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Sustainable limits to crop residue harvest for bioenergy: maintaining soil carbon in Australia's agricultural lands

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Abstract

The use of crop residues for bioenergy production needs to be carefully assessed because of the potential negative impact on the level of soil organic carbon (SOC) stocks. The impact varies with environmental conditions and crop management practices and needs to be considered when harvesting the residue for bioenergy productions. Here, we defined the sustainable harvest limits as the maximum rates that do not diminish SOC and quantified sustainable harvest limits for wheat residue across Australia's agricultural lands. We divided the study area into 9432 climate-soil (CS) units and simulated the dynamics of SOC in a continuous wheat cropping system over 122 years (1889 – 2010) using the Agricultural Production Systems sIMulator (APSIM). We simulated management practices including six fertilization rates (0, 25, 50, 75, 100, and 200 kg N ha^{-1}) and five residue harvest rates (0, 25, 50, 75, and 100%). We mapped the sustainable limits for each fertilization rate and assessed the effects of fertilization and three key environmental variables – initial SOC, temperature, and precipitation – on sustainable residue harvest rates. We found that, with up to 75 kg N ha^{-1} fertilization, up to 75% and 50% of crop residue could be sustainably harvested in south-western and south-eastern Australia, respectively. Higher fertilization rates achieved little further increase in sustainable residue harvest rates. Sustainable residue harvest rates were principally determined by climate and soil conditions, especially the initial SOC content and temperature. We conclude that environmental conditions and management practices should be considered to guide the harvest of crop residue for bioenergy production and thereby reduce greenhouse gas emissions during the life cycle of bioenergy production.

Keywords: bioenergy, crop model, lignocellulosic biofuel, management, residue harvest, soil carbon, sustainability

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Introduction

Climate change and rising fuel prices have stimulated the harvest of crop residues for bioenergy production (Hill *et al.*, 2006). Second-generation biofuel produced from crop residue has the potential to curb greenhouse gas (GHG) emissions, enhance energy security, benefit local environments and rural area economies, yet not compete for land with food production (Tilman *et al.*, 2009). Wheat residue has been recognized as a primary lignocellulosic material for biofuel production in Australia. O'connell *et al.* (2007) estimated that the upper limits for second-generation biofuels production could be between 10 and 140% of current petrol usage in Australia's transportation sector. The large uncertainties in this estimate mainly resulted from a lack of information on the environmental and economic sustainability. The limiting factors should be balanced to make the biofuel production sustainable (Wilhelm *et al.*, 2010). Within a sustainable limit with regard to the environmental impacts, even modest crop residue harvest rates can provide a significant amount of bioenergy feedstock.

Crop residue plays a key role in replenishing soil organic carbon (SOC) (Zhao *et al.*, 2013b) and nitrogen pools (Rasmussen *et al.*, 1980), reducing soil erosion (Laflen & Colvin, 1981), preserving soil moisture (Govaerts *et al.*, 2007), and maintaining soil productivity (Mann *et al.*, 2002). Residue harvest could reduce SOC and diminish soil fertility. The effects depend on the amount of residue produced and harvested, and the environmental conditions (Powlson *et al.*, 2011). In some environments with proper management, part of the residue could be harvested without negatively affecting

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SOC and mitigate the N_2O emission, which is a potent greenhouse gas (GHG) and ozone depleting substance (Chen *et al*., 2013). The SOC change accounts for a large share of GHG emissions in cropping land (Follett, 2001; Lal, 2004a). Thus, the impact of residue harvest on SOC should be quantified in assessments of the life cycle GHG emissions from bioenergy (Blanco-Canqui, 2012; Kochsiek & Knops, 2012). To produce residue-based biofuel in an environmentally and economically sustainable way, the negative effects on the SOC should be taken into account. A comprehensive and objective assessment of the effects of different residue harvest rates on SOC is needed before using crop residue as a source of feedstock for bioenergy production (Lal, 2005; Sparling *et al*., 2006; Blanco-Canqui & Lal, 2007). Here, we address this knowledge gap by quantifying the maximum residue harvest rates for sustaining SOC stocks in Australian croplands.

