Potential change of soil carbon in Australian agro-ecosystems as affected by conservation management: data synthesis and modelling

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Abstract
Conservation agricultural practices (CAPs) have been suggested to be an effective way to enhance carbon (C) sequestration in agricultural soils to mitigate climate change. In this paper, we synthesised data from 49 peer-reviewed papers to examine the effects of adopting CAPs on soil C dynamics in Australian agro-ecosystems. We also used the Agricultural Production Systems Simulator (APSIM) to simulate changes in soil C under an annual wheat system as affected by nitrogen (N) application and stubble management across the Murray-Darling Basin (MDB). These results show that in Australian agro-ecosystems, cultivation led to C loss for more than 40 years, with a total loss of ~50% in the surface 0.1 m of soil. Adoption of CAPs generally increased soil C. Increasing crop frequency and perennial crops, when combined with stubble retention, had the greatest impact on increasing soil C, but the long-term impacts remain unclear. The same CAPs can have different outcomes on soil C under different climate and soil combinations. Modelling results using APSIM show that under an annual wheat system, 100% stubble retention and optimal N supply would lead to a basin-wide average increase in soil C of 8 Mg ha^{-1} to a depth of 1.5 m in 100 years. Under such a system, the rates of soil C accumulation increases along a transect from northwest to southeast of MDB. Fertilization and stubble retention must be combined in order to achieve the full C sequestration potential of the system. A modeling approach, combined with measurements, is an effective way to estimate the spatial distribution of soil C sequestration.

Key Words
Soil carbon sequestration, cropping system, tillage, stubble management, fertilization, climate.

Introduction
Cultivation of natural ecosystems has led to significant loss of carbon (C) from soil. Adoption of conservation agricultural practices (CAPs) has been widely recommended to enhance C sequestration in agricultural soils to mitigate climate change (Smith 2004; Lal *et al.* 2007). Lal (2004) estimated that the world cropland soils could potentially sequester 0.4-0.8 Pg C per year by adopting CAPs. This would correspond to 33.3-100% of the total potential of C sequestration in world soils. However, different CAPs will have distinct impact on soil C dynamics depending on soil, climate, and/or other agricultural practices (West and Post 2002; Chan *et al.* 2003; Christopher *et al.* 2009).

The impact of different CAPs on soil C has been extensively studied in recent years in Australian agro-ecosystems (Wells *et al.* 2000; Chan *et al.* 2003; Valzano *et al.* 2005). The most commonly held view is that CAPs lead to an increase in soil C. However, research results are inconclusive and vary depending on the specific CAPs and environmental conditions. For example, Heenan *et al.* (1995) showed that different agricultural practices caused significant differences in the soil organic C trend over 14 years, ranging from no change to an annual loss of 400 kg ha^{-1}. Several studies divided Australian agricultural areas into wetter (rainfall > 500 mm) and drier regions (Chan *et al.* 2003; Valzano *et al.* 2005), and found that whilst the adoption of conservation tillage increased soil C in wetter regions, it could not reverse the decline of soil C of croplands in drier regions. These inconsistencies in results may be due to the mix of different types of CAPs as well as the impact of different environments where the experiments were conducted. It is necessary to understand the effects of specific CAPs on soil C change, and how the interaction of climate, cropping systems and management strategies determine the net change in soil C in the different agro-ecological zones. In this paper, we synthesise the available information on soil C change following cultivation and the adoption of CAPs in Australian agroecosystem, and review the effects of adopting CAPs (i.e., the enhancement of rotation complexity, stubble retention and conservation tillage, and fertilization) on soil C content over time and space. Additionally, we use simulation modelling to investigate the potential capacity of soil to sequester C under different management scenarios and climate condition across the Murray-Darling Basin of Australia.

Methods and Materials

Synthesis of available data from literature

We focused on three major types of CAPs: i) cropping systems and rotation, ii) stubble management and tillage, and iii) the application of fertiliser. First, we extracted data from 49 peer-reviewed papers that studied the responses of soil C to adoption of CAPs in Australia. These data include the duration of experiments, soil sampling depth, soil C, soil type, and types of CAPs. For each CAP type and study, we calculated the relative change of soil C (C_r) under CAPs relative to conventional agricultural practices in paired experiments (i.e., other conditions and duration were kept similar), i.e., C_r = *(soil C under CAPs – soil C under conventional practices) / soil C under conventional practices x 100*. The relative change of soil C as affected by the duration of experiment and soil type were analysed for each type of CAPs.

