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Can the sequestered carbon in agricultural soil be maintained with changes in management, temperature and rainfall? A sensitivity assessment

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ABSTRACT

Carbon (C) sequestration in agricultural soil has the potential to mitigate climate change and help sustain soil productivity. Continual nutrient input and residue retention are needed to attain the C sequestration potential and to maintain the sequestered C. However, few studies have assessed the vulnerability of the sequestered soil C to changes in agricultural management and climate. Here we applied the Agricultural Production Systems sIMulator (APSIM) to simulate the soil C dynamics to equilibrium under optimal management with 100% residue retention and no nitrogen (N) deficiency at 613 sites across the Australian croplands. We examined the response of sequestered soil C to potential warming and rainfall change, under these optimal practices and under suboptimal management with reduced residue retention and/or N input. On average, soil C was lost at rate of 0.14 Mg C ha^{-1} yr^{-1} when residue retention was halfed. Removing all residues doubled the rate of C loss (i.e., 0.28 Mg C ha^{-1} yr^{-1}). Reducing the application rate by half of the optimal N rate or to zero led to C loss of 0.089 and 0.27 Mg C ha^{-1} yr^{-1}, respectively. Multivariate linear regression analysis indicated that C loss rate increased with active C stock (non-inert C) in the sequestered C. Given an active C stock, the loss rate increased with increasing temperature and/or rainfall. Future warming was estimated to increase soil C loss, especially in cooler and/or wetter regions. The effect of potential rainfall change was relatively moderate and depended on the direction (increase or decrease) of rainfall change. Management strategies for effective C sequestration in agroecosystems should and can be developed based on local climatic conditions and soil-specific amount of active organic C.

1. Introduction

Carbon (C) sequestration in agricultural soils has been recognized as an effective approach to mitigate climate change, if management practices can be improved, such as adoption of no-tillage, residue retention and fertilizer application matching crop nutrient demand (Freibauer et al., 2004; Lal, 2004; Post and Kwon, 2000; Smith, 2004). The role of no-tillage in soil C sequestration has been questioned by recent studies (Baker et al., 2007; Luo et al., 2010a; Powlson et al., 2014). These studies suggested that different tillage practices just altered C distribution with depth but not the total amount of soil C. Residue retention and fertilizer application, however, are widely accepted for enabling C sequestration (Dalal et al., 2011; Khan et al., 2007; Liu et al., 2014; Luo et al., 2014; Luo et al., 2013; Zhao et al., 2013) because of their direct effect on C inputs. Wang et al. (2015) estimated that an average C input of 2.1 Mg C ha^{-1} yr^{-1} is required in order to stop soil C loss in China's croplands and 5.1 Mg C ha^{-1} yr^{-1} to approach the global mean of 55 Mg C ha^{-1} in the top 30 cm soil by 2050. The long-term experimental results in the United States also showed that soil C sequestration rate was significantly and positively correlated with C input (Kong et al., 2005), consistent with other findings in Europe (Smith et al., 1997) and Australia (Luo et al., 2014; Zhao et al., 2015). All these findings suggest that continual input of C is critical to increase or maintain soil C under a specific cropping system, soil and climate.

The amount of C input, however, is very sensitive to changes in management, such as residue retention and fertilizer application, due to their impact on residue production. Optimal management (e.g., 100% residue retention and/or no nutrient deficiency) is usually assumed to estimate soil C sequestration potential (Freibauer et al., 2004; Luo et al., 2013; Smith, 2004; Yagasaki and Shirato, 2014), although the optimal management for C sequestration may not necessarily be optimal for other outcomes such as economic return, resource use efficiency, and environmental impact. For example, excessive nitrogen (N) fertilizer application can pollute and degrade the environment (Khan et al., 2007; Powlson et al., 2011) as evidenced by the eutrophication of water (Moss, 2008), greenhouse gas emissions (Zaehle et al., 2011), and soil acidification (Guo et al., 2010). Residue retention may

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be also limited by residue harvest for bioenergy (Elshout et al., 2015; Zhao et al., 2015) and feed production. The potential changes in these management practices will influence both C input and soil environment such as microbial activity, soil water retention and nutrient availability. The consequences of management change on the sequestered C need to be quantified in order to identify context-specific effective management strategies for persistent C sequestration in agricultural soils under diverse management and environmental conditions across large scales.

Climate change (e.g., warming and changes in rainfall) is another factor that influences the fate of sequestered C through its effect on C input and decomposition. Previous studies mainly focused on the effect of climate change on the estimation of soil C sequestration potential (Álvaro-Fuentes et al., 2012; Grace et al., 2006; Jiang et al., 2014; Thomson et al., 2006) but not the fate of the sequestered C. The sensitivity of sequestered C to climate change may vary with local soil and climatic conditions. It will impact the accounting of C in agro-ecosystems and assessments of the role of agricultural soils in climate change mitigation.

