Section 6

The potential use of the Rothamsted Carbon model, RothC, in GHG inventories

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6.1. Abstract

Currently there is a great need to document the world's carbon stocks in soils and changes in those stocks with time. Signatories to the UNFCC are obliged to make annual returns. Most make use of IPCC methodology but this is crude and there have been several attempts at improvement. Inevitably, however, improvements are costly in computer time and even with advances in processor speed, this cost can be prohibitive in detailed analyses. The Rothamsted Carbon model, RothC-26.3 (referred to hereafter as RothC), is a mechanistic model of the processes affecting the dynamics of carbon in soil that works at a time-scale appropriate to inventories. It has been embedded into an Excel spreadsheet for the Australian inventory (Richards, 2001) and has been used as an aid to validating the General Linear Model used in the New Zealand inventory (Tate *et al*., 2005). It forms the basis of RothCUK a spatially distributed version of RothC for the UK at a 1 km spatial resolution (Falloon *et al*., 2006). In practice, however, current inventories worldwide lag behind the detailed data collection needed to run RothCUK. Given this gap but given too the need to improve on IPCC methodology, the task we set ourselves to investigate is this: How might the mechanistic capability of RothC best be introduced into the UK carbon reporting process simply but with the capability for gradual improvement as data collection and reporting improve with time? We compare two likely options: (1) simple systems of equations; what we lose in mechanism we hope to gain in simplicity by this approach. (2) call the RothC model directly from within the inventory spreadsheet.

Although the meta-model system performed well in the sense that it could emulate RothC, it presents poor prospects in practice since the parameters required were rather variable. This is surprising because a simple meta-model is at the heart of the current UK inventory. An analytical solution to the differential equations underlying RothC appears attractive for some purposes such as assessing variability and uncertainty, but is likely to still require too many different parameter sets for deployment within the inventory. We conclude that the most effective means to improve the UK inventory is to call RothC directly from the inventory spreadsheet. Although this is a costly option in computer time, it future-proofs the system, since upgrades to RothC will always be easily available. This option supports the gradual adaptation of the inventory not only to improvements in databases as and when such information becomes available but also the incorporation new modules such as the introduction of vegetation modelling (BIOTA elsewhere in this report). Because we see evolution of the inventory as vital, we discount embedding RothC directly in the inventory.

6.2. Introduction

There is currently a great need to estimate the effect of changes in land use and climate on the global environment. RothC-26.3 (RothC) is a model of the turnover of carbon in soils and is one of a very few models currently used world-wide to study global carbon dynamics and to report in national inventories of carbon stocks for the United Nations Framework Convention on Climate Change (e.g. Richards 2001). Although current computing power is large and although RothC is a relatively simple model, computer-intensive applications such as estimating changes in carbon stocks world-wide may still require programme components to be simplified as far as is possible in order to run in realistic times. This is especially important where estimates of uncertainty are required and obtained by running the models many time with different inputs to reflect all possible outcomes (Monte-Carlo methods). For these reasons and for uniformity or reporting, current national inventories have tended to make use of the IPCC methodology for specifying the changes that happen to soil carbon following land-use change (LUC). Although a little crude, IPCC (1996 and 2000) methodology is reviewed and updated periodically (e.g. Paustian *et al.*, 1997). In the UK our current inventory makes use of knowledge derived from an analogue of the IPCC methodology that has become known as the coefficient method (Cannell, *et al.*, 1999). Essentially the turnover processes of organic carbon dynamics in soil are expressed by means of a simple equation. There is, however, a half-way house between the simplicity of say a single equation and a fully mechanistic model known as a meta-model. A great advantage of meta-models is that they can be used easily in order to study its sensitivity to particular changes in a computer-intensive Monte-Carlo fashion. Furthermore it can be helpful to have a simplified version of a more complex model in other mathematical expressions of parameter optimisation routines such as the Levenberg-Marquadt algorithm.

6.3. The Rothamsted carbon model (RothC)

The Rothamsted carbon model (RothC) is a model for the turnover of organic carbon in non-waterlogged topsoils that allows for the effects of soil type, temperature, moisture content and plant cover on the turnover process. It uses a monthly time step to calculate total soil organic carbon, microbial biomass carbon and delta^{14}C (from which the equivalent radiocarbon age of the soil can be calculated) on a years to centuries timescale. (Jenkinson *et al.* 1987; Jenkinson, 1990; Jenkinson *et al.* 1991; Jenkinson *et al.* 1992; Jenkinson and Coleman, 1994).

Soil organic carbon is split into four active fractions and one small inert organic matter (IOM) fraction (Figure 6-1). The active fractions are: decomposable plant material (DPM), resistant plant material (RPM), microbial biomass (BIO), and humified organic matter (HUM). Each fraction decomposes by a first-order process with its own characteristic rate. The IOM fraction is considered to be resistant to decomposition.