The effects of residue harvest on SOC depend on a range of factors including crop types, climate and soil conditions, previous land use, and management practices – especially tillage practices, fertilization, and organic amendments such as farmyard manure, slurry, or compost (Agbenin & Goladi, 1997; Lemke *et al*., 2010). A greater proportion of crop residue can be harvested sustainably (i.e. without diminishing SOC) from croplands with high primary productivity and a low SOC decomposition rate (Wilhelm *et al*., 2007). Primary productivity and SOC decomposition rates are influenced by environmental factors (i.e. initial SOC content, temperature, rainfall) and management practices such as tillage practices, fertilization, and crop rotation systems (Ransom *et al*., 2011; Luo *et al*., 2013). These factors, and their resultant influence on SOC, vary spatially (Van Der Hilst *et al*., 2012). Spatially explicit assessment is essential for informing the sustainable limits for crop residue harvest (Ransom *et al*., 2011). Zhang *et al*. (2010) provided a framework for estimating residue-based bioenergy feedstock in Australia using regional yield statistics data and land-use maps, but they did not consider the constraints from environmental sustainability. Long-term field experiments can quantify the impact of environmental and management variables on SOC (Van Wesemael *et al*., 2010), but it is impractical and expensive to comprehensively sample multiple climate, soil, and management practices over large areas. Alternatively, process-based models can be used to simulate the impact of environmental conditions and management practices on SOC and derive sustainable residue harvest limits. For example, Gollany *et al*. (2010) and Liang *et al*. (2008) used a carbon sequestration model (CQESTR) to simulate the effects of residue harvest on SOC dynamics to inform residue-based bioenergy production. Using a mechanistic model with different decomposition rates for different organic substrates, Neill (2011) concluded that crop residue management could reach a compromise between bioenergy production and soil conservation. Blanco-Canqui (2012) asserted that more work is needed to understand the effectiveness of mitigation strategies in different environmental conditions to overcome SOC loss when crop residue was removed.

In this study, we quantified the sustainable limits to residue harvest rates for maintaining SOC and guide agricultural management practices for bioenergy production. Sustainable limits were defined as the maximum rate of residue harvest that does not diminish SOC content over time. We used a process-based agricultural systems model – the Agricultural Production Systems sIMulator (APSIM, Keating *et al*. (2003)) – to simulate SOC dynamics under a wheat system over 122 years in Australia's cereal-growing regions. We mapped sustainable residue harvest limits for SOC under six fertilization rates to show the interactions between residue harvest and fertilization. We also investigated the response of sustainable limits to three environmental constraints and one management constraint. We discuss the implications for informing environmentally sustainable agricultural management practices in bioenergy feedstock production.

Materials and methods

Study area

The study area is dominated by dryland cropping (2.52×10^7 ha), grazing modified pastures (6.91×10^7 ha), irrigated cropping (1.14×10^6 ha), and irrigated modified pastures (8.75×10^5 ha) (Fig. 1, left). As climate and soil conditions are the main environmental factors that influence biomass production and SOC dynamics (Davidson & Janssens, 2006), we divided the study area into 9432 climate-soil (CS) units with homogeneous soil and climate properties (Fig. 1, right). These were defined by intersecting a layer of 38 climate zones created by the iterative *k*-means cluster analysis of historical monthly mean climate layers (maximum temperature, minimum temperature, rainfall, solar radiation), with a broad soil type classification layer (Mckenzie *et al*., 2005; Zhao *et al*., 2013b).

