Simulation of soil organic carbon dynamics under different land use and crop management practices

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Prologue

The main layout of the thesis follows the Style Guide of the University of New England http://www.une.edu.au/research-services/forms/thesis-submission-instructions.php.

Each experimental chapter is written in as individual journal article format, targeting different specific journals. Parts of the literature review, material and method, study site description and references might be repeated in the subsequent chapters. Formatting of each experimental chapter follows the editorial style of the relevant journal. For other chapters, the format follows that of *Soil Research*. Figures and tables are located throughout the text.

Thesis structure

Chapter 1:

"Introduction, scope and objectives" – this chapter contains a general introduction, and states the scope and objectives of the present study.

Chapter 2:

"Review of Literature" – this chapter contains a general review of literature.

Chapter 3:

"Measuring turnover times of Soil Organic Carbon fractions in contrasting land use systems as revealed by radiocarbon signature" – this chapter reports on soil organic carbon (SOC), fractionated by a combination of physical and chemical methods, to study whether the combined method could partition SOC in accordance with the hierarchy of SOC stabilization mechanisms, and with distinct ages and turnover times as proposed in SOC turnover models.

Chapter 4:

"Effect of land use change on soil organic carbon dynamics: Evaluation of RothC using paired-site data sets" – here, in the absence of long-term experimental data, the performance of the Rothamsted carbon model (RothC) was evaluated using paired-site data. The partitioning method of SOC as proposed by Zimmermann et al. (2007) was examined to evaluate its potential to quantify different SOC pools, as required by RothC. The initialization method of RothC was assessed to determine whether initialization with measured SOC pools rather than using default model equilibrium pools improves the model predictability.

Chapter 5:

"Modelling soil organic carbon dynamics using the Rothamsted carbon model in a cotton based cropping system on irrigated Vertosol" – in this chapter, RothC performance was evaluated using a long-term field experiment data set in simulation of SOC dynamics under cotton based cropping system in irrigated Vertosols. Different scenarios of SOC dynamics under different proposed cotton based cropping systems were also explored.

Chapter 6:

"Projections of changes in grassland soil organic carbon under climate change are relatively insensitive to methods of model initialization" – here, the sensitivity of RothC to the model initialisation method in projection of changes in SOC under climate change was examined by using data from 12 native grassland sites across the northern slopes and plains of New South

Wales (NSW), Australia. The global climate model CSIRO Mk3.5 was used for climate projection for the period 2008-2100. Three different methods of model initialization were used viz. model initialization with (i) spin-up of model pools with Inert Organic Matter (IOM) pool size calculated from a regression equation (Falloon et al., 1998), ii) spin-up of model pools with measured IOM, and (iii) all pools estimated from measured SOC fraction.

Chapter 7:

"Projected changes in grassland SOC under climate change in the northern slopes and plains of New South Wales, Australia, 2008-2100" – in this chapter, climate change impacts on grassland SOC was projected with three different global climate models forced with four different climate scenarios for the time period 2008-2100, using RothC in the northern slopes and plains of NSW, Australia. Sensitivity of projected SOC to soil C inputs, and the increase in C inputs necessary to offset the climate impacts on grassland SOC for the period 2008-2100 were also determined.

Chapter 8:

"General conclusion and future research" – this chapter contains general conclusions and outlines scope for future research.

References

References are presented for each chapter rather than in a final cumulative bibliography. This is made necessary by the differing bibliographical styles required by the publishing journals.

Publication arising from the Thesis

Journal articles

Senapati N, Smith P, Wilson B. Yeluripati JB, Daniel H, Lockwood P, Ghosh S (2013) Projections of changes in grassland soil organic carbon under climate change are relatively insensitive to methods of model initialization. *European Journal of Soil Science* (*in Press*).

Senapati N, Hulugalle NR, Smith P, Wilson B. Yeluripati JB, Daniel H, Ghosh S, Lockwood P (2013) Modelling soil organic carbon dynamics using the Rothamsted carbon model in a cotton based cropping system on irrigated Vertosol. *Soil Research* (*under review*).

Senapati N, Smith P, Wilson B. Yeluripati JB, Daniel H, Ghosh S, Lockwood P (2013) Projected changes in grassland SOC under climate change in the northern slopes and plains of New South Wales, Australia, 2008-2100. *Soil Science Society of America Journal* (*under review*).

Senapati N, Hua Q, Lockwood P, Daniel H, Wilson B, Ghosh S, Yeluripati JB, Pete Smith (2013) Measuring turnover times of Soil Carbon fractions in contrasting land use system as revealed by radiocarbon signature. Manuscript to be submitted to *Radiocarbon*.