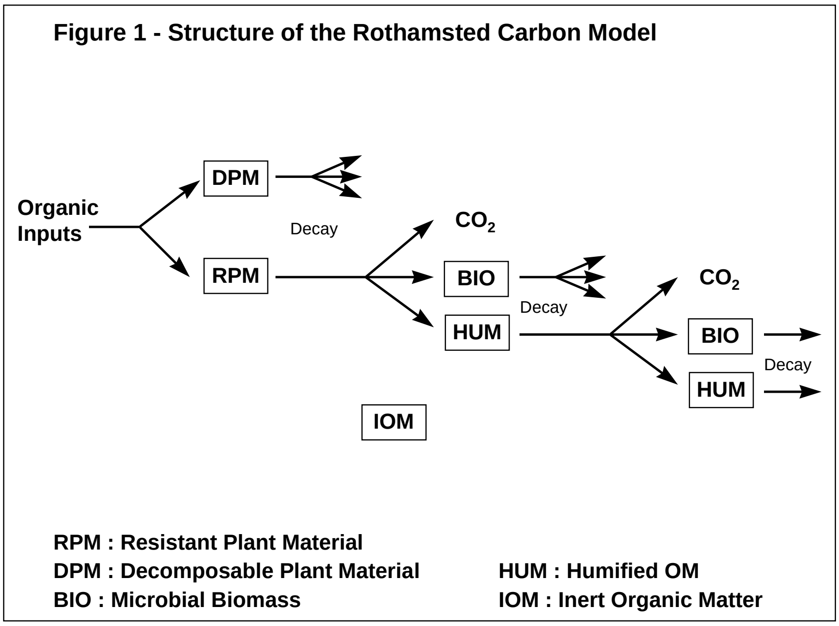

Figure 6-1 Structure of the Rothamsted Carbon model RothC, showing the compartments and flows of carbon between compartments.

RothC was originally developed and parameterized to model the turnover of organic C in arable topsoils from the Rothamsted Long Term Field Experiments - hence the name. Later, it was extended to model turnover in grassland and in woodland and to operate in different soils and under different climates. It should be used cautiously on subsoils, soils developed on recent volcanic ash, soils from the tundra and taiga and not at all on soils that are permanently waterlogged.

RothCUK is itself an interface to the code for the RothC model. RothCUK utilises 1km scale soils, land use and land use change data developed under the parallel DEFRA projects, along with relevant current and future climatic datasets, and has been used to investigate the effects of changes in land use, land management and climate change on national C stocks. The model may be run for Great Britain or Northern Ireland, and runs separately for different land uses (arable, grass, semi-natural and forest) and two soil depths (0-30cm and 30-100cm). These choices were based on the available datasets, as well as for land use change matrix data for Great Britain. Output data include total soil C and CO_2 emissions in formats suitable for import into GIS packages.

Whatever the basis of the underlying description of organic matter processes in soil, current inventories tend to be written for widely used and accessible frameworks such as the spreadsheet package Excel©. We investigate here the best means by which RothC might be incorporated into a carbon inventory with particular reference to the UK reporting requirements. We consider and evaluate the performance of four options:

1. Meta-models equivalent to RothC.
2. Using a version of RothC encoded directly within a spreadsheet (Richards, 2001; Janik *et al*. 2002).
3. Obtaining an analytical solution for the equations underlying RothC (Parshotam 1996)
4. Using a version of RothC linked through an interface.

Option (2) has been attempted before (Richards, 2001) and so will be given less space here. Options (1) and (4) are novel and will form the majority of this report.

6.4. Materials and Methods

6.4.1. RothC as a meta-model

RothC supposes soil organic carbon to consist of five compartments in soil each with a characteristic decay rate (Figure 6-1). Expected inputs of carbon from plant cover are supplied to the model.

Since RothC is itself a combination of exponential decays of carbon in soil, it seems logical to see if the changes in soil organic carbon might be simulated with a simpler system of fewer equations. What we lose by no longer being able to ascribe mathematical meaning to the exponentials we hope to gain in simplicity. We test here three simplifications of the RothC system against the output from RothC itself. In particular Eqs [3] were chosen to be multi-exponential improvements of the forms of the equations currently used in the inventory (Baggott *et al*., 2004; Cannell *et al*., 1999, who used Eq [3a]). The systems are:

(1) Simple (parallel) exponentials

$$C = A_1(1-\exp(-k_1 t)) \quad [1a]$$
$$C = A_1(1-\exp(-k_1 t)) + A_2(1-\exp(-k_2 t)) \quad [1b]$$
$$C = A_1(1-\exp(-k_1 t)) + A_2(1-\exp(-k_2 t)) + A_3(1-\exp(-k_3 t)) \quad [1c]$$
$$C = A_1(1-\exp(-k_1 t)) + A_2(1-\exp(-k_2 t)) + A_3(1-\exp(-k_3 t)) + A_4(1-\exp(-k_4 t)) \quad [1d]$$

(2) Sequential single exponentials (terms are added to A_0 if LUC leads to an increase in soil C, otherwise subtracted).