APSIM

APSIM is a process-based agricultural systems model that simulates crop growth and its interaction with soil and atmospheric environments under various management options of sowing, irrigation, fertilization, surface residue management, and tillage (Keating *et al*., 2003; Wang *et al*., 2002). In APSIM, the SoilN module – coupled with modules of soil water (SoilWat), surface organic matter (SurfaceOM), and plant

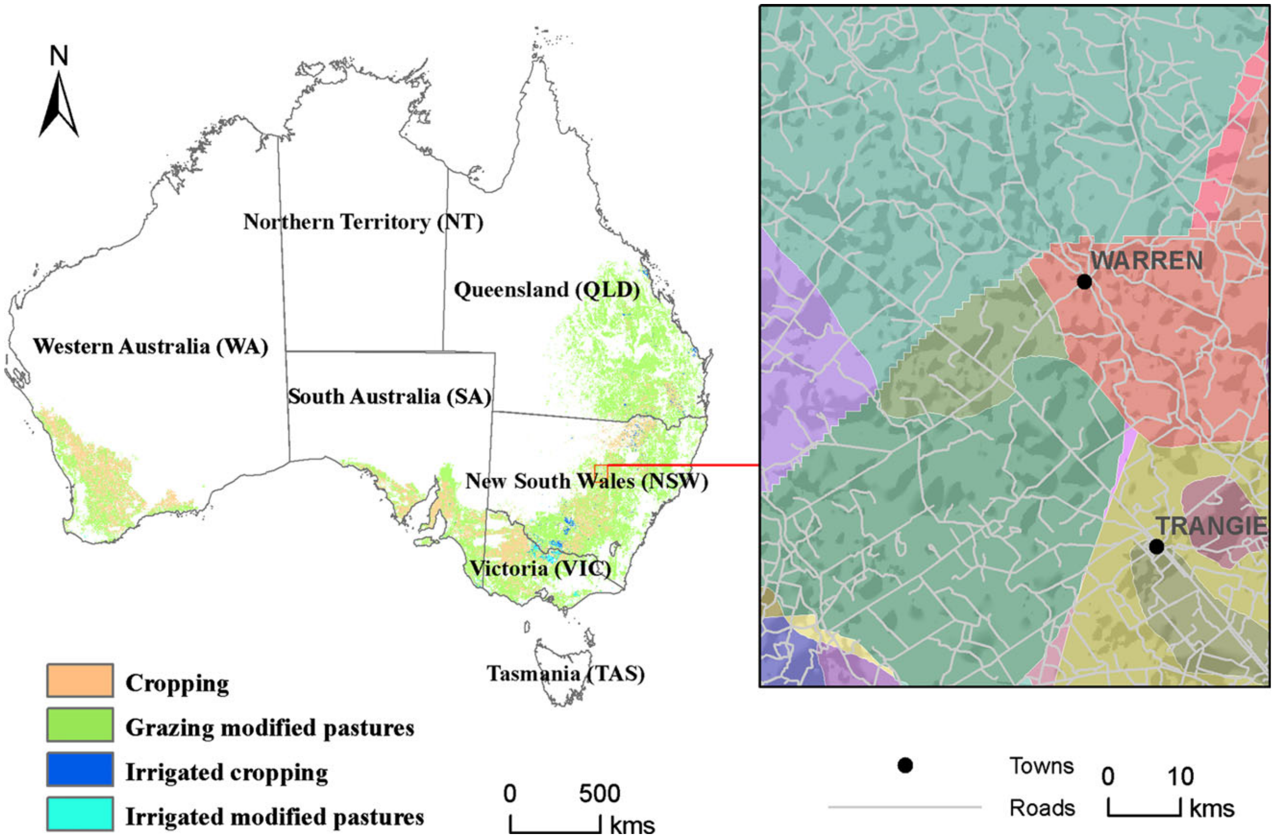

Fig. 1 Location and land use of the study area (left) and an example of the spatial scale of the CS units (right). Each of the CS unit was represented by a unique colour. The small cropping areas in Tasmania and the Northern Territory were not included in this study.

modules – simulates SOC dynamics on a daily time step (Probert *et al.*, 2005).

