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Potential impacts of climate change on soil organic carbon and productivity in pastures of south eastern Australia

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ABSTRACT

Increasing soil organic carbon (SOC) stocks is an often-mentioned option to mitigate greenhouse gas emissions. However, increasing carbon stocks in agricultural soils is difficult and the ability of soils to store carbon as the climate changes is uncertain. This is due to many interacting factors, including those that vary spatially, contributing to organic matter inputs and decomposition rates. We used two models, the Sustainable Grazing Systems whole-farm system model (SGS) and the RothC soil carbon model, to investigate the potential impacts of climate change on SOC stocks in pastures in a temperate, winter-dominant rainfall region of south eastern Australia. A wide range of possible future climates were simulated from 2017 to 2090 at two sites, each with two soil types. Results demonstrate that projected rainfall, the factor with the most variability between climate scenarios, was the primary source of uncertainty in SOC response. Dry climate projections resulted in lower SOC content than other scenarios. The two models were similar in their projected trends, but the RothC model generally gave larger percent changes in soil carbon over the simulation period and a larger range of responses due to changes in site characteristics, particularly clay content. Sustainable stocking rates were determined by the whole-farm system model based on climate, pasture production, and maintaining minimum dry matter coverage. Wet future climates lead to increased production that supported increases in stocking and increases in SOC stocks. While soil carbon accumulated at slower rates or remained steady under dry projections, lower production meant this was accompanied by decreased average 2070–2090 stocking rates, which approached zero by 2090 on the low-rainfall site. This highlights an important interaction between SOC and grazing management. The results demonstrate the extent of the uncertainty associated with soil carbon trading for farmers and the need for adaptation options that allow farms to remain sustainable and productive as the climate changes.

1. Introduction

Increasing soil organic carbon (SOC) has received much attention as a mitigation strategy because of the potential for soil to store substantial amounts of CO_2 from the atmosphere. Examples of global estimates of technical potential include 4.4–11.4 Gt CO_2eq/year for 25 to 50 years (Lal, 2013) and 4.8 Gt CO_2eq/yr for agricultural soil management and restoration (Smith et al., 2013). Despite limitations, such as the reversibility of SOC storage, there have been efforts to develop carbon trading markets using SOC related offset methodologies. Australia has developed national level SOC offset methodologies to meet emission reduction targets under its Emissions Reduction Fund, including the "increase in soil carbon due to conversion from cropping to grazing" methodology (Australian Government Department of the Environment, 2015).

Converting cropping lands to grazing is an option that consistently results in increases in soil carbon (Guo and Gifford, 2002; Lam et al., 2013). It has been estimated that conversion of cropping lands in Victoria to a crop - pasture rotation and stubble retention could result in carbon accumulation of up to 4.5 Mt. CO_2eq/year, 3.7% of Victoria's emissions (Robertson and Nash, 2013). Overgrazing typically results in lower soil carbon levels than observed under more moderate stocking

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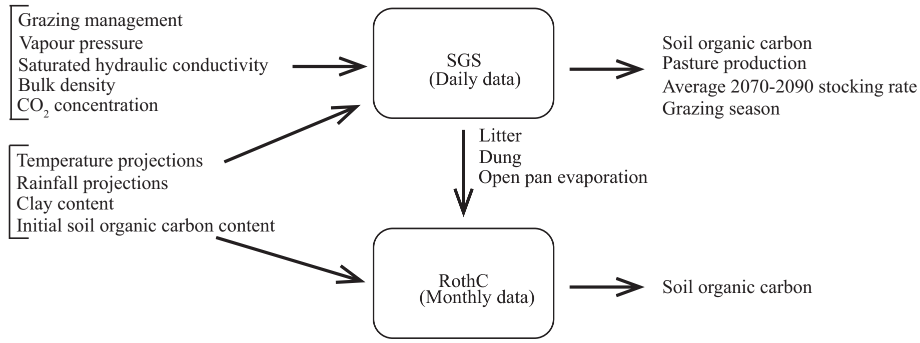

Fig. 1. The methodolgical framework of the analysis showing the use of two models, the unique and overlapping inputs into the models, the RothC inputs obtained from SGS, and the outputs used.

rates (Conant et al., 2001; Liu et al., 2016; Soussana et al., 2010). The impacts of climate change on the potential of converting cropping to grazing lands as a mitigation option, and the stocking rates required to achieve soil carbon accumulation in future climates has not been investigated.