Two:

$$\begin{aligned} C &= A_0 \pm A_1(1-\exp(-k_1 t)); t < t_1 \\ &= A_0 \pm (A_1(1-\exp(-k_1 t_1)) + A_2(1-\exp(-k_2(t-t_1)))); t \geq t_1 \quad [2a] \end{aligned}$$

Three:

$$\begin{aligned} C &= A_0 \pm A_1(1-\exp(-k_1 t)); t < t_1 \\ &= A_0 \pm (A_1(1-\exp(-k_1 t_1)) + A_2(1-\exp(-k_2(t-t_1)))); t \geq t_1; t < t_2 \\ &= A_0 \pm (A_1(1-\exp(-k_1 t_1)) + A_2(1-\exp(-k_2(t_2-t_1)) + A_3(1-\exp(-k_3(t-t_2)))) \quad [2b] \end{aligned}$$

Four:

$$\begin{aligned} C &= A_0 \pm A_1(1-\exp(-k_1 t)); t < t_1 \\ &= A_0 \pm (A_1(1-\exp(-k_1 t_1)) + A_2(1-\exp(-k_2(t-t_1)))); t \geq t_1; t < t_2 \\ &= A_0 \pm (A_1(1-\exp(-k_1 t_1)) + A_2(1-\exp(-k_2(t_2-t_1)) + A_3(1-\exp(-k_3(t-t_2)))); t \geq t_2; t < t_3 \\ &= A_0 \pm (A_1(1-\exp(-k_1 t_1)) + A_2(1-\exp(-k_2(t_2-t_1)) + A_3(1-\exp(-k_3(t_3-t_2))) + A_4(1-\exp(-k_4(t-t_3)))) \quad [2c] \end{aligned}$$

(3) Differential forms (against transformed data) analogous to the coefficient method

$$C = C_f - (C_f - C_0)\exp(-k_1 t) \quad [3a]$$
$$C = C_f - (C_f - C_0) * (M_1 \exp(-k_1 t) + M_2 \exp(-k_2 t)) \quad [3b]$$
$$C = C_f - (C_f - C_0) * (M_1 \exp(-k_1 t) + M_2 \exp(-k_2 t) + M_3 \exp(-k_3 t)) \quad [3c]$$

where C is the change in soil carbon, A_1, A_2, A_3 and A_4 are coefficients representing the change in carbon stock, M_1, M_2 and M_3 fractional changes of carbon stocks, k_1, k_2, k_3 and k_4 are coefficients representing the rate of that change and t_1, t_2 and t_3 are the times at which a transition from one set of coefficients to another takes place.

Models can be compared statistically two at a time, one with another using a variance ratio (F) test as follows,

$$F = (\Delta RSS / \Delta DF) / (RMS \text{ more complex model})$$

where ΔRSS is the change in the residual sum of squares in moving from one model to the next, ΔDF is the change in the number of degrees of freedom and RMS is the residual mean square. This $F_{(\Delta DF,\ DF \text{ more complex model})}$ was tested against standard values at known probabilities (Table 6-1 and Table 6-2).

Table 6-1 (a) Values of parameters and variability found during fitting Arable-2-Forest 100 year data, (b) Values of parameters and variability found during fitting Pasture-2-arable 100 year data, (c) Values of parameters and variability found during fitting Pasture-2-seminatural 100 year data, (d) Values of parameters and variability found during fitting Pasture-2-Forest 100 year data

(a)

Equation	RSS	Df	RMS	Comparison	Delta df	F
1a	256.9	98	2.622	1c with 1a	4	230091.2
1b	0.1083	96	1.128e-3	1c with 1b	2	147.0
1c	0.02624	94	2.791e-4			
1d				Not converged		
2a	1.333	94	1.418e-2			
2b	0.09029	91	9.922e-4	2c with 2b	3	153.3
2c	0.0145	88	1.648e-4	2c with 1c	6	11.9
3a	2148	99	21.7			
3b	0.03516	96	3.662e-4	3c with 3b	2	8.5
3c	0.02979	94	3.169e-4	2c with 3c	6	15.46

(b)

Equation	RSS	Df	RMS	Comparison	Delta df	F
1a	42.64	98	0.4351	1c with 1a	4	139.7
1b	0.1739	96	0.001811	1c with 1b	2	45.7
1c	6.140	94	0.06532			
1d				Not converged		
2a	0.2904	94	3.03e-3			
2b	0.05761	91	5.761e-2	2c with 2b	3	225.02
2c	6.644e-3	88	7.55e-5	2c with 1c	6	13539.42
3a	132.8	99	1.342			
3b	0.06019	96	6.27e-4	3c with 3b	2	113007
3c	2.502e-5	94	2.662e-7	2c with 3c	6	14.61

