SECTION 7
Combining plant and soil C cycling models - consideration of methods.

Combining plant and soil c cycling models – consideration of methods

Pete Falloon[1] & Pete Smith[2]
[1]*Soil Science Department, IACR Rothamsted, Harpenden, Herts, UK. AL5 2JQ, UK*
[2]*Department of Plant and Soil Science, University of Aberdeen, Cruikshank Building, Aberdeen, AB24 3UU, UK*

1. Introduction

The Rothamsted Carbon Model (RothC; Coleman and Jenkinson, 1996) is currently being developed to assess changes in soil carbon stock for the UK when coupled to the National Soils Inventory (NSI) for England and Wales and equivalent databases for Scotland and Northern Ireland. Current methods (Falloon *et al.* 1998b; Parshotam *et al.* 1995) use inverse modelling (i.e. fitting the model to high-quality long-term datasets) to derive C inputs to be used by RothC. Other approaches include linked soil C and plant C routines. This paper examines some examples of the methodological issues faced when combining plant and soil C models using the plant components of a general ecosystem model (CENTURY; Parton *et al* 1987) with the simple and transparent soil C routines of RothC as a model. The future coupling of RothC with other plant C models, such as CEH's BIOTA model will build on this experience.

We have developed a method to extract carbon input data from the CENTURY plant module, for use with the RothC model. This allows an equal comparison of how the soil organic matter (SOM) turnover components of both models perform with the same input datasets, and also allows RothC to be loosely linked with the plant components of the CENTURY general ecosystem model. We present model simulations for three sites, using the CENTURY model alone, using RothC and 'inverse' modelling (described below), and with RothC driven by C inputs generated by CENTURY.

2 Methods

2.1 Model input data

Input data for RothC and CENTURY were collected for three sites covering arable, grassland and forest management, and different soil types (Table 2.1).

In order to compare the performance of RothC and CENTURY on an equal basis, all data inputs to the model were, where possible, identical. Major input data for RothC and CENTURY are given in Table 2.2. Annual meteorological records were used for all sites. For some variables, the use of identical data input data was possible, for example RothC and CENTURY both use monthly rainfall data and soil textural information. In other cases, different model input parameters were required. To allow close comparison, RothC was always run using evaporation data estimated using the CENTURY model water modules. Plant inputs of C to soil for RothC were set in one of two ways. Firstly, RothC was run using 'inverse modelling' of SOC (or in 'reverse mode': Coleman *et al.*, 1997): by adjusting the annual plant input of C to soil to obtain the best fit to modelled SOC values. In this case, model best fit was assessed using the Root Mean Square Error (RMSE), a measure of overall model fit to measured data (Smith *et al.*, 1996). Secondly, RothC was run using plant inputs of C to soil estimated by the CENTURY model. CENTURY model plant C inputs to soil were the same as those obtained during the CENTURY model simulations presented in this chapter.

A FORTRAN program (READSITE) was created to extract evaporation and plant C input data from monthly CENTURY output files, and to create weather and land management files for running the RothC model.

Initial pool sizes for RothC and CENTURY were estimated as follows. If both total SOC measurements and soil ^{14}C dates were available, an inverse modelling procedure was used to derive the IOM content of the soil for the RothC model (Geescroft Wilderness and Park Grass; from former model evaluations). In the absence of soil ^{14}C dates the equation derived in Falloon *et al* (1998), relating IOM content to total SOC content, was used to estimate the IOM content of the soil. For CENTURY, initial pool sizes were set according to the guidelines given by Metherell et al (1993), dividing total SOC into active SOM (2-3 times the soil microbial biomass C, or 2-4% of total SOC), slow SOM (approximately 55% of total SOC), and passive SOM (30-40% of total SOC).

Model input files were created using the input data collected, and model runs executed to accurately simulate management regimes at each of the sites studied. Model outputs were then studied, model fit to measured data assessed using the RMSE, and plant C inputs to soil recorded.

Table 2.1: Summary of long-term experiments selected for model evaluation

Site & Reference	Country	Land use	Equilibrium land use	Treatments	Soil clay %	Initial SOC (t C ha^{-1} to 20cm)	Mean total annual rainfall (mm)	Mean annual temperature (^{O}C)
Geescroft Wilderness (Poulton, 1995a)	UK	Natural woodland regeneration	Arable	No additions	21.0	24.94	704.00	9.29
Park Grass (Poulton, 1995b)	UK	Grassland	Grassland	Unmanured, NPKNaMg	23.0	78.00	704.00	9.29
Woburn ley arable (Johnston, 1973)	UK	Ley-arable	Grass then arable rotation	Arable with roots, arable with hay, ley arable	63.0	32.64	506.68	9.28

