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Project title

Modelling soil organic carbon under different cotton production systems in north-western NSW using the RothC Model.

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Abstract

Soil organic carbon (SOC) is an indicator of soil health, as it exercises vital roles as a nutrient source as well as a contributor to a favourable soil structural conditions. It is well documented that cultivation and cropping of soil under native vegetation may lead to reduction in SOC. Estimates of 54% and 60% loss of SOC from initial levels have been reported for cotton and cereal based farming systems in the cropping region of north-western NSW. These estimations are useful in terms of gauging SOC levels under past management practices. However, of greater interest is the need to know how and at what rate SOC had changed over time as well predicting these changes into the future under existing and improved management practices. The Rothamsted Carbon Model (RothC) is a tool that facilitates the estimation of SOC changes in the past and their prediction into the future.

In his study, we used soil profile data from the Australian Cotton Soil Database (ACSD) (Odeh *et al.* 2004) as inputs for a modified version of the RothC model to simulate SOC changes under existing management practices in a 3000km² study area, west of Narrabri, NSW. Based on actual measurements performed in 1996, modelled estimates of SOC were considered reasonable. Estimates for 'continuous cotton' systems performed best (RMSE=0.19%), followed by 'cotton-legume rotation', 'cotton-grain rotation', 'native vegetation' and 'continuous grain' systems (RMSE=0.24, 0.31, 0.35, 0.40% respectively). We then used the model outputs to interpolate onto a dense grid of the study area, the change in SOC from initial levels to 2003, using various ancillary data. We concluded that, in areas of irrigated cotton, there has been between 45-53% reduction in SOC from initial levels. To improve upon the models predictive ability, adjustments to some model inputs, verification of initial levels of SOC, determination of land clearing events and a harmonious land use classification, compatible to the ACSD are some means in which to do so. Overall, the base methodology developed during this exercise could be extended to other areas detailed by the ACSD. Value adding to this data through estimation of SOC fluxes under modified management systems and future climate scenarios are likely possibilities in future studies.

Introduction

Soil organic carbon (SOC), consisting of undecomposed cellular residue of plants, living microbial biomass and humic compounds, is an indicator of soil health (Knowles and Singh 2003). In cultivated soils SOC plays a vital role as a source of nutrient elements such as nitrogen and phosphorous; and by contributing to the maintenance of favourable soil structure; retaining cations as well as in complexing micronutrient elements such as copper and zinc among other factors (Dalal and Mayer 1986).

It is the practice of cultivation and tilling of the land that affect soil chemical, physical, and biological characteristics. It is now well known that clearing of native vegetation and subsequent cultivation of pristine land generally leads to reduction in SOC (Dalal and Chan 2001; Dalal and Mayer 1986; Davidson and Ackerman 1993; Knowles and Singh 2003). The detrimental effects of losing SOC due to cultivation and cropping of the land include nutrient depletion, increase in bulk density, loss of

pedological aggregation, decrease in cation exchange capacity (CEC) and loss of microbial biodiversity; all of which contribute to reduced yields, and essentially unsustainable farming systems (Dalal and Chan 2001). Added to these effects is the potential of the soil acting as a source rather than a sink for greenhouse gas emissions which in Australia accounts for 15.2% of the national total emissions (State of the Environment Advisory Council, 1996). The decline in SOC under cultivation can be attributed to a number of factors i) reduced input from the crop compared with native vegetation, ii) change in soil water status, and iii) the physical effects of tillage which increase soil aeration as well as ensuring that soil decomposer organisms are constantly brought into contact with crop residues and soil carbon fractions (Skjemstad *et al.* 2001). For sustainable and productive farming systems to be realised and effective mitigation against greenhouse gas emissions (and hence global climate change), it is necessary to modify land management practices that increase or maintain high level of SOC (Hulugalle, 2000; Knowles and Singh, 2003; and Dalal and Chan, 2001). As such, the estimation and mapping of carbon storage in agricultural soils is an important for monitoring carbon fluxes under a range of management practices. Davidson and Ackerman (1993), in their review of this topical issue, concluded that about 20-40% of the soil carbon inventory is lost when a soil is cultivated. A 20% loss of the total SOC inventory in the first 5 years following disturbance of natural vegetation has been reported by Houghton *et al.* (1991). In the cotton growing region of north-western NSW, Knowles and Singh (2003) reported loss of up to 54% SOC due to cultivation and related increases in mineralisation under continuous cotton production system. Dalal and Chan (2001) estimated SOC loss of up to 60% for land use under cereal crop rotation in the same region over a 50 year time frame.