(c)

Equation	RSS	Df	RMS	Comparison	Delta df	F
1a	280.3	98	2.860204	1a 1c	4	7078259.3
1b	0.1951	96	0.002032			
1c				Not converged		
1d				Not converged		
2a	1.441	94	0.01533			
2b	1.15E-01	91	0.001259	2c 2b	3	126.4
2c	2.17E-02	88	0.000246	2c 1c	6	14.1
3a	1807	99	18.25253			
3b	6.41E-03	96	6.68E-05	3c 3b	2	23.24
3c	1.27E-02	94	0.000135	2c 3c	6	6.08

(d)

Equation	RSS	Df	RMS	Comparison	Delta df	F
1a	59.85	98	0.610714286	1a 1c	4	8293.9
1b	0.7124	96	0.007420833			
1c				Not converged		
1d				Not converged		
2a	6.02E-01	94	0.006406383			
2b	7.03E-02	91	0.000772418	2c 2b	3	5.24
2c	5.96E-02	88	0.000677614	2c 1c	6	26.9
3a	968.3	99	9.780808081			
3b	1.65E-01	96	0.001714583	3c 3b	2	0.3
3c	1.64E-01	94	0.001748936	2c 3c	6	25.77

Table 6-2 (a) Values of parameters and variability found during fitting Arable-2-Forest 300 year data, (b) Values of parameters and variability found during fitting Pasture-2-arable 300 year data, (c) Values of parameters and variability found during fitting Pasture-2-seminatural 300 year data, (d) Values of parameters and variability found during fitting Pasture-2-Forest 300 year data

(a)

Equation	**RSS**	**Df**	**RMS**	**Comparison**	**Delta df**	**F**
1a	2428	299	8.121	1a 1c	4	14347.7
1b	13.53	297	4.554e-2			
1c				Not converged		
1d				Not converged		
2a	4.147	295	1.406e-2			
2b	1.90E-01	292	6.489e-4	2c 2b	3	568.4
2c	2.75E-02	289	9.53e-5	2c 1c	6	21672.8
3a	5580	300	18.60			
3b	4.92E-02	297	1.656e-4	3c 3b	2	62.2
3c	3.46E-02	295	1.174e-4	2c 3c	6	12.4

(b)

Equation	**RSS**	**Df**	**RMS**	**Comparison**	**Delta df**	**F**
1a	162.3	299	0.5427	1a 1c	4	10300.8
1b	0.8201	297	2.761e-3			
1c				Not converged		
1d				Not converged		
2a	4.51E-01	295	1.527e-3			
2b	7.65E-02	292	2.62e-4	2c 2b	3	604.2
2c	1.05E-02	289	3.641e-5	2c 1c	6	5234.4
3a	272.5	300	9.084e-1			
3b	6.20E-02	297	2.086e-4	3c 3b	2	283995.4
3c	3.22E-05	295	1.091e-7	2c 3c	6	47.9

(c)

Equation	**RSS**	**Df**	**RMS**	**Comparison**	**Delta df**	**F**
1a	2181	299	7.293	1a 1c	4	15212.2
1b	11.72	297	3.945e-2	1c 1b	2	16.8
1c	10.52	295	3.567e-2			
1d				Not converged		
2a	9.331	295	3.163e-2			
2b	2.25E-01	292	7.692e-4	2c 2b	3	481.5
2c	3.75E-02	289	1.298e-4	2c 1c	6	13459.8
3a	4681	300	15.6			
3b	1.14E-02	297	3.828e-5	3c 3b	2	30.6
3c	9.44E-03	295	3.199e-5	2c 3c	6	36.0

(d)

Equation	**RSS**	**Df**	**RMS**	**Comparison**	**Delta df**	**F**
1a	861.7	299	2.8832	1a 1c	4	6815.4
1b	9.246	297	0.03113	1c 1b	2	0.4
1c	9.224	295	0.03127			
1d	2.65E-03	295	9.052e-6			
2a	1.55	295	5.247e-3			
2b	9.08E-02	292	3.11e-4	2c 2b	3	46.1
2c	6.14E-02	289	2.126e-4	2c 1c	6	7183.0
3a	2473	300	8.244			
3b	1.934e-1	297	6.513e-4	3c 3b	2	0.0
3c	1.934e-1	295	6.557e-4	2c 3c	6	103.5

RothC was run with four land-use changes: arable to pasture, pasture to semi-natural, arable to forest and pasture to forest. Baseline data of the change in soil carbon stocks using RothC was generated for 300 years. The functions above were evaluated for their ability to reproduce the full 300 years of data and separately for their ability to reproduce the first 100 years only. Climate will also affect the results and so a meta-model system will either need to incorporate the affects of climate directly within the calculations as in RothC or different parameters, particularly the rates of decomposition, will be required in a model. Accordingly we assess the effects of a range of climate zones in the UK and North West Europe (Table 6-3), in order to mimic potential climate change) on the stability of the parameters sets in our meta-model systems. We focus on a single LUC as an example: pasture to forest.