Table 2.2: Major input variables for the RothC and CENTURY models

	RothC	CENTURY
Soil variables	Clay content	Sand content
	Inert Organic Matter content	Silt content
	SOC content	Clay content
		Bulk density
		SOC content
		Active SOM content
		Slow SOM content
		Passive SOM content
Weather variables	Total monthly precipitation	Total monthly precipitation
	Mean monthly temperature	Mean monthly maximum temperature
	Total monthly evaporation	Mean monthly minimum temperature
Management variables	Residue quality factor (DPM/RPM ratio)	Residue lignin/N ratio
	Soil Cover	Plant C and N content
	Residue C input	Atmospheric N deposition
	Manure C inputs	

3 Results and discussion

3.1 CENTURY simulations

Geescroft Wilderness, UK

Kelly et al. (1997) formerly used CENTURY to simulate SOC changes in the Geescroft Wilderness Experiment. Their values for the initial distribution of total SOC amongst model pools were used in this simulation. The CENTURY model run for Geescroft included simulation of the early scrub-forest succession. The CENTURY model simulation of Geescroft Wilderness showed a dramatic increase in SOC, close to the measured values (Fig. 3.1a). The increase in SOC at Geescroft is attributed to the change in management from arable land to natural woodland regeneration. C inputs to soil under woodland are more resistant to decomposition than those under arable land, and the total amount of C input to soil under woodland may also often be greater than that under arable land. This decrease in decomposability and increase in quantity of C inputs results in increased SOC concentrations. The CENTURY model showed a reasonable fit to the measured SOC values (RMSE=19.83), with a slight overestimation of measured SOC in general. C input to soil as estimated by the CENTURY model were 2.87 t C ha^{-1} y^{-1}.

Park Grass, UK

Kelly *et al.* (1997) formerly simulated SOC changes in the Park Grass Experiment with CENTURY. Their estimation of the initial SOC pool size distribution for the CENTURY model was used for these runs. CENTURY model simulations were run for two treatments at this site, Plot 3d (unmanured) and Plot 14d (NPKNaMg). In general, the CENTURY model simulations showed similar patterns to the measured SOC values (Fig. 3.1b), although there was little overall variation in observed SOC values. The CENTURY model predicted little difference in SOC values between the two treatments, whilst the measurements suggest a slightly greater SOC concentration in the unmanured treatment compared to the NPKNaMg treatment. The reason for this difference is unclear (Coleman *et al.* 1997) - it would normally be expected that the fertilization of the grassland would lead to a greater grass yield, and hence greater C inputs to soil. C inputs to soil as estimated by CENTURY were 4.10 t C ha^{-1} y^{-1} in the unmanured plot and 3.53 t C ha^{-1} y^{-1} in the NPKNaMg treatment. Model fit to the measured SOC values was good for both treatments (RMSE=6.72 and 5.84 for the unmanured and NPKNaMg plots, respectively).

Woburn Ley Arable, UK

Three treatments of the Woburn Ley-Arable experiment were simulated with CENTURY (Fig. 3.1c), the 'arable with roots, no FYM (Arable-Roots)', 'arable with hay, no FYM (Arable-Hay)', and 'grazed ley, no FYM (Grazed-Ley)' treatments. The Arable-Roots treatment consisted of a five-course rotation of potato-cereal-root followed by potato-barley, sugar beet-barley, or barley-barley. The five-course