While the above estimations of the SOC inventory, plus other predictive models such as those proposed by Minasny *et al.* (2006) and Odeh *et al.* (2003) are useful indicators and tools for gauging SOC levels, they provide us only with information regarding past management practices. Of greater interest is the need to know how and at what rate SOC changes over time as well as prediction of gains and losses into the future under existing, changing and improved management practices. The RothC (Rothamsted Carbon) simulation model (version 26.3) (Coleman and Jenkinson 1996) is such a tool that enables such a modelling approach. RothC was designed to model the rate of carbon loss or sequestration for specific crops under agricultural soils using various management practices in monthly time steps over a year to centuries time scale. It is a five pool model (carbon fractions) consisting of two pools of plant residue and three soil pools as inputs. It allows for the affects of soil type, temperature, water content and plant cover to be factored into calculations. The RothC model has been widely used due to its few required inputs which are easily obtainable. It has also been validated for different conditions around the world and has been calibrated to operate under Australian agricultural conditions (Skjemstad *et al.* 2004). It is generally to simulate C at relatively spatial extent, e.g., at the paddock to farm scale (Jenkinson and Rayner 1977; Smith *et al.* 1997) However, recent applications at regional and ecosystem extents (Falloon *et al.* 1998; Skjemstad *et al.* 2004) and at a national and global scales (Jenkinson *et al.* 1991; Smith *et al.* 2005) have been reported.

In this study we applied a modified version of the RothC model (Richards 2001) by using a small subset of soil profile data contained in the Australian Cotton Soil Database (Odeh *et al.* 2004) as inputs to simulate the effect existing management practices (crop rotations) temporal variation of soil carbon pool in the Lower Namoi

Valley, NSW. The interpolation of the model outputs onto a dense grid using a regression tree model would show a pattern of the total soil carbon pool through time for the different land uses across the study area. We then mapped the change in SOC from initial levels prior to clearing to 2003. Depending on the models predictive capability, the base methodology developed during this exercise could possibly be extended to other areas with detailed soil data as contained in the Australian Cotton Soil Database (Odeh *et al.* 2004).

Materials and Methods

Model introduction

RothC model, used to quantify the turnover of carbon in soil, was developed to simulate the effects of agricultural management on the stocks of organic carbon (Coleman and Jenkinson 1996). It was designed to operate in monthly time steps on a year to centuries time scale, using soil C data to a depth of 30 cm. In applying the model the input plant material is split the above and below ground plant residues and detritus , including root exudates, into decomposable plant material (DPM) and resistant plant material (RPM), both of which accumulate at various times throughout a year. The ratio DPM/RPM is used directly in the model to allow for changes in the decomposability of the input from vegetation i.e. ratios of 1.44 and 0.67 are used to signify agricultural crops and scrubland respectively (Coleman and Jenkinson 1996). Both DPM and RPM are decomposed into microbial biomass (BIO) and humified organic matter (HUM) and CO₂ as gas emissions, with subsequent further decomposition of the BIO and HUM to produce more CO₂, BIO and HUM (Skjemstad *et al.* 2004) (Figure 1). The model also recognizes a fifth, inert pool of organic matter (IOM). With the exception of IOM, each compartment decomposes by a first-order process with its own characteristic theoretical rate (Table 1).

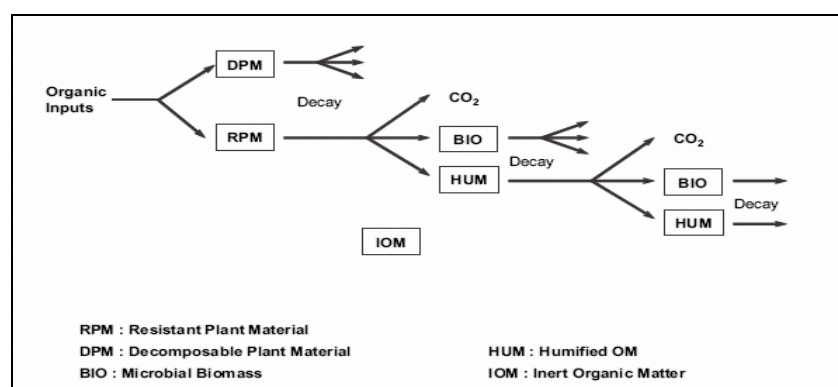


Figure 1- Schematic representation of RothC model.