The SurfaceOM module simulates management impacts on surface residues which can be burnt, removed from the system, incorporated into the soil by tillage, or decomposed on the surface of the soil. The SoilN module simulates the SOC in three pools: fresh organic matter pool (FOM), microbial biomass pool (BIOM), and humic matter pool (HUM) (Keating *et al.*, 2003). The FOM pool receives matters from the roots and crop residues. According to the decomposition rate, the roots and crop residues in the FOM pool are further classified into three classes: carbohydrate-like, cellulose-like, and lignin-like. The BIOM pool simulates the soil microbial biomass and microbial products from the decomposed roots and crop residues. The HUM pool contains the rest of the matter. A maximum decomposition rate is set for each pool. Inert carbon in the HUM pool is assumed as indecomposable. Decomposition rates of each pool are mainly influenced by soil temperature and moisture. The products of decomposition of the FOM pool are CO_2 and organic carbon. The organic carbon is then transferred into the BIOM and HUM pools. The performance of APSIM in simulating SOC dynamics has been comprehensively tested in Australia against observed SOC data under a wide range of climate and soil conditions (Paustian *et al.*, 1992; Huth *et al.*, 2010; Luo *et al.*, 2011).

Climate and soil data

Continental-scale daily historical climate data layers [0.05° spatial resolution (Jeffrey *et al.*, 2001)] were obtained from the Bureau of Meteorology, Australia (http://www.bom.gov.au) over a period of 122 years (1889 – 2010). We summarized the climate data by calculating the spatial average for each CS unit (Zhao *et al.*, 2012). Soil parameters in five depths including bulk density, pH, drained upper limit, 15 bar lower limit (LL15), and layer depth were extracted from the Australian Soil Resources Information System (ASRIS) (Mckenzie *et al.*, 2005). As the initial SOC values in ASRIS only covered a small area, we obtained these layers from the ISRIC-WISE (≈9 km grid cell resolution), a global soil database (Batjes, 2006). We resampled these layers to 0.01° and calculated the average values for each CS unit.

Quantifying sustainable residue harvest rates

We simulated a continuous wheat cropping system, as wheat is a dominant crop in the study area. The sowing window, wheat cultivar, and sowing date were determined according to known local practices (Zhao *et al.*, 2013a). We simulated six fertilization rates (0, 25, 50, 75, 100, and 200 kg N ha^{-1}) and five residue harvest rates (0, 25, 50, 75, and 100%) for each CS unit over

122 years. In total, 282 960 (5 × 6 × 9432) simulations were run. The common fertilization rates in the regions were 50–80 kg N ha^{-1} (Zhao *et al.*, 2013b). Each simulation took about 4 min to finish, which presented a significant computing challenge. We overcame the challenge by running the simulations through a hybrid computing approach combining grid computing and parallel programming (Zhao *et al.*, 2013a).

Thirty-two years (1889–1920) of spin-up model runs were used to distribute the SOC over the carbon pools in a way that is realistic for the cropping system, thus minimize the sensitivity to initial model and data settings. Change in SOC (ΔSOC) between 2010 and 1920 in the top 30 cm of soil was calculated as: $\Delta SOC = SOC_{2010} - SOC_{1920}$. Under each fertilization rate, the highest residue harvest rate that can maintain positive ΔSOC was specified as the sustainable limit.

Influences on sustainable residue harvest rates

We assessed the impact of three environmental variables (initial SOC content, mean annual temperature, and mean annual precipitation) and one management variable (fertilization rate) on the sustainable limit. We chose these four variables as they were recognized as the most influential variables that determine ΔSOC in Australian agricultural regions (Zhao *et al.*, 2013b). For each of the three environmental variables, we classified the CS units into five categories or *quintiles* (e.g. 0th – 20th, 20th – 40th, 40th – 60th, 60th – 80th, and 80th – 100th). For each category, we calculated the proportion of the CS units with different sustainable limits (Fig. 3). For the management variable, for each of the six fertilization rates (0, 25, 50, 75, 100, 200 kg N ha^{-1}), we calculated the proportion of the CS units with different sustainable limits.

