Agriculture, Ecosystems and Environment 213 (2015) 272–280

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

journal homepage: www.elsevier.com/locate/agee

Process modelling to assess the sequestration and productivity benefits of soil carbon for pasture

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ARTICLE INFO

Article history:
Received 4 September 2014
Received in revised form 26 June 2015
Accepted 26 July 2015
Available online 2 September 2015

Keywords:
Soil organic carbon
Sequestration
Agroecosystem services
Pasture
Adaptation
Greenhouse gas mitigation
SGS Pasture Model

ABSTRACT

Soil carbon is often cited as having potential to provide both climate change mitigation and adaptation benefits. Given the extensive ecosystem service benefits of soil organic matter (SOM), including increasing N supply and plant-available water-holding capacity (PAWHC), we hypothesized that on-farm benefits provide ample justification for maintaining high levels of SOM, separate to its carbon sequestration potential. To investigate this we used whole-farm system modelling to simulate pastures with high SOM (initial carbon amount similar to long-term pasture) and low SOM (initial carbon condition similar to long-term cropping). These scenarios are deliberately confounded with land use change, as this allowed for comparison of the mineralization, PAWHC, and associated productivity benefits on high and low carbon soils with the same management. Low-carbon soils were modelled with two amounts of PAWHC to investigate the importance of this effect in isolation. These three scenarios (one high carbon and two low carbon with differing PAWHC) were run for two climatic zones each with two soil types. Across both climatic zones and soil types, soil C accumulated at a rate of 0.30 0.48 t C ha^{-1} $year^{-1}$ (0–30 cm) over the first 20 years in soils with low initial carbon amounts. On soils in a high-rainfall climate, annual pasture production in low-SOM soil was 590–900 kg DM ha^{-1} less than for high-SOM soil, attributable primarily to increased N mineralization (68–77 kg N ha^{-1} $year^{-1}$) overcoming an N limitation in spring. On low-rainfall sites, a reduction in annual pasture production of 290–810 kg DM ha^{-1} on low carbon soils compared to high carbon soils was attributable to reduced PAWHC. The increased pasture production associated with higher SOM was valued between AUD 26 and 95 ha^{-1}, across the soils and sites. The entire value on low-rainfall sites (AUD 26-85) was attributable to differences in PAWHC, while on high-rainfall sites, increased pasture production was attributed to N mineralization valued from AUD 85–105 ha^{-1}. These results indicate that soil carbon sequestration, through increased SOM, can provide substantial on-farm benefits that contribute to future productivity.

1. Introduction

Soil carbon sequestration is often cited as beneficial for both climate change mitigation and adaptation (Olesen, 2006; Rosenzweig and Tubiello, 2007; Olesen and Porter, 2009; Stokes and Howden, 2010). The mitigation potential of soil carbon globally was estimated by Smith et al. (2007) as 1.4–2.9 Gt CO_2 equivalents $year^{-1}$, reaching capacity in 50–100 years. Lal (2004) estimated cumulative sequestration potential over 25–50 years of 30–60 Gt C. More recently, Smith et al. (2013) reported a technical mitigation potential through agricultural soil management and restoration in the range of 4.8 Gt CO_2 equivalents $year^{-1}$.

Soil carbon accumulates in agricultural systems by increasing organic matter inputs into soils, mainly through plant root growth but also through incorporating residues, adding manure or compost, and/or reducing soil disturbance that results in loss of carbon present in the soil (Grace et al., 2010; Oladele and Braimoh, 2011; Aguilera et al., 2013; Benbi, 2013; Lam et al., 2013). The rate of soil carbon accumulation depends on many factors including amount and characteristics of carbon inputs (Baldock, 2009), soil characteristics (Oladele and Braimoh, 2011; Page et al., 2013), and climatic factors (White, 1997; Oladele and Braimoh, 2011). Soil disturbance associated with cropping typically leads to lower SOM than undisturbed native vegetation (Stevenson and Cole, 1999; Guo and Gifford, 2002; Ostle et al., 2009). Conservation management such as no-till or reduced-till may lead to higher amounts of

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http://dx.doi.org/10.1016/j.agee.2015.07.024
0167-8809/

SOM than those under conventional management (Aguilera et al., 2013), but use of these practices generally do not prevent a decline in SOM associated with land conversion to agriculture (Sanderman et al., 2010; Page et al., 2013). Converting land from cropping to pasture increases SOM pools (Guo and Gifford, 2002; Chan et al., 2010; Lam et al., 2013). However, pasture lands are also associated with higher emissions than cropping due primarily to enteric methane from livestock (Nijdam et al., 2012; Gerber et al., 2013).