Table 1- SOC decomposition rate constants

SOM Fraction	Decomposition rate constant (k) -year ⁻¹
DPM	10
RPM	0.15*
BIO	0.66
HUM	0.02

* Changed from 0.3 as in Coleman and Jenkinson (1996) by Skjemstad *et al.* (2002 and 2004) to incorporate model usage for Australian conditions and rectify divergence from measured RPM pools.

The actual rate of decomposition for each pool is determined using modifiers for temperature (a), soil moisture (b), plant cover (c), the decomposition rate for that particular compartment (k), and a constant (t)= 1/12 to convert k to a monthly time step. The model of the amount of carbon (Y) that decomposes from any active pool in a particular month follows an exponential decay function, whereby Y_0 = the initial amount of carbon in the particular pool is derived from (Eqn1):

$$Y = Y_0(1 - e^{-abck/t})$$

In the model, the clay content of the soil also affects the allocation of SOC between the evolved CO₂, the BIO and the HUM pools (Coleman and Jenkinson 1996). As such, an adjustment is required using the exponential equation (Eqn2):

$$X = 1.67 (1.85 + 1.6e^{-0.0786 \cdot \%Clay})$$

Where X is the ratio of CO₂/ (BIO+HUM), in which BIO and HUM are the respective initial pools of biomass and humus formed by the incoming plant material. The overall monthly change of SOC is then calculated as the sum of the 5 aforementioned pools.

Study area

The study area (3000 km² approx) is located in the Lower Namoi Valley catchment area, specifically west of Narrabri in north-western NSW. The townships of Burren Junction (30.08S, 148.59E) to the north, Pilliga (30.21S, 148.54E) to the south and Wee Waa (30.13S, 148.27E) to the east are all encapsulated within the study area (figure 2). Maximum and minimum temperatures for the area are 27.6°C and 11.7°C respectively with an average annual rainfall of 628mm. According to the NSW Department of Climate Change (2003), there are 83 separate land cover types in this study area. We rationalised these down to 5 broad land cover types: (1) Irrigated Cotton (48000 ha). (2) Continuous or rotational irrigated cropping (9000 ha). (3) Continuous or rotational dry land cropping (56000ha). (4) Native Vegetation (140 000 ha) which included areas of forest and remnant vegetation as well as native pasture grazing land. (5) Other (36000 ha) which included watercourses, townships and various private and public infrastructure types.

Model data

The data used in the modelling process was a subset from the Australian Cotton Soil Database (Odeh *et al.* 2004). The data set consists of 101 separate data points scattered throughout the study area. The data, obtained in 1996, include: soil type, % SOC, % clay, silt and sand for the top 30cm of soil. Land use types and the management practices, the year land was cleared or not, and whether cropping system is under irrigation or not were observed at the time of field survey (1996). Of the 101 sites, there were 27 under native pasture or woodland; 28- Continuous Cotton rotation, 31- Cotton-Grain rotation, 10-Cotton-Legume rotation; and 5- Continuous Grain. To simplify things we assumed that grain signifies wheat and legumes would signify either chickpeas or lupins based on the fact that both legume crops have near identical harvest indices and carbon contents (Australian Greenhouse Office, 2002).