Results

Sustainable limits for residue harvest rates under the six fertilization rates varied significantly across the study area (Fig. 2). Without fertilization, no residue harvest was sustainable in the eastern agricultural regions, while harvest rates of 25 – 50% in a small part of south-western Western Australia (WA) could be sustained when considering SOC content as a limiting factor for residue harvest. With 50 kg N ha^{-1} fertilization, sustainable limits increased for all agricultural regions in south-western WA with 50 – 100% of crop residue, and between 25 and 75% of crop residue in south-eastern Australia able to be harvested sustainably. Almost no residue could be sustainably removed in the inland area of southern Queensland (QLD).

Agricultural lands with low initial SOC content (9–23 t C ha^{-1}) had higher sustainable limits with more than 25% of crop residue sustainably harvestable over almost 70% of these areas (Fig. 3). Croplands with high initial SOC content (48–116 t C ha^{-1}) had low sustainable limits and required high residue input to maintain SOC. Only 0–25% residue could be sustainably harvested from 65% of these areas. Sustainable limits slightly increased with warmer climate peaking around 14–16 °C, then decreased with further increases in temperature. Sustainable limits were notably lower in areas with precipitation ranging from 466 to 602 mm yr^{-1} than areas with precipitation ranging from 269 to 466 mm yr^{-1}. Fertilization of 75 kg N ha^{-1} increased sustainable limits, with the proportion of croplands with >25% sustainable limit increased from 1% to 50%. Higher fertilization rates (100 and 200 kg N ha^{-1}) did not appreciably increase sustainable limits further.

Discussion

Currently, the net energy production and GHG mitigation benefits of residue-based lignocellulosic bioenergy are inconclusive and further bioenergy policy development needs a full assessment of the environmental performance and social implications (Williams *et al.*, 2009). As crop residue management has a considerable impact on soil organic carbon (SOC), residue harvest could significantly influence the greenhouse gas emissions associated with lignocellulosic bioenergy production. The SOC is also essential for maintaining agricultural productivity and other aspects of soil health such as nutrient accessibility and water holding capacity (Bauer & Black, 1992). Spatially explicit, sustainable residue harvest rates such as those presented in this study can inform multiple aspects of agricultural management for food and bioenergy production. At a national scale, this information prioritizes more sustainable areas for development of bioenergy industries. Within these areas, this information can also guide agricultural management practices. Specifically, they can provide useful information for the spatial targeting of sustainable limits to the harvest of residue for bioenergy production for sustaining soil health and agroecosystem productivity. Several studies assessing the GHG emissions of bioenergy have considered the impacts on SOC at a local and/or point scale (Allmaras *et al.*, 2004; Blanco-Canqui & Lal, 2007; Clair *et al.*, 2008; Gollany *et al.*, 2011), despite climatic and soil conditions varying significantly over the landscape. Failing to consider spatial variation, uniform and excessive residue harvest rates over large areas could lead to unsustainable outcomes for SOC (Gregg & Izaurralde, 2010). This will have adverse effects on the net GHG accounting for bioenergy as well. These results can underpin the sustainable use of crop residues for bioenergy production in Australia.

Maps of sustainable residue removable limit under six fertilization rates illustrated that most of the study area attained the maximum sustainable harvest rates under fertilization of 75 kg N ha^{-1}. Higher fertilization rates (e.g. 100 kg N ha^{-1}) provided little marginal