Figure 3.1a: Measured and CENTURY simulated SOC at Geescroft Wilderness

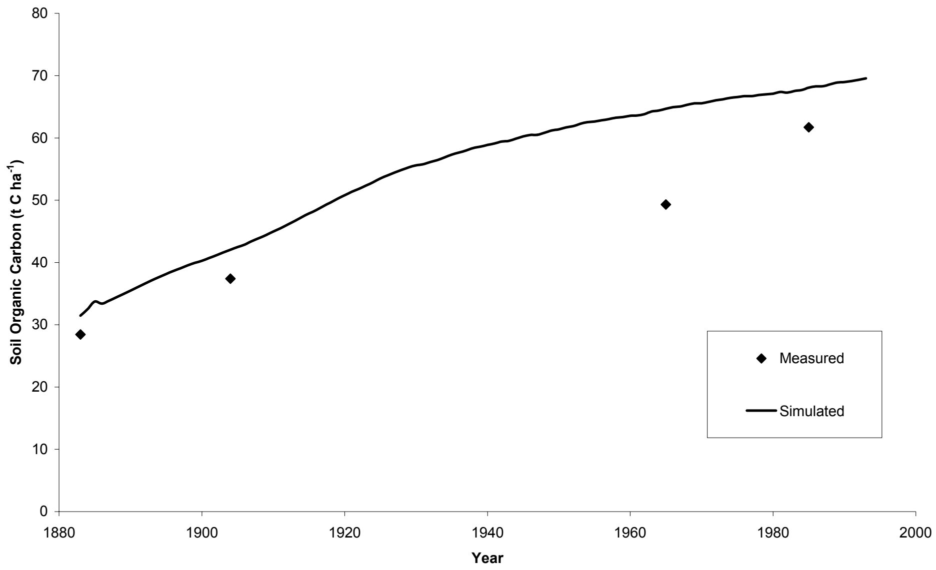
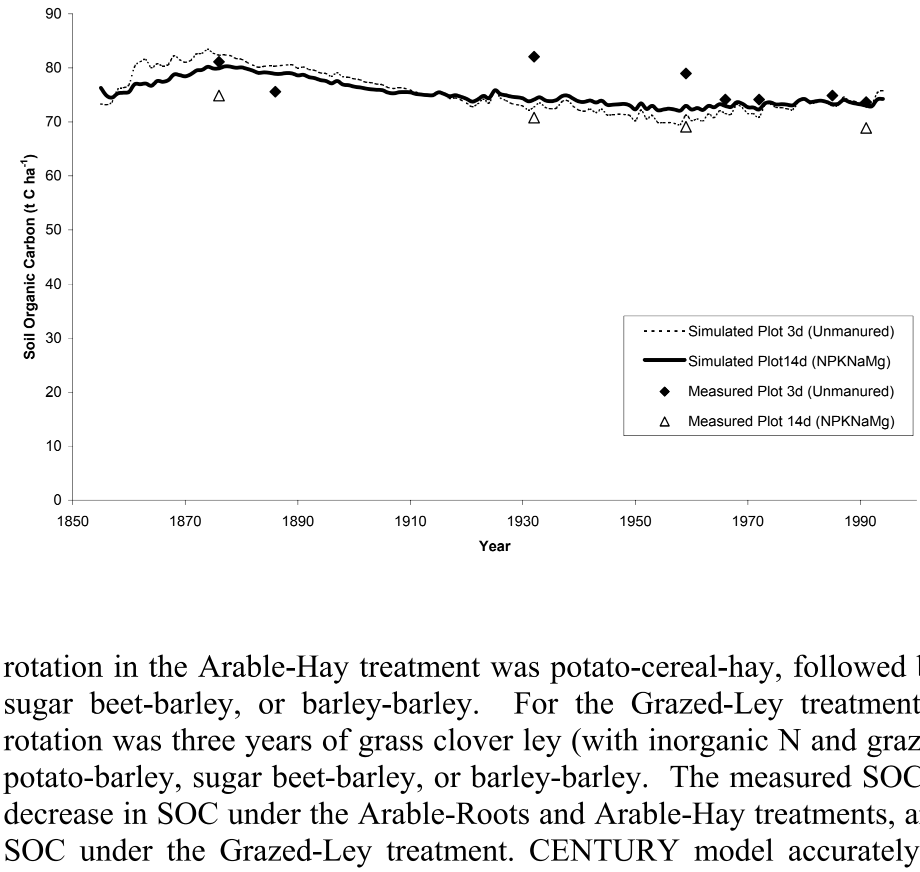


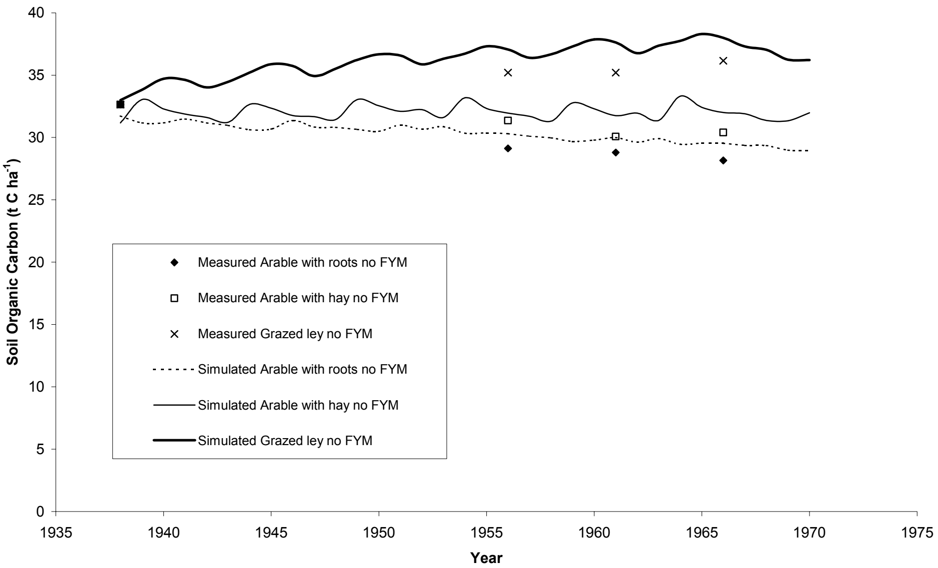
Figure 3.1b: Measured and CENTURY simulated SOC at Park Grass



rotation in the Arable-Hay treatment was potato-cereal-hay, followed by potato-barley, sugar beet-barley, or barley-barley. For the Grazed-Ley treatment the five-course rotation was three years of grass clover ley (with inorganic N and grazing) followed by potato-barley, sugar beet-barley, or barley-barley. The measured SOC showed a slight decrease in SOC under the Arable-Roots and Arable-Hay treatments, and an increase in SOC under the Grazed-Ley treatment. CENTURY model accurately simulated these changed in SOC with a good fit to measured data (RMSE=3.96, 4.51 and 5.16 for the Arable-Roots, Arable-Hay and Grazed-Ley treatments, respectively). CENTURY also suggested some details of SOC dynamics not shown in the measured data. The CENTURY simulations of the Arable-Hay and Grazed-Ley treatments both showed a