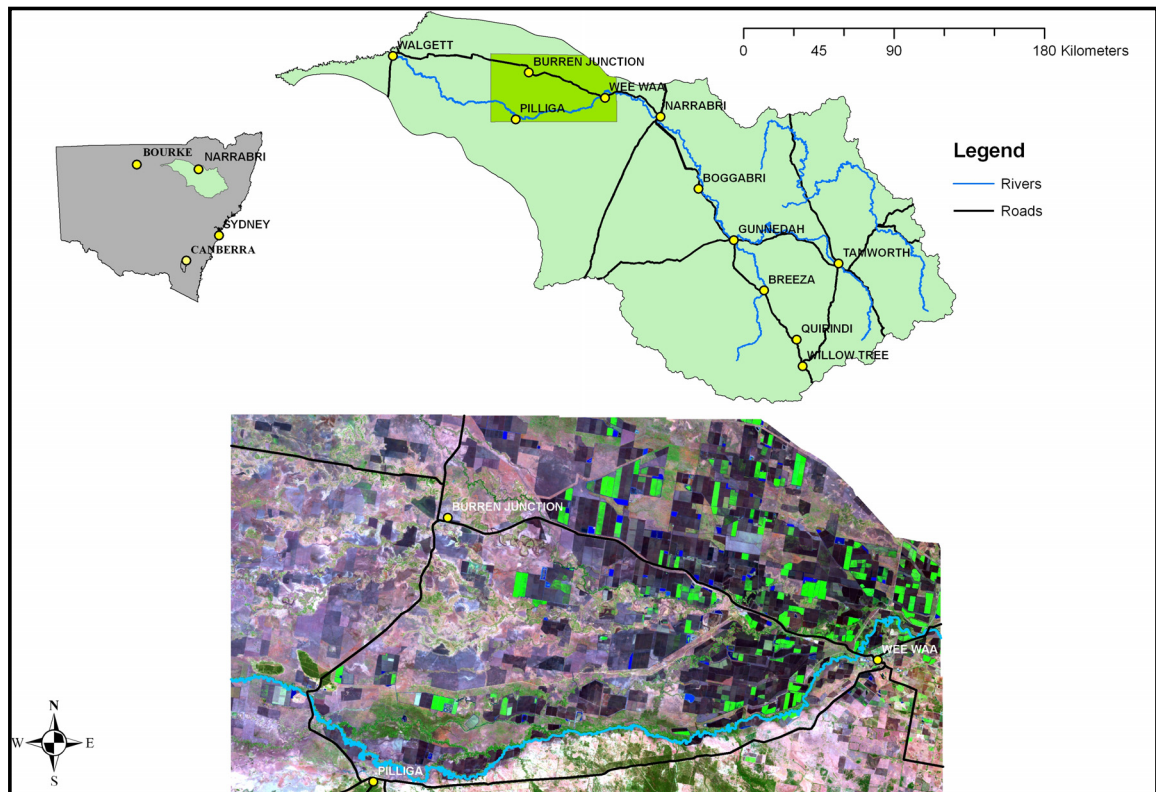


Figure 2- Study Area

Calibrating the RothC model

The RothC model can be used in two modes: (i) forward mode to simulate SOC under changed agricultural management and input of plant materials; and (ii) Inverse mode to calculate required plant inputs to reach the measured SOC content for equilibrium conditions with known land-use history. For calibration purposes, we ran the model in inverse mode to determine the starting points for each SOC pool including 3.8 t C ha^{-1} for the IOM pool. Assuming that the SOC at the 27 uncleared site points under native pasture or woodland had reached equilibrium at the time of measurement (1996), we ran the model iteratively under constant environmental conditions for 10000 years with different annual inputs of plant C until the SOC values of 1.52% or 1.31% (to account for different soil types i.e. Brown/Black Vertosols versus all other light texture soils respectively) were reached. Other model input requirements are listed in Table 2 below.

Running the model.

When once the starting C content was established we set about simulating SOC decomposition for each land use type for 34 years beginning in 1970 and ending in 2003. Management files were created for each land use type. The input files include: the year the land was cleared (if at all), whether soil type is Brown/Black Vertosol or other soil types (different starting C points) and whether the site is under irrigation or not. For the purpose of simulation and simplicity, cleared land prior to 1970 was taken as cleared in 1970. This alteration involved 18 of the 101 sites.

Table 2- Model input requirements for calibration.

Model input requirement	
Long-term monthly averages of rainfall, open pan evaporation and temperature	Centrally located point within the study area- Accessed from the Australian Greenhouse Office (AGO) website (http://www.greenhouse.gov.au/ncas)
Averaged clay content of the soil	Taken from the averages of the Brown Vertosol and the rest soil types
Estimate of DPM/RPM ratio	set to 0.67 (Coleman and Jenkinson, 1996)
Soil Cover	As all sites were uncleared; a 1 for every month of simulation (10000years) indicates permanent vegetative cover on the soil
Soil Depth	30cm
Soil Bulk Density Measurement	Used to calculate in $t\ C\ ha^{-1}$, the mass of each carbon pool. In this case from Tranter <i>et al.</i> (2007): $BD = 1.35 + (0.0045 * \%sand) + (44.7 - \%sand)^2 * (-6 * 10^{-5}) + ((0.060 \ln(\text{depth})))$

Other model requirements used in the calibration model involved some modifications and alterations to residue inputs, as derived using the harvest indices (AGO, 2002) (Table 3). For verification purposes, the accuracy of the model (root mean square error) and its outputs were compared to the measured SOC percentage values for each site as determined in 1996. Following the simulation analysis, the change in SOC from 1970 to 2003 (initial – final) for all sites was recorded and used to build a regression tree model to predict the change in SOC for the whole study area.

Regression Tree Model

Ancillary data were collected from various sources (Table 4) and mapped for the entire study area at a 200m resolution using ArcGIS (ESRI, 2007). This involved 72604 individual grid squares, each containing information as to soil type, radiometric data, terrain attributes, lithology, and land use. This ancillary data was also applied to each of the 101 site locations, based on each sites geographical position in the landscape.