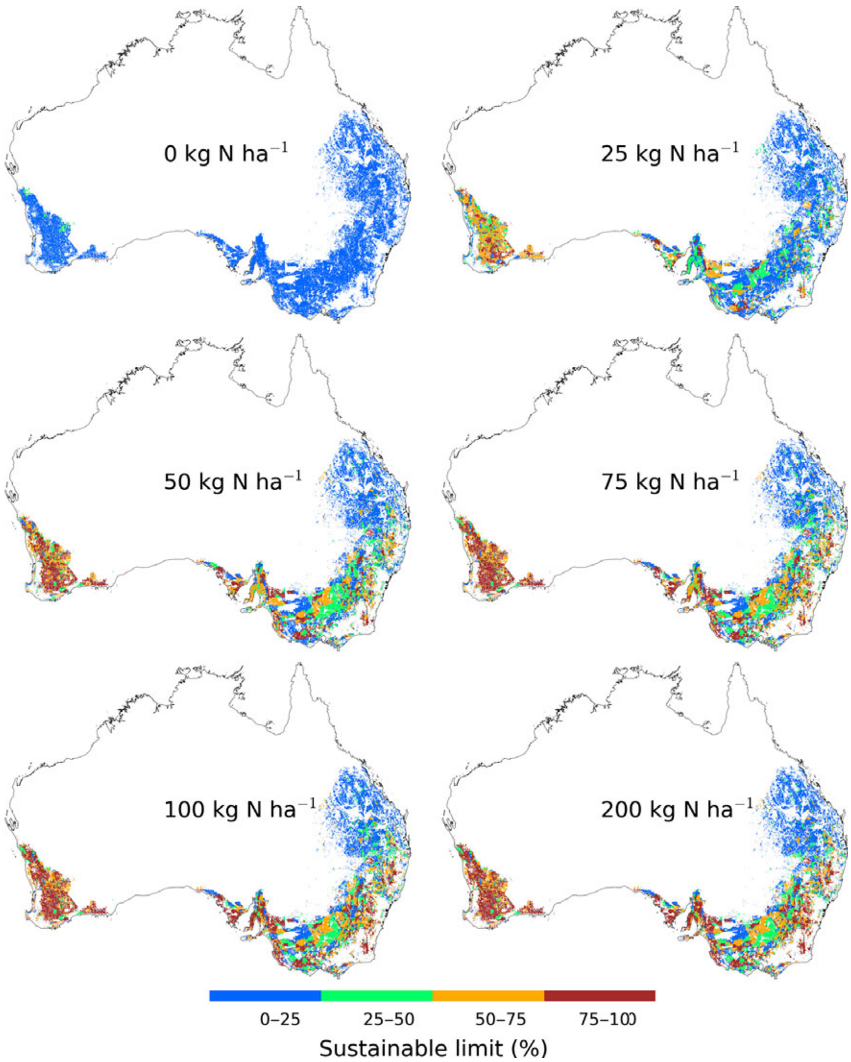

Fig. 2 Sustainable residue harvest limits under six fertilization rates of nitrogen (0, 25, 50, 75 100, and 200 kg N ha^{-1}).

increase in the removable residue rates (Fig. 2). This can be explained by fertilization switching the limiting factor of crop growth and primary productivity from nutrients to water supply. The low sustainable limit across much of Queensland was likely to be caused by the decomposition effects of higher temperature on SOC overwhelming the effects from fertilization (Dalal & Chan, 2001; Ranatunga *et al.*, 2001). In line with this study, both Bridge & Bell (1994) and Cogle *et al.* (1995) observed more than 50% loss of SOC in the tropical areas of Queensland after 50 years and 10 years of cropping, respectively. The high sustainable limits in WA are likely to be caused by the well-drained sandy soils (low initial SOC content) and the region's Mediterranean temperature and rainfall limiting decomposition (Henderson *et al.*, 1988). This indicated that a relatively low rate of fertilization could benefit both the grain yield and bioenergy production. A high rate of fertilization only could marginally increase the production of residue, while increasing N_2O emissions from cropland which have a much stronger effect on global warming (Huang & Tang, 2010; Xing *et al.*, 2011). Instead of fertilization, adding organic amendments such as livestock manure, slurry, or compost is another way to maintain the SOC in the cropland (Saviozzi *et al.*, 1999; Fronning *et al.*, 2008). The organic amendment could increase the SOC levels in a short-term and avoid the energy consumption and GHG emission in the process of fertilizer production and thereby improve the life cycle GHG balance of residue-based bioenergy production (Thelen *et al.*, 2010).