Both the carbon inputs and the outflows will be affected by changes in temperature, rainfall and CO_2 concentration in direct and indirect ways that vary based on the current conditions at a site and the expected changes in climate (Baldock et al., 2012; Gottschalk et al., 2012). In some locations temperature increases will increase pasture productivity, increasing SOC inputs (Cheng et al., 2011; Lu et al., 2013). In other regions, and for sensitive species, comparatively small increases in temperature can reduce plant productivity (Cullen et al., 2012; O'Leary et al., 2011; Wang et al., 2016). Higher amounts of rainfall have been shown to increase SOC primarily due to increased plant productivity (Falloon et al., 2007; Hobley et al., 2015; Shen et al., 2009). Increases in atmospheric carbon dioxide (CO_2) concentrations increase plant productivity in locations where water and nutrients are not limiting (Ainsworth and Long, 2005; Cao and Woodward, 1998; Runion et al., 2009).

The impacts of climate change on carbon outflow from soils are less well understood. Moist soils have higher respiration rates than dry soils (Baldock et al., 2012; Condron et al., 2014; Shen et al., 2009). Increases in temperatures increase soil respiration (Cheng et al., 2011; He et al., 2012; Shen et al., 2009) with the largest impact on cool soils (Kirschbaum, 1995) and areas with high SOC stocks (Crowther et al., 2016). However, the sensitivity of this response is debated, and several uncertainties remain (Bradford et al., 2016; Davidson and Janssens, 2006). Relationships between soil respiration and CO_2 concentration have also been documented (De Graaff et al., 2006; van Groenigen et al., 2014). It is possible that increased carbon inputs from increased plant productivity under elevated CO_2 increase microbial activity and therefore SOC turnover (Kuzyakov, 2011; van Groenigen et al., 2014). The implications of this priming effect are uncertain but could have long-term consequences on SOC turnover.

The net impact of these processes needs to be determined for particular areas (Gottschalk et al., 2012) and management options. If national mitigation policies are going to include increases in SOC, the potential of these offset methodologies to increase, or even maintain, carbon as the climate changes is integral information. Given that one of the most consistent and documented ways to increase SOC in soils is through conversion from cropping to pasture (Lam et al., 2013; Liu et al., 2016; Robertson and Nash, 2013) and that this is already an Australian Emissions Reduction Fund (ERF) offset methodology, we modelled the impacts of climate change on carbon stocks in Australian soils under pasture. We also addressed major sources of uncertainty in the potential response of SOC to climate change, namely climate projection uncertainty, both that from climate models and emissions scenarios, and uncertainty inherent in process-based soil carbon modelling.

2. Materials and methods

RothC version 26.3 in Microsoft Excel format (Coleman and Jenkinson, 2014) and the Sustainable Grazing Systems whole-farm system model (SGS) (version 5.2.15) (Johnson, 2013) were used to investigate the impacts of a wide range of future climate projections on SOC at two grazed pasture sites in south-eastern Australia. Sites were modelled with both high and low initial carbon contents, which were based on values from long-term pasture and long-termed cropped sites, respectively. The low carbon soils are simulated to investigate the climate impacts on soil carbon accumulation following a switch from cropping to pasture, while the high carbon scenarios address climate impacts on soils closer to equilibrium. Livestock were removed at low dry matter coverage to prevent overgrazing. Two models were used to address some of the SOC modelling uncertainty associated with projecting impacts of climate change on SOC stocks. Both models require inputs for climate and soil characteristics. The same temperature and rainfall data generated for the climate projections were used in both models. RothC uses average monthly temperature, while SGS uses daily minimum and maximum temperatures. SGS also requires vapour pressure and solar radiation, while RothC requires open-pan evaporation. To ensure consistency between the two model simulations, dung inputs and litter requirements of RothC were obtained from SGS outputs for the same scenario. The general framework of the methodology is shown in Fig. 1.

In the SGS model plant growth and grazing processes are integrally connected with the SOC and nitrogen cycles (Johnson et al., 2003). Indirect impacts of climate and atmospheric CO_2 concentrations on pasture and root growth, and consequently SOC inputs, are also included. The SGS model includes a simple carbon model with three pools: fast turnover, slow turnover, and inert carbon. The SGS model has been validated for pasture production (Cullen et al., 2008; White et al., 2008) and soil water content (Lodge and Johnson, 2008) in Australia, with the soil organic matter routines published in Meyer et al. (2015).

The RothC soil carbon model is more complex than the soil carbon routine in the SGS model, with carbon transfers between several conceptual soil organic matter pools, including decomposable plant material (DPM), resistant plant material (RPM), fast and slow microbial biomass, humified organic matter (HUM) and inert organic matter (IOM). RothC has been used extensively to model the impacts of climate and management on SOC stocks (Gottschalk et al., 2012; Robertson and Nash, 2013; Smith et al., 2007) and has been validated for Australian sites (Skjemstad et al., 2004). Direct climate impacts on organic matter turnover, specifically temperature and soil water status, are incorporated in both SGS (Johnson (2003)) and RothC (Coleman et al., 1997). The decomposability of organic inputs is a function of plant digestibility in SGS (Johnson, 2013) while a default value for improved grassland is used in RothC (Coleman and Jenkinson, 2014). The impact of low ground-cover on soil processes and the role of clay in influencing