SOC increase during the years when the treatments were under grass, due to the greater quantity, and lower decomposability of C input under grassland compared to arable management. Average C inputs to soil predicted by CENTURY were 0.66, 0.88, and 1.00 t C ha^{-1} y^{-1} for the Arable-Roots, Arable-Hay and Grazed-Ley treatments, respectively, with the average C input during grassland management being 1.55 t C ha^{-1} y^{-1}.

Figure 3.1c: Measured and CENTURY simulated SOC at Woburn Ley Arable



3.2 RothC simulations - inverse modelling

Geescroft Wilderness, UK

SOC dynamics at Geescroft Wilderness have been simulated previously with RothC by Coleman *et al*. (1999). The simulation presented here uses slightly different input data to their simulation, in using evaporation estimated from the CENTURY simulation of Geescroft Wilderness, to allow maximum comparability between RothC and CENTURY model simulations. The IOM content of the soil was set at 2.5 t C ha^{-1}, as previously estimated using soil ^{14}C dates and SOC measurements (Coleman *et al*. 1997). RothC predicted a sharp increase in SOC (Fig. 3.2a), and gave a good fit to measured SOC data (RMSE=9.26). Plant inputs of C to soil predicted by RothC were slightly higher than those estimated by Coleman *et al*. (1997), at 3.85 t C ha^{-1} y^{-1}.

Park Grass, UK

Coleman *et al*. (1997) previously simulated changes in SOC in the Park Grass Experiment using RothC. The simulations presented here simulation presented here differ from their simulation since evaporation data estimated from the CENTURY simulation of Park Grass were used (rather than measured data from the site), to allow maximum comparability between model simulations. The IOM content of the soil was set at 6.9 t C ha^{-1}, as previously estimated using soil ^{14}C dates and SOC measurements (Coleman *et al*. 1997). The model predicted similar changes in SOC to those measured (Fig. 3.2b), with little overall change in SOC through time, and a slightly greater SOC concentration in the un-manured plot (3d) compared to the NPKNaMg treatment (plot

14d). Model fit to measured data was good, with RMSE=4.09 and 2.34 for the un-manured and NPKNaMg treatments, respectively. RothC predicted C inputs of 4.08 and 3.67 t C ha^{-1} y^{-1} for the un-manured and NPKNaMg treatments, respectively. As discussed in section 1.3.1, the reasons for this treatment difference are unclear, and it would normally be expected that inorganic fertilization would increase herbage yield and thus C input to soil, although it may be that more C is allocated below ground in the unfertilized plots, relative to fertilized plots.

Woburn Ley Arable, UK

Jenkinson et al. (1987) previously simulated changes in SOC in the Woburn Ley Experiment using RothC. The simulations presented here simulation presented here differ from their simulation since evaporation data estimated from the CENTURY simulation of the Woburn Ley Arable Experiment were used (rather than measured data from the site), to allow maximum comparability between RothC and CENTURY model simulations. In the absence of soil ^{14}C dates, the IOM content of the soil was estimated as 2.49 t C ha^{-1} using the equation relating IOM content to total SOC, derived in Chapter 4. RothC gave an excellent fit to the measured SOC data (RMSE=1.48, 1.41, and 3.74 for the Arable- Roots, Arable-Hay, and Grazed-Ley treatments, respectively. RothC followed trends in the measured SOC data (Fig. 3.2c), with a steady decline in SOC under Arable-Roots, a 'saw-tooth' decline in SOC under Arable-*Hay, and a* 'saw-tooth' increase in SOC under Grazed-Ley. RothC predicted average plant inputs of C to soil as 1.16, 1.26 and 1.76 t C ha^{-1} y^{-1} under Arable-Roots, Arable-Hay and Grazed-Ley, respectively, with the average C input during grassland management being 1.95 t C ha^{-1} y^{-1}.