Table 3- Ancillary data used for regression tree model

Ancillary Data	Source
Land Use	Department of Environment and Climate Change (2003)
Austrlain Soil Classification Soil Class (Isbell, 1996)	Nelson and Odeh (in prep) (2008)
Radiometric Data	Nelson and Odeh (in prep) (2008)
Potassium	
Thorium	
Uranium	
Terrain Attributes	Shuttle Radar Topography Mission (SRTM) at: http://www2.jpl.nasa.gov/srtm/
Topographic Wetness Index (TWI)	
Slope	
Aspect	
Elevation	
Lithology (1:1 000 000 map sheet)	Geoscience Australia at: http://www.ga.gov.au/nmd/mapping/

Table 4- Management inputs for each land used for RothC modelling

Land Use Management	Model Inputs
Continuous Cotton	Comment: Growing season begins in Oct and ends in Aril, then there is a five month fallow between crops. Starting C: Determined by site soil type *Residue Inputs: 4.06 t C ha⁻¹ (Swift and Skjemstad, 2002) distributed throughout a 7 month growing season Years since cleared: As determined by site observation Soil Cover: Only during the growing season i.e. 7 months Clay Content: As determined by site measurement DPM/RPM ratio: 1.44 (Coleman and Jenkinson, 1996) Climate Data: (rain, temp, evap) Actual monthly observations from central point of study area for the 34 years of simulation. **Irrigation: 6.8 ML/ha during the 7 month growing season (ACCRC, 2004)
Cotton-Grain (wheat) rotation	Comment: Essentially a two-year rotation with a 10-month fallow in the middle. Starting C: Determined by site soil type *Residue Inputs: As for continuous cotton then 1.38 t C ha⁻¹ (Swift and Skjemstad, 2002) distributed throughout an 8-month growing season. Years Since Cleared: As determined by site observation Soil Cover: Only during the respective growing seasons 7 months – cotton and 8 months -wheat Clay Content: As determined by site measurement DPM/RPM ratio: As for continuous cotton Climate data: As for continuous cotton **Irrigation: Only during cotton crop is the 6.8ML/ha applied during the 7-month growing season.
Cotton-Legume rotation (Chickpeas or Lupins)	Comment: As for Cotton-Grain rotation Starting C: Determined by site soil type *Residue Inputs: As for continuous cotton then 1.71 t C ha⁻¹ (Scott <i>et al.</i> 2003; Whish <i>et al.</i> 2007) distributed throughout an 8-month growing season. Years Since Cleared: As determined by site observation Soil Cover: As for Cotton-Grain rotation Clay Content: As determined by site measurement DPM/RPM ratio: As for continuous cotton Climate data: As for continuous cotton **Irrigation: As for Cotton-Grain rotation
Continuous Grain	Comments: Growing season begins in Apr and ends in Nov, then there is a four month fallow between crops. Starting C: Determined by site soil type *Residue Inputs: 1.38 t C ha⁻¹ (Swift and Skjemstad, 2002) distributed throughout an 8-month growing season. Years Since Cleared: As determined by site observation Soil Cover: Only during the growing season Clay Content: As determined by site measurement DPM/RPM ratio: As for continuous cotton Climate data: As for continuous cotton **Irrigation: No irrigation
Native pasture/woodland	Same inputs as in calibration except for actual weather data. Residue inputs set to 6.4 t C ha⁻¹ (average of inputs from the two different soil type groups). Only simulated to gauge the reliability of modelled results.

* Crop residues were determine from harvest indices (allocation to plant component) for the crop plants (AGO, 2002) and long-term average yield data in north-western NSW- 2.94t/ha and 1.77t/ha for cotton and wheat respectively (Swift and Skjemstad, 2002) and 1.60t/ha for lupins and chickpeas ((Scott *et al.* 2003; Whish *et al.* 2007). All residues were assumed to have a carbon content of 46% (Skjemstad *et al.* 2004).

** 6.8ML/ha is based upon the industry average for cotton growing in north-western NSW (ACCRC, 2004). This equates to an extra 97mm per month during the cotton growing season, in which was added to the existing rainfall for that particular month.

A predictive regression tree model was built to determine the change in SOC from 1970 to 2003 (derived from running the RothC model) using a number of ancillary data. The model with the highest variance explained (r^2) and lowest RMSE was used to predict the change in SOC for the rest of the study area (72604 points) which was subsequently mapped and tabulated according to the rationalised DECC (2003) land use codes.

Results and Discussion

Calibrating the RothC model.