Senapati N, Yeluripati JB, Daniel H, Wilson B, Smith P, Lockwood P, Ghosh S (2013) Effect of land use change on soil organic carbon dynamics: Evaluation of RothC using paired-site data sets. Manuscript to be submitted to *Soil Research*.

Conference proceedings/presentation

Senapati N, Hua Q, Lockwood P, Daniel H, Wilson B, Ghosh S, Yeluripati JB, Pete Smith (2012) Estimating turnover times of soil organic carbon fractions based on natural C-14 abundance. Joint Australian and New Zealand Soil Science conference. Soil solutions for diverse landscapes. Hobart Tasmania, Australia, 2-7 December, 2012.

Senapati N**,** Daniel H, Wilson B, Lockwood P, Ghosh S (2011) Application of RothC to predict the effect of land use change on soil organic carbon in northern grains region of New South Wales, Australia. In: Proceedings of 3rd International Symposium on Soil Organic Matter 2011, Organic matters dynamics – from soils to oceans, Leuven, Belgium,11-14 July, 2011.

Senapati N, Daniel H, Wilson B, Lockwood P, Ghosh S (2010). Application of RothC model to predict the effect of land use change on soil organic carbon in northern New South Wales, Australia. Organic matter stabilization and ecosystem functions: SOM 2010 Conference Cote d'Azur, France, 19-23 September 2010.

Senapati N, Daniel H, Wilson B, Yeluripati J, Ghosh Subhadip and Lockwood P (2011) Simulating land use change effect on soil carbon dynamics in northern New South Wales, Australia. In: *Symposium on Rural Climate Change Solutions*, May 3-4, 2011, University of New England, Armidale, NSW, Australia.

Abstract

Soils are the largest reservoir of terrestrial carbon (C) (~1500 Pg organic C in top one meter) and any change in this large soil organic carbon (SOC) stock due to change in land use, management practice or climate change may have significant and long-lived effects on the global C cycle. The SOC turnover models can project the change in SOC storage and turnover rate under future scenarios of land use, management practice, technological improvement and climate change, and investigate hypotheses that are beyond the feasibility of experimental work. In Australia, there is a greater need for modelling such scenarios across a wider range of agro-ecological regions and land uses.

In this thesis, SOC dynamics under different land uses and crop management practices in the northern plains and slopes of New South Wales (NSW) was explored using the Rothamsted carbon model (RothC). The specific objectives were (i) to determine turnover times of SOC fractions, separated by a combination of physical and chemical methods, in contrasting land use systems by natural ^{14}C abundance, (ii) to examine whether a combination of physical and chemical laboratory methods of SOC fractionation has the potential to quantify different SOC pools, as required by RothC, (iii) to evaluate the performance of RothC in simulating the effect of land use change (LUC) on SOC dynamics, particularly following a proposed land use change from native vegetation to cropping, using paired-site data sets, (iv) to examine whether initializing RothC with measured SOC pools, rather than using default model equilibrium pools, improves RothC performance in prediction of LUC effects on SOC dynamics, (v) to evaluate RothC performance in simulation of SOC dynamics under a cotton based cropping system on an irrigated Vertosol using long-term field experiment data, (vi) to explore different scenarios of SOC dynamics under different cotton based cropping systems in irrigated Vertosol, (vii) to test whether RothC projections of grassland SOC under climate change were sensitive to the model initialisation method, and (viii) to projected climate change impacts on grassland SOC with three different global climate models (GCMs) forced with four different climate scenarios for the time period 2008-2100, using RothC in the northern slopes and plains of NSW, Australia.

Results showed that a combination of physical size separation and chemical oxidation methods are able to partition SOC into a short to medium (~10-360 yr) turnover time fraction (particulate organic carbon), medium (~230 - 3100 yr) turnover time fraction (silt and clay

associated C) and a stable old (radio C age ~ modern – 2000 BC) inert organic C fraction in accordance with different SOC stabilization mechanisms. The combined physical and chemical SOC fractionation methods resulted in meaningful fractions which could be related to conceptualized pools of SOC turnover models. Assessment of a similar type of combined physical and chemical fractionation methods showed a good potential of the laboratory fraction method in determining model conceptual pools as required by RothC across different land use systems.

For evaluation of RothC performance in simulation of the LUC effect on SOC dynamics, data from 16 paired-sites across the northern slope and plains of NSW was used. RothC was initialized with both measured and default equilibrium SOC pool structure of native vegetation, and then run to simulate total SOC stock after LUC from native vegetation to cropping, given the known climate, land clearing and management history. RothC performed satisfactorily with both the initialization methods. However, model performance was not improved significantly when RothC was initialized with measured SOC pools (r = 0.98, EF = 0.96, RMSE = 5.89, E = -1.82) as compared with initialization with model default equilibrium pools (r = 0.97, EF = 0.93, RMSE = 7.82, E = 2.64). RothC could be used to predict total SOC stock at any point in time after LUC from native vegetation to cropping in the region, as long as total SOC in adjacent remnant native vegetation and crop management history at the site are known. The paired-site SOC dataset was shown to be useful in evaluating the ability of RothC to predict LUC effects on SOC dynamics. The analytical effort of SOC laboratory fractionation may not be required to initialize the model to simulate total SOC in such a case.