Table 6-3 Meteorological data used to asses the variability of parameters within the meta-model systems.

Met station	Average Temp	Total Rainfall	Total Evaporation
Rothamsted	9.3	704	597
Newport_Salop	9.0	657	963
Morley_St_Botolph	8.9	640	606
Warsop	9.0	627	559
Terrington_St_Clement	9.6	592	607
Martyr_worthy	9.5	774	595
Cranwell & Kirton	9.1	588	603
Bad Lauchstadt, Germany	9.0	474	644
Ruzyne, Czech Rep.	7.9	526	852
Calhoun, USA	15.5	1263	1344

6.4.2. RothC into an Excel spreadsheet

The model was re-written, changing the top part of the program so that the compiler would make a .DLL and not an .EXE file (orthodox compiled application to run directly under an operating system). Code was added to pass the arguments to and from the .DLL. The STOP statement was replaced with a RETURN statement and input-output operations were directed to files on disks rather than to and from the screen. In this way the model could be compiled as a .DLL and declared separately in Excel visual basic code. After creating a macro to call the .DLL a new toolbar is needed with a button to the toolbar and the macro is assigned to the button. If preferred, instead of creating a toolbar and button, a new menu could be created with a sub-menu and the macro would then be assigned to the sub-menu.

6.5. Results and Discussion

6.5.1. RothC as a meta-model

Generally the agreement between each of the models [1-3] and RothC is very good indeed in the statistical sense (residual mean square values, RMS, in Table 6-1 & Table 6-2). Taking account of the loss of degrees of freedom that occurs with increasing complexity, it appears that model [2c] is the best overall, although for one land-use change (pasture to arable), model [3c] was better. Model [2c] is best in the sense that it can be fitted to curves of output from RothC better than the other models (least RMS). Two important reservations must be expressed in relation to this conclusion, however, both of which have to do with the values of the estimated parameters. First the parameter set differs depending upon whether the land-use change studied increases the amount of carbon in soil or decreases it. The break points t_i and amounts of carbon active during each time period A_i or M_i differ significantly with LUC (Figure 6-2 to Figure 6-5, Table 6-4 & Table 6-5). The rates of change also differ with weather. These differences between land-use changes make it necessary to use a different set of parameters for the separate LUC. Because of the large number of parameters that would be needed to calculate changes in carbon stocks at many different locations, it seems that RothC is simpler in this sense than any of the meta-models derived from it. This result is not immediately intuitive but the essence is that RothC is *robust* in its parameters. The RothC model has been widely tested and found to work well in a range of environments and LUC without the need to alter internal parameters. The meta-models need many more sets of parameters in order to describe different LUC whereas RothC which uses just one set for all LUC. The differences between parameters lie mainly in the break point times (t_i) and values for the storage of carbon (A_i, M_i) at these times (Figure 6-2 to Figure 6-5, Table 6-4 & Table 6-5). Generally the agreement between rate constants (k_i) is much closer, apart from the value of k_1 under pasture-to-arable (Figure 6-2 & Figure 6-3). No explanation can be offered for this oddity but it may well explain the preference for model [3c] with this land-use change (Table 6-1b & Table 6-2b). As well as the other parameters, rate constants vary with climate data. This is not unexpected, however, since RothC itself varies the rate of decomposition with climate. This component of the meta-model system could probably adjusted for climate in the same way as is done for RothC, but the variability in the other parameters does not make it worthwhile to attempt. Similarly clay content modifies the way in which carbon is retained in soil within RothC and the ways in which carbon decomposes depends on the different moisture relations found in different soils. Given the variability found above not attempt has been made to take account of the effect of different soil types within the meta-model system. It seems likely that it would add to the complexity still further.

The sheer number of parameters (Table 6-4) needed to make the meta-model system work begins to tell against its use. In principle a database might be constructed to hold the values and an inventory could access these numbers as well as any others. But the system is clumsy compared with the elegance of RothC. Some models fail to converge during fitting (Table 6-1 &Table 6-2), which in this instance is a sure sign that the model is over parameterised with respect to the data and that a simpler model is better. Even more telling, however, is the empirical nature of these numbers as opposed to the universal values in RothC that describe decomposition under a wide range of soils and climates for most LUC. Their empirical nature means that a separate set must be obtained for each new LUC transition brought into the inventory. Equally the anticipated change in climate will mean that new parameter values must be obtained periodically. RothC, on the other hand, has been widely tested, validated and used in current climates world-wide and on this basis will not tread outside its tested range of climate within the UK during the foreseeable future. Other further advantages derive from accepting that somehow RothC should be used within an inventory as opposed to translating it into meta-models. Firstly updates, improvements and extensions (e.g. BIOTA see elsewhere in this report) to RothC can be easily and automatically incorporated by this means, secondly the system is future-proofed against climate or other major environmental change and thirdly the system as a whole can move gradually towards implementation of the spatial version of RothC, RothCUK, the current input demands of which exceed the information currently available with reliability at the spatial resolution required in the inventory.