Figure 3.2a: Measured and RothC simulated SOC at Geescroft Wilderness

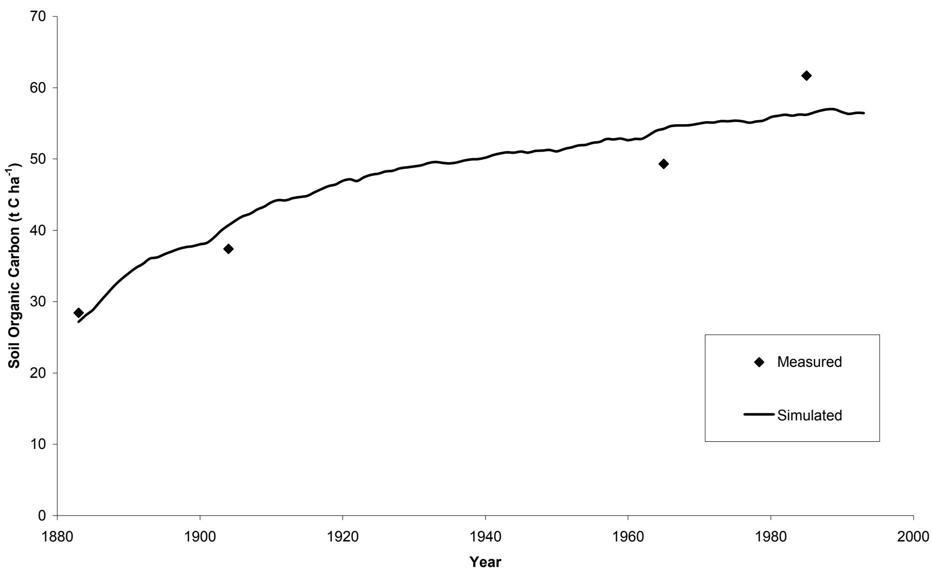


Figure 3.2b: Measured and RothC simulated SOC at Park Grass

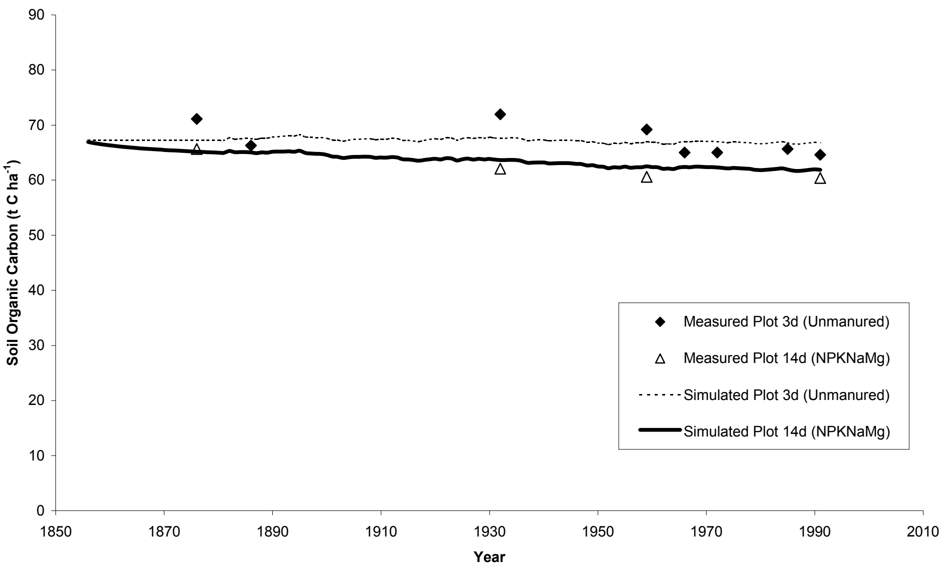
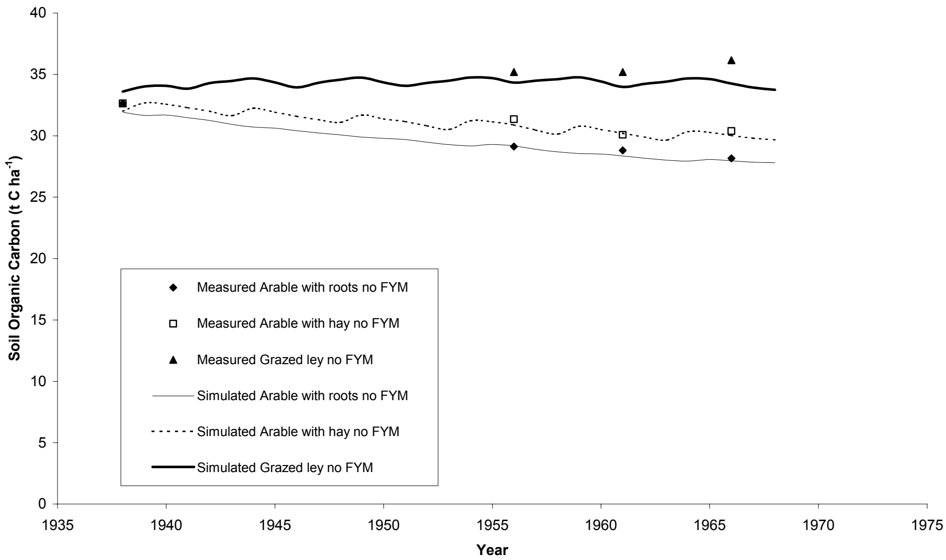


Figure 3.2c: Measured and RothC simulated SOC at Woburn Ley Arable



3.3 RothC simulations with CENTURY plant C inputs

Geescroft Wilderness, UK

The simulation of SOC changes at Geescroft Wilderness using RothC driven by C inputs derived from CENTURY also resulted in an underestimation of measured SOC values (Fig. 3.3a). Although the model did predict a pattern of SOC increase similar to that measured, the fit of simulated SOC to measured SOC values was poor, with RMSE=25.61.