Long-term soil C change induced by management and climate (e.g., warming and rainfall change) are difficult to quantify based on observational approaches and datasets (e.g., soil inventories and field experiments). For example, it is impractical, if not impossible, to implement field experiments with multiple agricultural management practices over large spatiotemporal scales. Soil inventories and baseline datasets are needed to provide reliable and spatially explicit data on soil C (Viscarra Rossel et al., 2014), but to detect long-term changes in soil C or to understand the corresponding underlying mechanisms causing such changes they need to be used together with models (Meersmans et al., 2008; Meersmans et al., 2011). Process-based models can be used to simulate the biogeochemical processes influencing changes in soil C over large space and long periods of time. Indeed, a number of models including CENTURY (Parton et al., 1987), RothC (Jenkinson, 1990) and Agricultural Production Systems sIMulator (APSIM) (Keating et al., 2003) have the capability of modelling the effects of various management and environmental interventions, and thus have been widely used to simulate soil C dynamics in agro-ecosystems. The process-based models have the advantage that they can be used to explicitly analyse the impacts of management practices and environmental variables on soil C dynamics. In addition, simulation outputs of process-based models can be summarised to understand the primary factors that affect soil C dynamics (Luo et al., 2013; Marie and Simioni, 2014).

Here, we assessed the vulnerability of soil C that was sequestered under the optimal management (100% residue retention and no fertilizer deficiency) to changes in management options with reduction in C input, potential warming and rainfall change. Using the APSIM model and detailed soil profile datasets at 613 sites across Australian cereal growing regions, we simulated soil C dynamics in a typical continuous wheat system (growing wheat every year) under different scenarios, changing management, temperature and rainfall. Our objectives were to i) quantify the vulnerability of sequestered C (expressed as C loss) to potential changes in management, temperature and rainfall, ii) assess the spatial pattern of C loss, and iii) investigate how the C loss correlates to climatic and soil conditions.

2. Materials and methods

2.1. Data sources

The study region covers the whole Australian cereal growing regions (Fig. 1). Within this region, there are 613 soil sites where detailed soil profile data are available. The soil sites are roughly randomly distributed in the Australian grain regions (Fig. 1). These are point soil profile data collected by Agricultural Production Systems Research Unit, available via the Australian Soil Resource Information Systems (http://www.asris.csiro.au/mapping/hyperdocs/APSRU/). They are fully characterized soil profiles with information needed to run APSIM model, including soil bulk density, organic C content, hydraulic properties (saturation water content (SAT), drained upper limit (DUL), 15 bar lower limit (LL15)), pH etc. for each soil layer. Daily recorded weather data from 1957 to 2010, including daily global radiation, rainfall, maximum and minimum temperatures, are available from the Australian Bureau of Meteorology weather stations. These data are obtained from SILO Patched Point Dataset (https://www.longpaddock.qld.gov.au/silo/).

2.2. The APSIM model

APSIM simulates biophysical processes in farming systems, and has been comprehensively verified and used to study productivity, nutrient cycling and environmental impacts of farming systems as influenced by climate variability and management interventions (Holzworth et al., 2014; Keating et al., 2003). APSIM simulates crop growth and soil processes on a daily time-step in response to climate (i.e., temperature, rainfall, and radiation), soil water availability, and soil nutrient status (i.e., N and Phosphorus) (Wang et al., 2003).

APSIM simulates the dynamics of both C and N in the soil. Soil organic matter is divided into four conceptual pools (i.e., fresh organic matter, microbial biomass, humic and inert organic matter) and decomposition of each pool is treated as a first-order decay process, leading to release of CO_2 to the atmosphere and transfer of the remaining decomposed C to other pools. For each pool, a maximum potential decomposition rate constant is assumed, and the actual decomposition rate is obtained by modifying the maximum rate according to soil moisture, temperature and nutrient availability. Flow of N depends on C:N ratio of the receiving pool. Decomposition of surface residue also takes into account the degree of contact of residue with soil to modify the maximum decomposition rate of residue. APSIM allows flexible specification of management options such as crop type, residue management, and fertilizer application.

APSIM has been tested for its performance to simulate soil organic C dynamics against measurement data in a number of studies (Huth et al., 2010; Luo et al., 2011; Probert et al., 2005; Thorburn et al., 2001; Wang et al., 2013). Results generally showed that APSIM is able to predict soil organic C dynamics under different cropping and management systems at many locations and over long time periods. This forms the basis for us to use the model in the current study.

2.3. Model simulations and scenario analysis

Due to the variation in SOC initial values and the different trajectories of soil organic C change caused by complex interaction of climate, soil and management conditions, the time needed for simulated SOC to reach the equilibrium state may be as long as 900 years (Luo et al., 2013). Therefore, 1020 years of climate data series were generated by randomly sampling the historical data from 1957 to 2012 with replacement. This treatment of data extension does not include any climate change trend.

The APSIM model was first run for 1000 years at the 613 references sites in order to reach the equilibrium state of soil organic C dynamics. A continuous wheat system was assumed for the simulation under 100% residue retention. To identify the optimal N requirement for C sequestration, the simulation was run under an N fertilizer application scenario of 0–300 kg N ha^{-1} yr^{-1} in 20 kg N ha^{-1} increments. In all except the non-fertilizer application scenario, 25 kg N ha^{-1} was applied as a base fertilizer incorporated into soil at time of sowing, with any additional N being applied at the stem elongation stage as a top-dressing (broadcast). Under each of the 16 N application rates and each site, we regarded the average of crop yield and soil organic C stock (in the top 30 cm soil) in the last 100-year simulations as the crop yield and soil C stock at the equilibrium state respectively.

At a specific site, crop residue production is the predominant factor controlling soil C input in the simulation. In real croplands, however,