Croplands with low initial SOC content had high sustainable residue removal limits, and vice versa (Fig. 3). The main effect here is due to different baselines

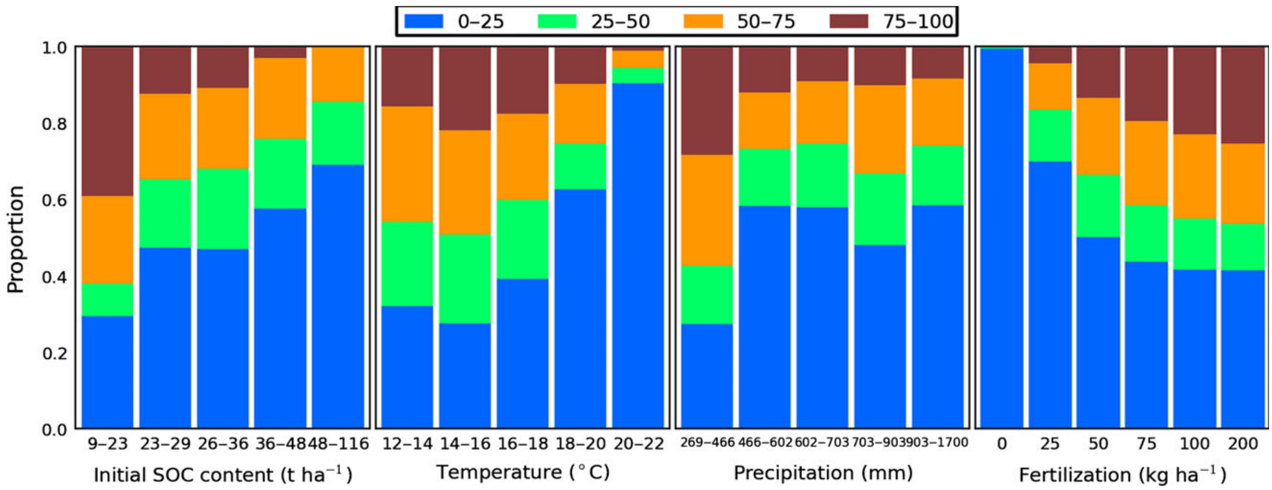

Fig. 3 Influence of four variables (initial SOC content, temperature, precipitation and fertilization) on the sustainable residue harvest limits. The vertical axis is the proportion of CS units that belongs to the four different sustainable limits in the cropping regions. The fertilization level for the graph of initial SOC content, temperature and precipitation was 50 kg ha^{-1}. The values for the horizontal axis of initial SOC content, temperature and precipitation were the 0th – 20th, 20th – 40th, 40th – 60th, 60th – 80th, and 80th – 100th of the values of these variables across all the CS units.

(Goidts *et al.*, 2009). Previous farming practices and land-use history are the major determinants of the initial SOC content (Aggarwal, 1995; Grogan & Matthews, 2002; Frazão *et al.*, 2013). Croplands with high initial SOC content cannot tolerate high residue removal rates and still maintain their high levels of SOC content. Conversely, in areas with low initial SOC content, fairly high rates of residue removal could be tolerated before reductions in SOC were observed. Nonetheless, despite the strong effect from the land-use history, residue removal from croplands with high initial SOC could reduce SOC content and negate the GHG mitigation potential of the bioenergy produced.

Croplands in colder climates and warmer climates both had relatively low sustainable limits (Fig. 3). Colder climates have not only lower decomposition rates but also lower productivity. Although warmer climates without water limitation normally promote crop productivity, high decomposition rates reduce sustainable limits (Guo & Gifford, 2002; Lal, 2004b). Hence, environmental conditions such as temperature and soil properties need to be considered when quantifying the net energy production and net reduction in CO_2 emissions of residue-based bioenergy (Anderson-Teixeira *et al.*, 2009; Blanco-Canqui, 2010).