Park Grass, UK
In common with observed SOC values, RothC predicted a greater SOC concentration in the Un-manured treatment (3d) at Park Grass relative to the NPKNaMg treatment (14d), when run using C inputs derived from CENTURY (Fig.3.3b). RothC also predicted little temporal variation in either treatment, which was also observed in the measured SOC data. However, RothC did underestimate measured SOC values in general, with a poorer fit to measured SOC in both treatments than obtained using either RothC with inverse modelling, or the CENTURY model alone. RMSE values for these runs were 9.37 for the Nil treatment (3d) and 6.74 for the NPKNaMg treatment (14d).

Figure 3.3a: Measured and RothC simulated SOC (using CENTURY-derived C inputs) at Geescroft Wilderness

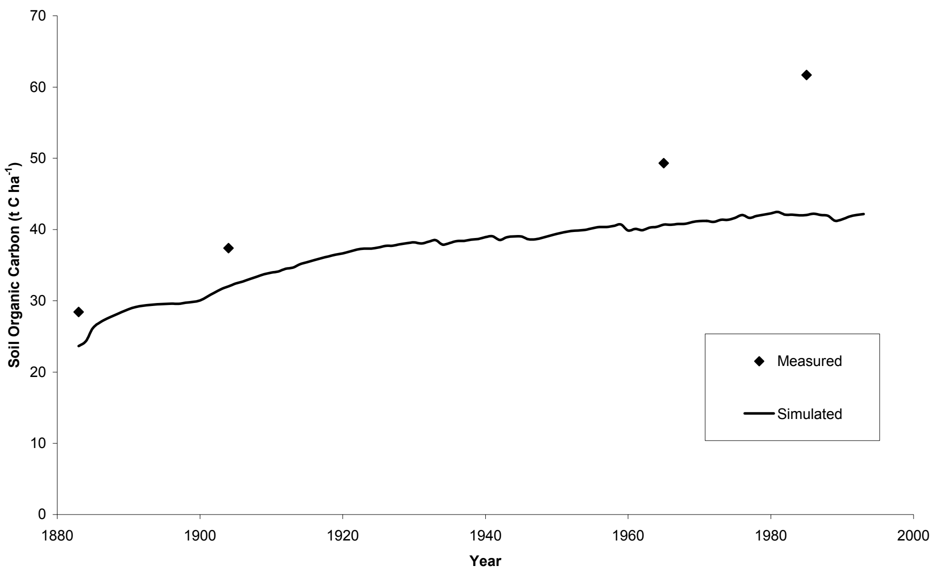
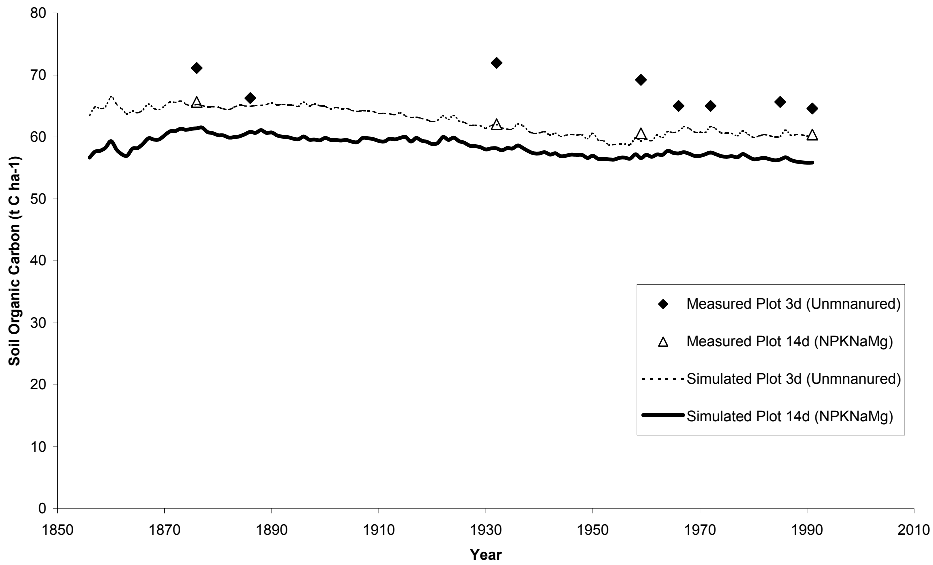