The equilibrium averaged SOC percentages of 1.52 for Brown/Black Vertosols and 1.31 for the rest (soil types) was reached well before the end of the 10000 year simulation with annual plant residue carbon inputs of 6.5t C/ha and 6.3t C/ha respectively. However, in comparison to other related studies regarding carbon residue inputs in native grassland or woodland ecosystems, it is difficult to determine the validity of these predictions. Predictions vary from 3.72t C/ha for grasslands in Europe (Fallon *et al.* 1998), 1-9t C/ha for various grassland and woodland types in New Zealand (Tate *et al.* 1995) and 1.75t C/ha in grasslands in Germany (Kuziyakov and Domanski 2000). Due to heterogeneity of environmental and landscape attributes, our predictions may not be as equally accurate throughout the study area. However, there is scope to categorise the data further to account for this heterogeneity through individual categories for soil types. The problem with this solution is, as found with our dataset, was the apparent high variation of SOC within soil classes, particularly when there are few observations for a particular soil type.

Running the model

The results presented in Table 5 are estimates of accuracy (RMSE) of the modelled in comparison with the actual SOC measurements made in 1996. Based on this, estimates of SOC for Cotton-Cotton performed best with modelled data being 0.19% either side of actual measurements for that rotation. This is followed by RMSE estimates of 0.24, 0.31, 0.35 and 0.40% for Cotton-Legume, Cotton-Grain, Native Pasture and Grain-Grain rotations.

Table 5- Accuracy results of actual and modelled SOC estimates

Management Practice (rotation)	RMSE
Cotton-Cotton	0.19
Cotton-Grain	0.31
Cotton-Legume	0.24
Grain-Grain	0.40
Native Pasture	0.35

While not being entirely indicative of actual measurements, these results allow for significant scope in which to fine-tune the model inputs, as we have the luxury of comparative analysis hardly the case in large scale studies using the RothC model (Fallon *et al.* 1998; Jenkinson *et al.* 1991). Inputs such as climate variables were taken from only one location, whereas for true simulation it would be more sensible to use point data from interpolated datasets as used by Skjemstad *et al.* (2004), or if multiple weather stations exist; or perhaps model the data using the closest weather

station. Other assumptions such as residue inputs and irrigation usage were also based on averages of industry figures for the north-western NSW area. This may be adequate; however, there is capability in which to use actual long-term datasets (particularly yield data) to account for year to year yield and water usage variations (Swift and Skjemstad 2002). Initial levels of SOC (prior to clearing) also need to be properly verified. Perhaps a main underlying weakness of the modelling process which can be rectified (as mentioned above) with fine-tuning the data is the need to include more categories in the calibration phase.

In relation to the areas that had been cleared for agriculture (all management practices besides native vegetation), it was found that the year in which the land had been cleared had an impact on the models predictive ability. We ran the Cotton-Cotton rotation with a input information indicating that each site had been cleared in 1970 and found that the RMSE changed from 0.19% to 0.24%. From our understanding of the dataset, it was found that, the longer the land had been cleared, the lower the site SOC level (generally), which is not surprising.

Regression Tree Model

Of the available ancillary variables (Table 4) used in the regression tree model, only land use, slope, wetness index and the radiometric data of thorium and potassium contributed significantly for them to be included in the final model. (figure 3). The regression tree model (Figure 4) achieved an R^2 of 58% (explained variance) and RMSE of 0.19%.