The standard errors (SE) of parameter values derived in fitting the meta-models to RothC output are also reported in Table 6-4 (100 year data). It can be seen that these SEs also vary with LUC. This is a potentially serious issue since it means that the model variance is not stable. Note that the variance of models fitted to *real* data, as with the current inventory (Eq. [3a]), is not tested by this analysis. It raises another question mark, however, against the use of a meta-model whose parameters are derived from comparison with the parent model, RothC. An estimate of uncertainty derived using such a meta-model within an inventory would be suspect.

Table 6-4 a Arable-2-Forest parameters derived from 100 year runs

Equation	**K1**	**SE**	**K2**	**se**	**K3**	**Se**	**K4**	**se**
1a	0.04541	.00156						
1b	0.119234	0.000447	0.007626	0.000128				
1c	0.114798	0.000752	0.0065295	0.0000546	0.12144	0.00448		
1d								* not converged
2a	0.08148	.00085	.01124	.000348				
2b	.090754	.000553	.04246	.0016	.00861	.000167		
2c	.093586	.00036	.06375	.0016	.024403	.000657	0.007910	08.45e-7
3a	0.01458	0.000393						
3b	0.1187	0.000187	0.007114	5.05e-6				
3c	0.1181	0.000216	0.007192	0.000261	0.007039	0.000165		

Equation	**A0**	**SE**	**A1/M1**	**se**	**A2/M2**	**Se**	**A3/M3**	**se**	**A4**	**SE**
1a			36.64	0.348						
1b			19.3911	0.0609	37.043	0.323				
1c			16.982	0.305	40.272	0.197	2.929	0.306		
1d										* not converged
2a	62.16	.0915	30.78	.0905						
2b	61.74	.0325	29.70	.0638	11.712	.277	26.17	.000553		
2c	61.66	.0151	29.30	0.0482	10.94	0.320	13.01	0.272	26.26	0.0156
3a										
3b			0.3820	0.000281	0.6675	0.00022				
3c			0.3820	0.000336	0.2627	0.00873	0.4041	0.00864		

Equation	**T1**	**SE**	**T2**	**SE**	**T3**	**SE**
1a						
1b						
1c						
1d						
2a	28.40	0.79				
2b	18.62	.581	37.27	1.06		
2c	14.626	0.542	26.98	*	44.36	*
3a						
3b						
3c						

Table 6-4b Pasture-2-Arable parameters derived from 100 year runs

Equation	**K1**	**SE**	**K2**	**se**	**K3**	**Se**	**K4**	**se**
1a	0.02521	0.00089						
1b	0.2094	0.00457	0.010452	0.000161				
1c								* not converged
1d								* not converged
2a	0.07999	0.00326	0.01033	0.000246				
2b	0.14584	0.00698	0.046665	0.0000439	0.009636	0.000000249		
2c	0.436	0.0209	8.20E-02	5.45E-08	2.79E-02	4.23E-08	9.33E-03	3.28E-10
3a	0.011934	0.000167						
3b	0.16902	0.00169	0.009041	0.0000097				
3c	0.156553	0.0000329	3.6811	0.0832	0.009009	0.000000174		

Equation	**A0**	**SE**	**A1/M1**	**se**	**A2/M2**	**Se**	**A3/M3**	**se**	**A4**	**SE**
1a			-18.98	0.289						
1b			-3.8878	0.0452	-22.404	0.151				
1c										* not converged
1d										* not converged
2a	92.9006	0.0708	10.52	0.142	18.903	0.284				
2b	93.3843	0.0473	7.941	0.162	8.243	0.202				
2c	94.1525	0.0582	4.989	0.0497	7.7242	0.0224	9.2525	0.0114	18.03854	0.00663
3a										
3b			0.174949	0.000893	0.854486	0.000482				
3c			0.166591	0.0000296	0.5006	0.0411	0.852584	0.00000846		

Equation	**T1**	**SE**	**T2**	**SE**	**T3**	**SE**
1a						
1b						
1c						
1d						
2a	18.263	0.898				
2b	7.557	0.505	23.92	*		
2c	2.9989	0.0309	13.956	0.00114	29.28	*
3a						
3b						
3c						