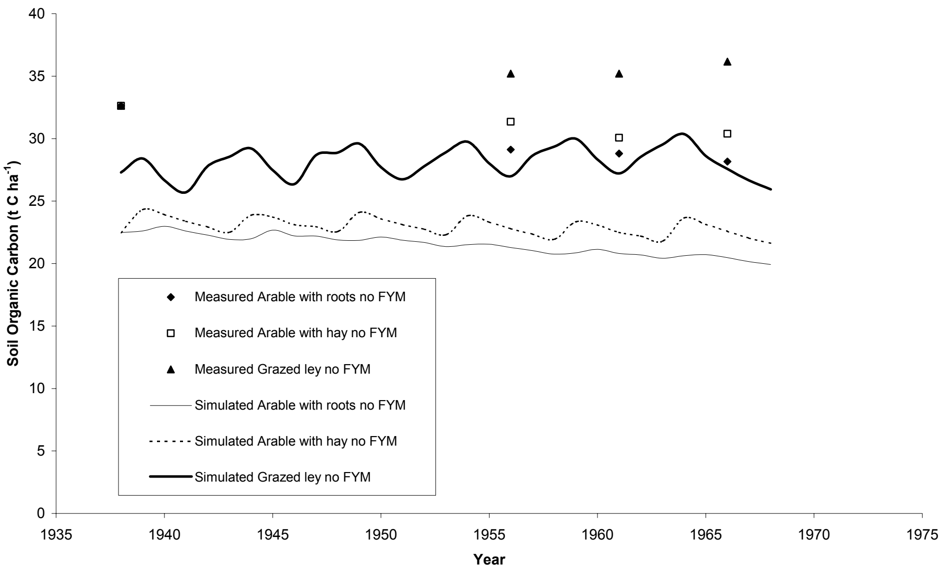
Figure 3.3b: Measured and RothC simulated SOC (using CENTURY-derived C inputs) at Park Grass



Woburn Ley Arable, UK

The simulation of SOC changes in the Woburn Ley Arable experiment using RothC driven by C inputs derived from CENTURY also resulted in an underestimation of measured SOC values (Fig. 3.3c). RothC did predict patterns of SOC change similar to that measured, with a slight decrease in SOC in the Arable-Roots treatment, little overall change with a 'saw-tooth' pattern of SOC change in the Arable-Hay treatment, and a 'saw-tooth' pattern of SOC increase in the Grazed-Ley treatment. However, the RothC generally underestimated measured SOC values, with RMSE=28.58, 27.60 and 21.97 for the Arable-Roots, Arable-Hay, and Grazed-Ley treatments, respectively. The RothC fit to measured SOC values was poorer for these simulations than the fit obtained using RothC and inverse modelling or using CENTURY alone.

Figure 3.3c: Measured and RothC simulated SOC (using CENTURY-derived C inputs) at Woburn Ley Arable



4. Discussion and Conclusions

In general, both models gave a reasonable or good fit to measured long-term SOC data at arable, grassland and forestry management sites. RothC did tend to give a slightly better fit to measured SOC data than did CENTURY. This is almost certainly due to the way in which modelled SOC values may be fitted to measured SOC values by iteratively changing the annual C input to soil, or 'inverse' modelling. RothC runs using the inverse modelling procedure tended to require greater annual C inputs to soil than were predicted by the CENTURY model for the same treatments at the same sites. The probable reason for this is that, in general, the SOM in RothC turns over somewhat faster than in CENTURY, thus requiring a greater C input to maintain the same SOC stock. This is a fundamental functional difference between the models that requires further investigation (though not in this project).

Runs of RothC using annual C inputs to soil derived from CENTURY model runs therefore also had a tendency to underestimate measured SOC values, and thus generally had the poorest fit to measured SOC values of all model runs.

RothC and CENTURY predicted differences between management treatments similar to those observed. The linkage of RothC and CENTURY using the READSITE program has enabled RothC to be run using C inputs derived from CENTURY model runs. This allows C inputs for RothC to be estimated independently, using a process-based plant production model. Running RothC in this way, with C inputs derived from CENTURY can, however, be expected to give lower estimates of SOC concentrations than comparable CENTURY runs.

This study highlights some of the problems associated with linking independent models. RothC and CENTURY have been shown, when run according to normal modelling practice, to produce similar results for changes in SOC in a range of long term experiments (Coleman *et al.* 1997; Kelly *et al.* 1997; Smith *et al.* 1997). This study has shown, however, that the C routines of RothC and CENTURY behave differently, with RothC simulating a more rapid turnover of C than CENTURY. It could be argued from the many studies in the literature, that independent tests of the model SOC routines of each model has shown each to be parameterised correctly, but this study suggests otherwise. Possible explanations are either that soil C turnover in RothC is too fast, or soil C turnover in CENTURY is too slow, compensated by a lower than actual input of C to the soil from the plant module (cancelling parameter errors). Since both models are used widely in global change studies and are being used in a number of National Carbon Accounting Systems for UNFCCC National Greenhouse Gas Inventory submissions, the discrepancies highlighted here merit further study.