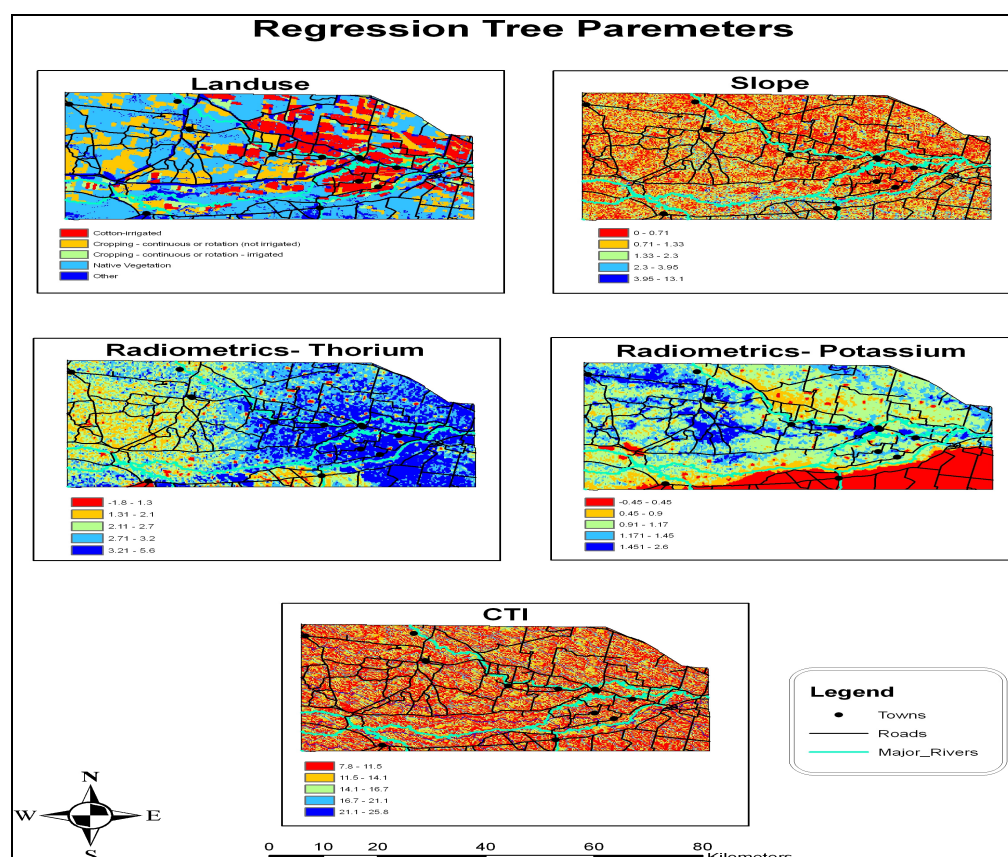


Figure 3- Ancillary data used in the regression tree

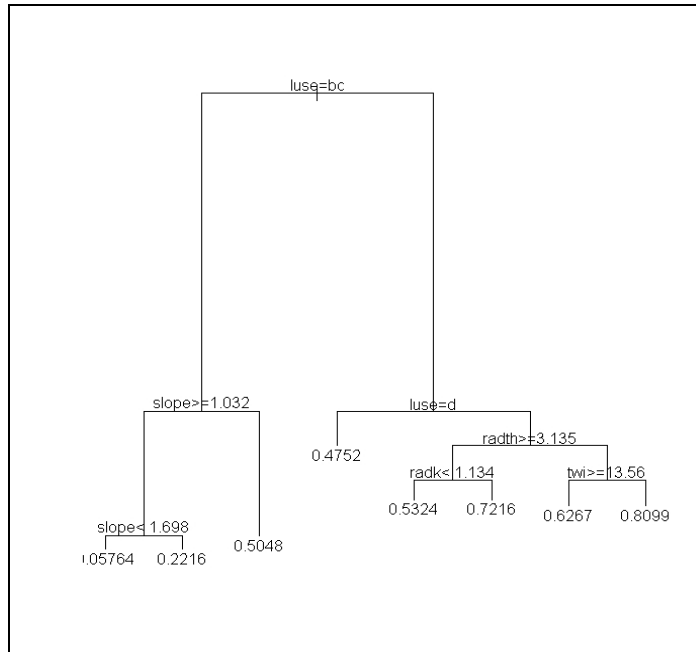


Figure 4- Schematic of regression tree.

Change in SOC from initial (pre-clearing) levels

Ancillary data for each grid square (72604) were fed into the derived regression tree to create the map of change in SOC in the top 30cm of the soils (Figure 5). It is apparent from the map that the land use features influenced the SOC spatial distribution very strongly. Areas shaded red indicating the largest SOC change are predominantly in the irrigated cotton and rotation cropping areas. As Table 6 indicates, average SOC losses for these land uses are 0.66 and 0.69% respectively. This equates to SOC losses of between 45-53% and 44-50% from initial levels prior to clearing for each respective land uses. These predictions are within range of those of Knowles and Singh (2003) and Dalal and Chan (2001) for similar geographic area. Comparatively, non-irrigated rotations had losses of between 31 and 36% from initial SOC levels. While it is difficult to determine the identity of the crops grown from the rationalised land use types, there appears to be some differentiation between irrigated and non-irrigated in terms of overall change in SOC. Such differences could be due to increased rates of SOC decomposition from higher soil moisture for irrigated areas as apposed to normal rain-fed systems. Besides temperature and residue quantity and quality, soil water availability is an important factor influencing soil respiration (Reichstein *et al.* 2005).

Table 6- Tabulated SOC change and respective land use.