Table 6-4c Pasture-2-semi natural parameters derived from 100 year runs

Equation	**K1**	**SE**	**K2**	**se**	**K3**	**Se**	**K4**	**se**
1a	0.03638	0.00128						
1b	0.12543	0.000731	0.008201	0.000131				
1c								* not converged
1d								* not converged
2a	0.075012	0.000939	0.010347	0.000257				
2b	0.08637	0.000726	0.03774	0.00117	0.008295	0.000121		
2c	0.091024	0.000616	0.05937	0.0012	0.022252	0.000686	0.007758	0.0000715
3a	0.012418	0.000274						
3b	0.119899	0.0000921	0.00712	0.00000169				
3c	0.120705	0.000224	0.008269	0.000166	0.006343	0.0000956		

Equation	**A0**	**SE**	**A1/M1**	**se**	**A2/M2**	**Se**	**A3/M3**	**se**	**A4**	**SE**
1a			40.104	0.462						
1b			16.5778	0.0786	45.327	0.358				
1c										* not converged
1d										* not converged
2a	90.554	0.0929	30.529	0.54						
2b	90.1032	0.0373	28.8814	0.0952	15.215	0.328	34.33	0.000726		
2c	89.9878	0.02	28.1346	0.0931	13.618	0.337	17.561	0.435	34.128	0.251
3a										
3b			0.29517	0.000106	0.743781	8.18E-05				
3c			0.29403	0.000333	0.32431	0.00811	0.42091	0.00815		

Equation	**T1**	**SE**	**T2**	**SE**	**T3**	**SE**
1a						
1b						
1c						
1d						
2a	25.854	0.743				
2b	17.008	0.575	35.59	*		
2c	12.666	0.493	24.91	*	42.4	*
3a						
3b						
3c						

Table 6-4d Pasture-2-Forest parameters derived from 100 year runs

Equation	**K1**	**SE**	**K2**	**se**	**K3**	**Se**	**K4**	**se**
1a	0.06562	0.00181						
1b	0.010665	0.000567	0.11723	0.00119				
1c								* not converged
1d								* not converged
2a	0.093205	0.000747	0.015933	0.000808				
2b	0.096499	0.000445	0.04721	0.00368	0.009177	0.000548		
2c	0.096999	0.000546	0.06236	0.00471	0.02447	0.00395	0.008102	*
3a	0.021431	0.000799						
3b	0.115035	0.000494	0.007009	0.0000291				
3c	0.114843	0.000326	0.006996	*	0.007008	*		

Equation	**A0**	**SE**	**A1/M1**	**se**	**A2/M2**	**Se**	**A3/M3**	**se**	**A4**	**SE**
1a			21.229	0.124						
1b			12.031	0.231	14.7	0.122				
1c										* not converged
1d										* not converged
2a	90.3552	0.0637	20.8066	0.0547	7.046	0.246				
2b	90.3465	0.0256	20.4672	0.0274	4.321	0.311	9.259	0.315		
2c	90.3324	0.0244	20.4334	0.0288	3.988	0.206	4.714	0.601	9.449	0.036
3a										
3b			0.58447	0.00117	0.492364	0.000943				
3c			0.5845	0.0016	0.361	0.468	0.131	0.468		

Equation	**T1**	**SE**	**T2**	**SE**	**T3**	**SE**
1a						
1b						
1c						
1d						
2a	35.369	0.794				
2b	23.53	1.15	42.08	3.73		
2c	21.4	*	33.72	*	50.47	*
3a						
3b						
3c						

Table 6-5 Time taken to run RothC from within Excel, ms

	Intel 2.4 GHz 512MB Ram	**Athlon 2.4GHz 1024 RAM**	
	DOS-RothC	**DOS-RothC**	**EXCEL-ROTHC**
Equilibrium	46	16	15
Equilibrium +10 years yearly output	54	15	16
Equilibrium +10 years monthly output	114	31	25
Equilibrium+10 years different inputs yearly output	761	122	53
Equilibrium+10 years different inputs monthly output	743	119	66
Broadbalk No inputs	1,336	231	109
Broadbalk mineral N	1,406	240	122
Broadbalk FYM	1,386	253	116
Broadbalk FYM+mineral N	1,426	238	135

As well as the methodology evaluated here, Parshotam (1996) has described how RothC might be expressed in continuous form, as a system of equations. This idea has merit: it has the advantage of preserving the error structure inherent in the mechanisms described in RothC and so avoids the problems with model variance described in the previous paragraph, but it is limited to a single set of unmodifiable rate constants. Because environmental conditions modify the rate constants in RothC, different versions of Parshotam's derivation would be needed for each cell in the inventory. In addition, RothC makes a distinction in decomposition between cropped and uncropped land. In this way different versions of Parshotham's model would be needed for each land-use change. Although not impossible to arrange, Parshotam's equations suffer from the majority of the disadvantages of the meta-model and would make it difficult to incorporate developments to RothC such as a vegetation model. Because Parshotam's derivation preserves the error structure of RothC, however, it might be very useful for studying sensitivity of particular conditions to change.