Crop residue harvest within sustainable limits can be used for bioenergy production, contribute to energy security, without diminishing SOC, which is of great importance in maintaining the productivity of agricultural systems. We mapped sustainable harvest limits of wheat residue in the Australian croplands under six fertilization rates and analysed the impact of initial SOC, temperature, and precipitation on the sustainable limits. Sustainable limits were higher in areas of low initial SOC, lower in warmer climates, and increased with fertilization, up to 75 kg N ha^{-1}. Our results can guide sustainable agricultural management practices for bioenergy production and improve the GHG mitigation potential of bioenergy produced from crop residues.

Limitations and future directions

One limitation of this study is the reliance on a single, continuous wheat farming system, while the land use of the agricultural lands is dominated by pasture (Fig. 1). Rotations influence several aspects of the farming system including yield, soil carbon, and water balance (West & Post, 2002). For example, Brandão *et al.* (2011) found significant differences in GHG emissions between different cropping systems. Consideration of different crops and rotations requires time series data for land use and management practices that were unavailable. Future work should consider new techniques for incorporating rotations (Bryan *et al.*, 2011). Additionally, APSIM predicts the production potential of a site based on environmental and management parameters. In reality, a range of other factors (e.g. pest, weed, crop disease) also conspire to reduce crop biomass production. This will further decrease sustainable residue harvest rates (Blanco-Canqui & Lal, 2009).

We found the sustainable limits were very sensitive to the initial SOC. The initial SOC values were derived from the ISRIC-WISE soil database, which had a relatively low spatial resolution, 9 × 9 km, although it covered the whole study area. Although every effort was made to use the best available data, the quality of initial SOC values is a source of uncertainty in the results of this study. To reduce the uncertainty of the SOC change to the initial distribution of SOC over the various pools, the first 32 years (1889–1920) of model runs were excluded in calculation of the SOC change. Hence, the 32-year spin-up model runs were used to distribute the SOC over the three carbon pools in a way that is realistic for the cropping system, which significantly decreased the sensitivity of sustainable limits to the initial SOC (not shown). As the historical initial SOC contents are rarely known in a large-scale study, spin-up model runs are essential for reducing the uncertainty of unstable initial condition of the simulation.

Crop residue harvest may also have other deleterious effects such as increasing the risk of soil erosion by wind and water runoff. The effects of harvesting residue on soil erosion depend on the rainfall intensity, soil properties, topography of the cropland and tillage regimes (Laird & Chang, 2013), all of which could display a significant spatial heterogeneity at a large scale. Future studies might consider setting a tolerance level to minimize the impact of residue harvest on soil erosion (Lindstrom, 1986). Empirical models like the universal soil loss equation (USLE) and wind erosion equation (WEE) could be used to calculate the amount of residues needed to prevent soil loss exceeding the tolerance level (Jong *et al*., 1983; Renard *et al*., 1997). Considering soil erosion may decrease sustainable limits, but would provide a more integrative measure of sustainable residue harvest rates (Gregg & Izaurralde, 2010).

A major finding of this study reinforced the strong influence of fertilization on sustainable residue removal rates. However, the production and application of fertilizer consume a great deal of GHG-emitting fossil fuel (coal, oil and natural gas), a certain proportion of which could be substituted by the bioenergy produced from crop residue (Hülsbergen *et al*., 2001; Pimentel, 2003). We are not suggesting here that farmers should increase fertilization rates in the appropriate environments so that more crop residue could be harvested for bioenergy production as emissions from fertilizer may be greater than the GHG benefits of both SOC and bioenergy production combined. The GHG emissions caused by fertilizer production and application (e.g. N_2O), feedstock transportation, production procedures, and by-product disposal need to be fully considered in an assessment of the net GHG benefits using life cycle analysis (Bryan *et al*., 2010; Galvez *et al*., 2012). These analyses need to be undertaken to quantify sustainable residue harvest limits for SOC, which can contribute to the integrated assessment of the net GHG emissions and energy balances of lignocellulosic bioenergy.

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