Land Use	COUNT	MIN	MAX	RANGE	MEAN	STD
Other	9037	0.06	0.81	0.75	0.30	0.19
Native Vegetation	34520	0.06	0.81	0.75	0.31	0.20
Cropping - continuous or rotation (not irrigated)	14121	0.48	0.48	0.00	0.48	0.00
Cropping - continuous or rotation - irrigated	2287	0.53	0.81	0.28	0.69	0.11
Cotton-irrigated	12003	0.22	0.81	0.59	0.66	0.12

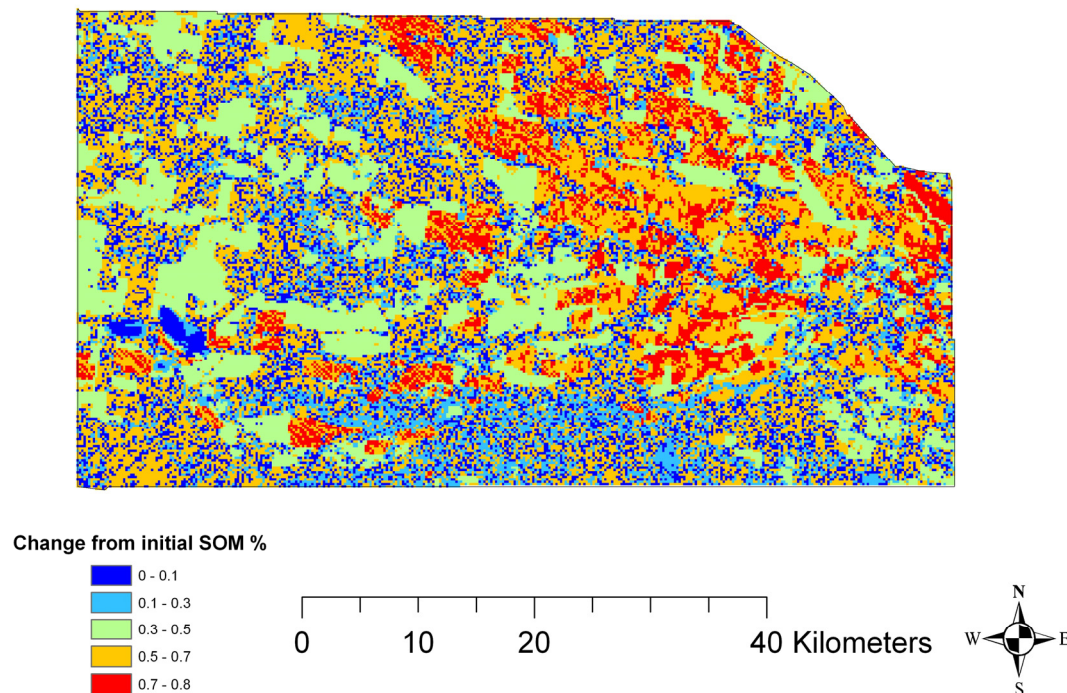


Figure 5- Modelled change in SOC for initial levels within the study area

The results also indicate that changes in SOC of between 20-24% for both Native Vegetation and Other land use types. As for 'Other' land use type which includes infrastructure and water body we are not too concerned at this stage of the findings. However, we were surprised to find significantly large estimates of SOC change for the native vegetation. While native vegetation land use type does not include areas of native grazing grassland, we believe that such a prediction is the result of some disharmony between management practices as in the soil database and the rationalised land use types. Ideally, a more robust method of land use classification would be suited to this application, as the data in the soil database is specific to the point of indicating the types of crop rotations, whereas from DECC (2003), land use types are too broad and ambiguous.

Conclusions

Modelling soil organic matter fluxes under various management systems with the RothC model has provided some feasible results. Land under irrigated cotton or other irrigated farming practices (rotation systems) experienced the largest decline in SOC in comparison to dry land farming systems. Estimates of SOC loss for irrigated cotton over time are equal to those of previously published studies. However, there is significant scope to improve these results through verification of initial SOC contents, determination of land clearing events and more detailed land use classification compatible to the Soil Cotton Database. Overall, output from the model has provided some information on SOC fluxes through time as caused by different land management practices. We are confident that the modified land management practices such as the sowing of cover crops during fallow periods (Hulugalle 2000) to increase or sustain levels of SOC can be adequately modelled using the RothC modelling

framework. As a value-adding exercise of the extensive cotton soil database, future studies could involve addressing how SOC will change in the future under the various cotton based management practices in relation to climate change scenarios as adduced by the Intergovernmental Panel on Climate Change (IPCC 2004).

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