Performance of RothC in simulating SOC dynamics under cotton based cropping systems in irrigated Vertosols was evaluated using data from a long-term cropping experiment, located at the Australian Cotton Research Institute, near Narrabri, in north-western NSW, Australia. The experimental treatments were three cropping/tillage combinations *viz.* continuous cotton/conventional tillage (CC/CT), continuous cotton/minimum tillage (CC/MT) and cotton-wheat/minimum tillage (CW/MT). Measured values showed a loss in SOC of 22%, 17% and 21% of the initial SOC stocks within 15 years (1994-2008) under CC/CT, CC/MT, and CW/MT, respectively. RothC satisfactorily simulated SOC dynamics under CC/MT (*LOFIT* = 44-46, *RMSE* = 3.1, *E* = -2.2 and *r* = 0.90) and CW/MT (*LOFIT* = 48-172, *RMSE* = 3.2-5.9, *E* = -1.9 to -4.8 and *r* = 0.88-0.92), whereas the model performance was poor under CC/CT (*LOFIT* = 220-223, *RMSE* = 7.5-7.6, *E* = -6.6 and *r* = 0.80-0.81). However, a minimum of 69% reduction in soil C input could significantly simulate the SOC dynamics under CC/CT (*LOFIT* = 58, *RMSE* = 3.9, *E* = -0.6 and *r* = 0.88). In an irrigated Vertosol, these present cropping systems were predicted to lose soil C continuously from 2009 onwards until they reached equilibrium. At equilibrium, a loss in SOC of 62%, 2% and 16% of their 2008 levels were predicted under CC/CT, CC/MT and CW/MT, respectively and the losses were 70%, 18% and 34%, respectively of their initial (1994) levels. Inclusion of vetch (*Vicia spp.*) with cotton monoculture and cotton–wheat system could potentially reduce the loss in SOC stocks from their initial levels to 2 - 17% and 7%, respectively within 15 years. Similarly, inclusion of a summer forage legume with the CW/MT system had the potential to reduce the loss in SOC stocks to 11%, whereas inclusion of summer grain cereals could improve SOC stock by 1 - 10% compared to initial SOC level within the same time period. These proposed cotton based cropping/tillage systems could potentially elevate equilibrium SOC levels by 0.5 - 2.0 times compared to the equilibrium levels under the current cropping systems and thus could reduce the loss of soil C under cotton based cropping systems in an irrigated Vertosol.

Sensitivity of RothC to the initialization methods in projection of SOC under climate change was assessed by running the model under climate change for the period 2008-2100 using 12 native grassland sites and three different initialization methods *viz.* model initialization with (i) spin-up of model pools with the Inert Organic Matter (IOM) pool size calculated from a regression equation, (ii) spin-up of model pools with measured IOM, and (iii) all pools estimated from measured fractions. Averaged over the sites and initialization methods, maximum absolute variations as well as averaged absolute variations throughout the projection period were very small (2.2 and 1.6%, respectively). There were no significant differences in projected grassland SOC stocks under climate change after 93 years (2008-2100) of simulation with model initialization by different methods and averaged over the sites, mean absolute variation in the projected SOC stocks was only 1.6% across the initialisation methods. The findings suggested that in a relatively undisturbed land use system such as native grassland, SOC projections under climate change are relatively insensitive to the model initialisation methods.

Potential climate change impacts on grassland soil organic carbon (SOC) was studied by running RothC from 2008-2100 at 12 native grassland sites across the northern slopes and plains of NSW, Australia, using three different GCMs (CSIRO Mk3.0, CSIRO Mk3.5 and Max Planck) forced with four Intergovernmental Panel on Climate Change (IPCC) emission scenarios. Averaged over the GCMs, SOC stocks were projected to fall by 6-12% compared to 2008 levels over the period 2008-2100, with the range determined by the climate scenario. Use of different GCMs did not cause any significant differences in projection. An average increase in annual soil C input by 15-27% is required to offset the climate change impact on grassland SOC in the region, depending on the climate scenario. Unless increased annual soil C inputs at these rates are realised, *e.g.* through improvements in management/technology or other mechanisms, a loss in grassland SOC can be expected under climate change in this region of northern NSW.

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