Due to the complexity of the cropping systems in the selected studies, the CAPs involved changes of crop types and rotation types. We further divided them into three categories: 1) increased crop diversity (ID), referring to a change from continuous monoculture to continuous rotation, 2) increased cropping frequency (IF), a change from one crop per year to two or more crops per year, and 3) increased perenniality (IP), a change from annual crops to a rotation with perennial crops. To assess the effects of nitrogen-fixing plants on soil C content, we also separated rotation systems with and without legume crops (e.g., wheat-cotton rotations vs. wheat-chickpea rotations). Further, we analysed the soil C change between cropping systems with and without a fallow period.

The APSIM simulation

In order to examine how soil C changes in agricultural soils are affected by climate variation and management options, we used the Agricultural Production Systems Simulator, APSIM (Keating *et al.* 2003) version 6.0, to conduct long-term simulations. The model APSIM has been designed and developed for simulation of plant and soil processes by allowing flexible specification of management options. It provides the functionality to model soil C change as affected by environmental and management changes through its SoilN and SurfaceOM modules.

A simplified continuous wheat system was assumed to represent an annual cropping system, and one soil type with a plant available water holding capacity of 139 mm and total C content of 59 Mg ha^{-1} in the 1.5m soil profile was used in the simulation. The main focus was to quantify the impact of climate and managements (N application & stubble management) on relative changes in soil C. Seventy three sites, roughly uniformly distributed across the Murray-Darling Basin, were selected and historical weather data from 1889 to 2006 were obtained from the SILO database (http://www.longpaddock.qld.gov.au/silo/) and used in the simulations. Simulations were carried out to investigate the impact of nitrogen (N) and stubble managements on soil C. Three levels of N application rates (zero, 150 and 300 kg N ha^{-1}) and three stubble management options (100% removal, 50% removal, and retention) were simulated. For the 150 and 300 kg N ha^{-1} application, N application was split into two applications: 50 kg N ha^{-1} at sowing and the rest as a top-dressing at stem elongation stage. Stubble managements were implemented after harvesting. Soil C change under each management practice scenario was calculated as the difference of simulated total soil C in the soil profile (1.5 m) between 2006 and 1889. Multiple regression analysis was applied to assess the relationship between soil C change and climate conditions (i.e., mean annual rainfall and temperature).

Results – Synthesis of literature

Soil C loss after cultivation

Cultivation has led to a reduction in soil C in Australia. Combining data from 20 published studies that reported the C status in adjacent natural soils across Australian agro-ecosystems the result shows an exponential loss of soil C after cultivation, with most loss occurring in the first 10 years. A quasi equilibrium was reached after about 50 years of cultivation. The total loss of soil C in the surface 0.1 m was 51%, and the loss in the surface 0.3 m of soil was variable, ranging from 0.9 to 73.4%.

Soil C change after adopting CAPs

Cropping systems and rotation: Soil C content increased in the first few years after increasing crop complexity (i.e., ID, IP and IF) and remained stable thereafter. Compared with monoculture (with or without long-fallow) as the baseline, increased crop frequency (IF) and perenniality (IP) led to significant increase in soil C (10.1%, $F_{(2, 209)} = 22.72$, $P < 0.01$), while increased crop diversity (ID) only resulted in 5.3% increase in soil C. Introducing annual legumes into the rotation did not lead changes in soil C compared with nonlegumes. Introducing perennial plants into rotation caused the most significant increase in soil C, especially compared with continuous cropping with a fallow.

Soil C change after adopting different cropping practices varied with soil types. Crop diversity increased soil C content by 10% in Kandosols, 6% in Dermosols and 3.5% in Vertosols. Increasing crop frequency had the greatest impact on soil C content in Dermosols (56%, $n = 3$), while IP had the greatest impact on Vertosols (15.2%). On average, soil C content increased by 16.9% in Dermosols, which is markedly higher than the 8.5% and 10.3% increases in Vertosol and Kandosol soils, respectively ($F_{(2, 200)} = 2.99$, $P = 0.051$). However, different soils have distinct baselines of soil C content under the conventional agricultural practices ($C_{Conventional}$) and the limited datasets do not allow for detailed analysis to trace the exact causes for such changes.

Stubble management and tillage: Combining stubble retention and conservation tillage increased soil C content by 16.4% compared with stubble burning and conventional tillage. The impact of this combination was significantly higher than the impact of separate application of these two practices, with 5.7% for stubble retention only and 2.96% for conservation tillage only.