For the purposes of this project, the potential problems associated with the results from linked models, describing different components of the terrestrial C cycle, are apparent. When linking RothC and CEH models such as BIOTA in years 2 and 3 of the project, care must be taken to ensure that parameter errors from each model component do not cancel. When linking soil and plant C cycling models, independent assessments should be made of the reliability of model predictions of a) the rate of C turnover, and b) carbon returns to the soil. This should be a priority in project years 2 and 3.

References

Falloon, P., Smith, P., Coleman, K. & Marshall, S. 1998a. Estimating the size of the inert organic matter pool for use in the Rothamsted carbon model. *Soil Biology and Biochemistry*, **30,** 1207-1211.

Falloon, P., Smith, P., Smith, J.U., Szabó, J., Coleman, K. & Marshall, S. 1998b. Regional estimates of carbon sequestration potential: linking the Rothamsted carbon model to GIS databases. *Biology and Fertility of Soils* **27**, 236-241.

Parshotam, A., Tate, K. R. & Giltrap, D. J. 1996. Potential effects of climate and land-use change on soil carbon and CO_2 emissions from New Zealand's indigenous forests and unimproved grasslands. *Weather and Climate*

Coleman K. & Jenkinson D.S. 1996. RothC-26.3- A Model for the turnover of carbon in soil. D.S.Powlson, P.Smith, J.U. Smith (Eds.) *Evaluation of soil organic matter models using existing, long-term datasets*. NATO ASI Series I. Springer-Verlag. Berlin. p237-246.

Coleman, K., Jenkinson, D.S., Crocker, G.J., Grace, P.R., Klir, J., Körschens, M., Poulton, P.R. & Richter, D.D. 1997. Simulating trends in soil organic carbon in long-term experiments using RothC-26.3. *Geoderma*, **81,** 29-44.

Jenkinson, D.S., Hart, P.B.S, Rayner, J.H. & Parry, L.C. 1987. Modelling the turnover of organic matter in long-term experiments at Rothamsted. *INTECOL Bulletin*, **15,** 1-8.

Johnston, A.E. 1973. The effects of ley and arable cropping systems on the amounts of soil organic matter in the Rothamsted and Woburn Ley-arable experiments. Rothamsted Experimental Station, Report for 1972, part 2: 131-159.

Kelly R.H., Parton W.J., Crocker G.J., Grace P.R., Klir J., Korschens P.R., Poulton P.R & Richter D.D. 1998. Simulating trends in soil organic carbon in long-term experiments using the CENTURY model. *Geoderma*, **81**, 75-90

Metherell, A.K., Harding, L.A., Cole, C.V. & Parton, W.J. 1993. *CENTURY Soil Organic Matter Model environment. Technical Documentation, Agroecosystem Version 4.0*. Great Plains System Research Unit Technical Report No. 4. USDA-ARS, Fort Collins, Colorado.

Parshotam, A., Tate, K. R. & Giltrap, D. J. 1995. Potential effects of climate and land-use change on soil carbon and CO_2 emissions from New Zealand's indigenous forests and unimproved grasslands. *Weather and Climate* **15,** 3-12.

Parton, W.J., Schimel, D.S., Cole, C.V. & Ojima, D.S. 1987. Analysis of factors controlling soil organic matter levels in Great Plains grasslands. *Soil Science Society of America Journal*, **51**, 1173-1179.

Poulton P.R. 1995a. Geescroft Wilderness, 1883-1995. In *Evaluation of soil organic matter models using existing long-term datasets* (ed: D.S.Powlson, P.Smith & J.U.Smith), NATO ASI Series I, Vol. 38, Springer-Verlag, Heidelberg: 385-390.

Poulton P.R. 1995b. Park Grass, 1856-1995. In *Evaluation of soil organic matter models using existing long-term datasets* (ed: D.S.Powlson, P.Smith & J.U.Smith), NATO ASI Series I, Vol. 38, Springer-Verlag, Heidelberg: 377-384.

Smith J.U., Smith P., & Addiscott T.M. 1996. Quantitative methods to evaluate and compare soil organic matter (SOM) models. In: . In *Evaluation of soil organic matter models using existing long-term datasets* (ed: D.S.Powlson, P.Smith & J.U.Smith), NATO ASI Series I, Vol. 38, Springer-Verlag, Heidelberg: 183-202.

Smith, P., Smith, J.U., Powlson, D.S., McGill, W.B., Arah, J.R.M., Chertov O.G., Coleman, K., Franko, U., Frolking, S, Jenkinson, D.S., Jensen, L.S., Kelly, R.H., Klein-Gunnewiek, H., Komarov, A., Li, C., Molina, J.A.E., Mueller, T., Parton, W.J., Thornley, J.H.M. & Whitmore, A.P. 1997. A comparison of the performance of nine soil organic matter models using seven long-term experimental datasets. *Geoderma* **81**: 153-225.