Sequestering carbon in soils as a mitigation strategy has many limitations. The capacity of soils to store carbon is finite. Soil carbon reaches a relatively stable state (Lucas et al., 1977; Johnston et al., 2009; Powlson et al., 2011; Lam et al., 2013) based on several factors; primarily climate, vegetation, topography, and time since land use change (Stevenson and Cole, 1999). Any soil carbon gains are reversible, with changes in management actions or climatic factors potentially resulting in loss of any soil carbon accumulated in previous years (Stokes and Howden, 2010; Powlson et al., 2011; Lam et al., 2013). Increasing carbon dioxide concentrations (van Groenigen et al., 2014), increases in temperature (Smith, 2005; Olesen, 2006; Stockmann et al., 2013), and reductions in plant growth associated with extraneous factors including those that decrease water availability (Baldock, 2009) may reduce the equilibrium amount of soil carbon. Climatic events, such as droughts, could also increase the risk of loss of soil carbon (Smith, 2005; Stokes and Howden, 2010). Importantly, in cases where agricultural land was converted from native grassland, forest, or other relatively high-carbon vegetation, any increase in soil carbon may merely be restoring losses from previous land use change, and not increasing total carbon stores (Mackey et al., 2013). In addition, modelling based on data from south-eastern Australia (Robertson and Nash, 2013) and Great Britain (Smith, 2004a) illustrate that only large increases in soil carbon are detectible on timeframes of less than about 10 years and more realistic accumulation rates and sampling intensities increase this to over 25 years. Lastly, costs associated with increasing soil carbon can be high (Carlyle et al., 2010; Kirkby et al., 2011; Lam et al., 2013), as are those associated with audit and compliance requirements of carbon markets (Renwick et al., 2002; Smith, 2004b; Sanderman et al., 2010).

In contrast to complications associated with mitigation via soil carbon, the ecosystem services provided by soil organic matter (SOM), and more specifically SOC, are tangible and largely undisputed. Soil carbon is generally agreed to improve potential yields (Stevenson and Cole, 1999). In Michigan an increase from 1% to 2.15% soil carbon increased yield potential of maize by 25% (Lucas et al., 1977). Higher yields were associated with higher amounts of soil carbon in the Morrow Plots of Illinois (Aref and Wander, 1997) and in Uganda, where reduced yield variability was also observed (Kato et al., 2010). Soil carbon is important for nutrient supply (Stevenson and Cole, 1999; Wander and Nissen, 2004), water availability (Hudson, 1994; Wander and Nissen, 2004; Sparling et al., 2006; Baldock, 2009; Harvey et al., 2013), increased cation exchange capacity (Rice et al., 2007), and improved soil structure and porosity (Wander and Nissen, 2004; Watts et al., 2006; Rice et al., 2007; Deurer et al., 2009; Stockmann et al., 2013). Soil carbon in interaction with bulk density has been associated with reductions in erosion risk (Lakshminarayan et al., 1996). These interrelated factors provide an integral component of productive farm enterprises.

To explore the synergies between soil carbon sequestration and productivity in agricultural systems we used process modelling to investigate soil carbon accumulation and pasture production following a transition in land use from cereal cropping to grazed pasture. This land use change was chosen because it represents an example of where soil carbon accumulation has consistently been achieved in agricultural systems (Guo and Gifford, 2002; Chan et al., 2010; Lam et al., 2013). We hypothesize that soil carbon, through SOM, provides farm systems a direct and substantial benefit. To test this we quantified the productivity impacts of greater N supply from mineralization and increases in plant-available water-holding capacity (PAWHC) associated with greater amounts of SOM, using a whole-farm system modelling approach.

2. Methods

2.1. Study Design

Comparison of productivity in soils with different amounts of SOM and associated N mineralization and PAWHC was undertaken using the dynamic whole-farm, SGS Pasture Model (SGS) (Johnson et al., 2003). In reality these factors are interrelated and cannot be separated into discrete factors as each influences the other. Thus a theoretical modelling framework was adopted to isolate the two factors to investigate their individual contributions.

This was investigated at two sites in south-eastern Australia using two representative soil types at each site. Three SOM scenarios were investigated that allowed for the quantification of individual contributions of N mineralization and PAWHC to the overall productivity benefit. The scenarios modelled were:

- HC-HW: The initial soil carbon concentration is high; similar to a long-term, permanent pasture site. The soil has high N mineralisation potential and high PAWHC.
- LC-HW: The initial soil carbon concentration is low; similar to a long-term cropping site. The soil has low N mineralisation potential but is simulated with same PAWHC as the high SOC scenario.
- LC-LW: The initial soil carbon concentration is low; similar to a long-term cropping site. The soil has low N mineralisation potential and low PAWHC. The PAWHC was lowered by reducing field capacity as described below.

2.2. Modelling tool and calibration

The SGS model was selected because it links plant growth and grazing interactions to the soil carbon and nitrogen cycles (Johnson et al., 2003). The SGS soil submodel is a simplification of many available soil models, such as RothC, and dynamically includes the impacts of grazing on soil nutrients and productivity (Moore et al., 2014). All aspects of the soil, plant, animal, management and climate are incorporated in a mechanistic framework that captures their interactions. In addition, the model is well validated for pasture production (Cullen et al., 2008 White et al., 2008) and soil water content (Lodge and Johnson, 2008) for high- and low-rainfall regions in Australia and New Zealand.

In SGS, soil organic matter dynamics are simplified by modelling fast, slow, and inert pools. The fast and slow pools are as aligned with the *particulate organic matter* and *humus*, respectively. The inert carbon pool, or *recalcitrant organic matter* is not subject to turn over. These SOC pools are aligned with the pools defined by Skjemstad et al. (2004) and Baldock et al., (2013a,b). The key soil carbon parameters in SGS are the decay rate constants for the fast and slow pools (proportion that decays per unit time), their efficiency of decay (proportion of carbon respired during decay), and the transfer rate from the fast to slow pool. The N concentration of the inputs is also required, and is calculated dynamically. Soil carbon dynamics are moderated by temperature and soil water status (as described in (Johnson, 2013)) and driven by inputs from the plant material and its digestibility. For more detail regarding the SGS soil carbon sub-model, see supplementary appendix A.