There is no apparent relationship between the magnitude of soil C change and the duration of both conservation stubble and tillage management. Both stubble retention and conservation tillage do not appear to lead to significant changes in soil C content in long-term (>30 years) based on currently available data. The effects of adoption of conservation stubble and tillage on potential soil C sequestration are dependent on soil types ($F_{(3, 273)} = 26.90$, $P < 0.001$). Soil C content increased by 26% on Kandosols, which is significantly higher than the 6.31% and 11.82% measured on Sodosols and Chromosols, respectively. Kandosols have a relatively higher baseline soil C content and the greatest increase in soil C among the four soil types. Vertosols show the lowest C increase of 3.3% following the adoption of conservation management. However, Vertosols have the highest soil C baseline, which makes the amount of soil C accumulation comparable with Sodosol and Chromosol.

Fertilization: In Australia, the response of soil C change to fertilization is largely dependent on available water supply to the crops. Higher N input occurs mostly in wet areas. After synthesising the data from 8 published studies on the relative change of soil C content ($F_{(4, 70)} = 16.27$, $P < 0.001$), the results indicated that, soil C increased with N input levels. However, the soil C did not continue to increase after the first several years.

Results - Modelled effects of fertilization and stubble retention on soil C and its dependence on climate

The APSIM simulation results show that in the Murray-Darling Basin, soil C would decrease rapidly under a continuous wheat cropping system if no fertiliser was applied or if all crop stubble was removed. At the basin-scale, if the crop growth is not limited by nitrogen stress (under optimal N supply, less than 150 kg N ha^{-1} for most cropping regions), at least half of the crop residue needs to be retained in the field in order to maintain the soil C level (to balance the C inputs with decomposition processes). Retaining all the stubble and optimal N supply would lead to a basin-wide soil C increase by around 8 Mg ha^{-1} in the upper 1.5 m of soil within 100 years.

The spatial pattern of the soil C change was significantly correlated with temperature and rainfall. Under the annual wheat system with 150kg N ha^{-1} and 50% stubble retention, the C accumulation rate increases along a transect from northwest to southeast of the basin. The simulated rate of change in soil C is negatively correlated with both temperature and rainfall in all simulation treatments, with the exception of high N (150 or 300 kg N ha^{-1}) combined with full stubble retention treatments, for which a positive correlation with rainfall was found. This implies that only under full stubble retention and optimal nitrogen supply can the soil C accumulation increase with productivity as a result of increasing rainfall.
Whether the agricultural soil is a C sink or source is dependent on local climatic conditions, cropping system and management strategies. Under the annual cropping system simulated with optimal N application, only about one third of the cropping regions were predicted to be C sinks. In contrast, if optimal N is applied and all the stubble is retained, more than 90% of the cropping regions may become C sinks.

Discussion and Conclusion

Soil C content decreased exponentially after cultivation in Australian agro-ecosystems. Although CAPs are considered to be effective to increase soil C, there are large variations in the effects of various CAPs over time and space. The review results show that only when increased crop frequency and perenniality are

combined with stubble retention can soil C be significantly increased. Other types of CAPs (e.g. no-tillage) had a lesser impact on total soil C change. Based on the available data, no consistent trend of increase in soil C can be found with the duration of CAPs applications. A question remains as to the long-term effectiveness of CAPs to sequester soil C. The impacts of fertilization are largely dependent on climatic regions and how the crop stubble is handled; a finding consistent with the APSIM simulation results. The modelling results show that the interaction of climate, soil, cropping and management systems determines C assimilation of the soil-plant system, the flux of C in and out of the soil, and thereby determines the net change in soil C.
In summary, the long-term impact of CAPs on soil C change is still inconclusive. Most of the studies are based on a limited number of experiments conducted at specific locations (climate and soil combinations) and in a relatively short period. Lack of explicit separation of different management options makes it difficult to analyse the impact of individual options. In addition, most studies are based on sampling obtained from only the top 20 cm soil and change in soil C in deeper soil are not considered. Due to the complexity of cropping systems and the large spatial variation of soils and climate, an experimental approach is always limited and impractical for spatial assessment of the soil C change region-wide. A system modelling approach based on sound understanding of processes in the soil-plant-atmosphere system provides an effective means to explore the impact of the complex interactions on soil C change.

Acknowledgement
The funding support from the CISRO-MOE (Ministry of Education, China) Scientific Exchange Agreement is gratefully acknowledged.

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