick peas (*Cicer arietinum*); L = lupin (*Lupinus angustifolius*); LD = dry sown lupin; N = canola (*Brassica napus*); P = annual pasture; W = wheat (*Triticum aestivum*).
Appendix II. Selected rotations on different soil types and their modelled 30 year average soil C-sequestration rates (kg C.ha$^{-1}$.yr$^{-1}$ in 0–30 cm topsoil) by soil category.

<table>
<thead>
<tr>
<th>Rotation</th>
<th>C-sequestration (kg C.ha$^{-1}$.yr$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Poor sand</td>
</tr>
<tr>
<td>NWBLD</td>
<td>20</td>
</tr>
<tr>
<td>PPPP</td>
<td>157</td>
</tr>
<tr>
<td>PPPW</td>
<td></td>
</tr>
<tr>
<td>3UWB</td>
<td></td>
</tr>
<tr>
<td>WBLD</td>
<td></td>
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<tr>
<td>WBL</td>
<td></td>
</tr>
<tr>
<td>WNBLD</td>
<td></td>
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<tr>
<td>WNBF</td>
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