The Australian national GHG reporting system makes use of a version of RothC embedded directly into the spreadsheet model (FullCaM, Richards, 2001). Clearly this will work as well as any other method using RothC, but will not easily allow upgrades or add-ins if the inventory or the need for the inventory evolves with time.

6.5.2. Running RothC from within a spreadsheet

RothC has been prepared to accept inputs and instructions from cells within an Excel spreadsheet. In general the compiled Fortran programme that does this (.DLL file) is rather different from the standalone executable image (.EXE file). However, the differences are largely concerned with how the programme starts and where it gets its information from. The time from calling RothC .DLL within the spreadsheet to receiving the requested numbers back into the spreadsheet was less than running RothC directly under the DOS system (Table 6-5). This statistic is misleading, however, since the DOS version of RothC accepts much input interactively. Processor time can only be calculated after all input has been made. Other versions include access time for reading input data. A typical requirement for which an inventory might interrogate RothC would be 10 years under LUC. If no starting conditions are available, RothC will need to derive these by running to equilibrium (typically 10,000 years) and simulating on for 10 years with the new land-use. Typically this will require 53 ms with output in the final year only and a change to carbon inputs if not to weather (Table 6-5). Although the extra time required for a further 10 years of calculation with the same inputs (i.e. no LUC) is small (~1ms), in practice input and output to files on the hard disk or within Excel costs time. These issues could be addressed reasonably easily in a .DLL file issued for use within the inventory. At these rates and assuming minimal further input-output, simulations for the whole of the UK (244,810 km^2) will take 3.6 hours if one simulation is need per km^2 with an averaged LUC Simulations at lower resolutions will take proportionally less time. If starting conditions are defined within the spreadsheet, as is likely, the determination of equilibrium conditions could be dispensed with and the inputs and environmental conditions would not need to be read in again. Under these conditions our results suggest that the model would run in about 1ms. This is 50 times faster than the calculations suggest above and would bring the computer time used by RothC in calculation for each km^2 down to about 4 minutes.

Furthermore, RothC carries out calculations that are unlikely to be of use to the inventory such as the tracing of radioactive ^{14}C in soil. These calculations could be taken out, or more attractively, made optional in the definitive version of RothC, so that more computer time could be saved.

6.5.3. Data resolution and availability

Two critical issues for the use of RothC are to know *when* and *where* a particular LUC takes place. The issue of where is also important because the soil on which the change takes place will also influence any eventual change in carbon. Much information is available in confidential databases. The UK has relatively good soils information systems available (usually for a fee) from NSRI, MLURI and DARD. General statistics on agricultural land-use are available from Defra, DARD and SEERAD but location-specific information is confidential because it is commercially sensitive. In principle, confidentiality is not an issue since the end-user of the information derived with the inventory does not need access to the confidential information. The *inventory* (including e.g. RothC) requires the access and it should be possible for an inventory to interrogate databases over a computer network without being allowed to report unprocessed data back to an end-user. A fee might be paid if required. Extensive negotiation with data-holders and land-owners is likely to be necessary before this can happen, however.

6.6. Conclusions

We conclude that the most sensible course of action if RothC is required within the current UK soils carbon inventory, is to call RothC directly from the inventory spreadsheet. However, since input-output operations are costly in computer terms, it seems wise to allow RothC to access the information it requires directly from disk rather than to pass data between spreadsheet and model many times. The current inventory makes use of Monte-Carlo methods in order to estimate uncertainty; this multiplies the number of simulations many-fold. If computer time to use RothC with orthodox Monte-Carlo methods is prohibitive, clever sampling design may help reduce the number of simulations greatly (e.g. Jansen, 1999). If the eventual aim is to amalgamate the inventory with RothCUK for LUC, soil and climate, calling RothC from within a spreadsheet has the advantage both that the code is ready now and that the inventory interface can be adapted progressively as reliable estimates of LUC and other data at finer and finer scales become available until the system converges with RothCUK. Other modules such as one for plant growth might be incorporated into this development in a straightforward fashion. A .DLL version of the RothC model is available for use and the following steps will allow its incorporation

1. Define computer locations of all ancillary information: weather, soils, LUC
2. Adapt RothC-Excel to obtain required information from a disk store defined by the inventory with a single (or few) read operation(s). Store information in memory.
3. Adapt the inventory to write the information required by RothC to the disk store
4. Adapt RothC-Excel to return the information required by the inventory in a single (or few) write operation(s).
5. Test run the combined system against a standalone RothC

If computer times for the Monte-Carlo runs appear prohibitive and design cannot help, the computer time needed to run RothC within the inventory could potentially be reduced by distributing the tasks in a parallel computing scheme.

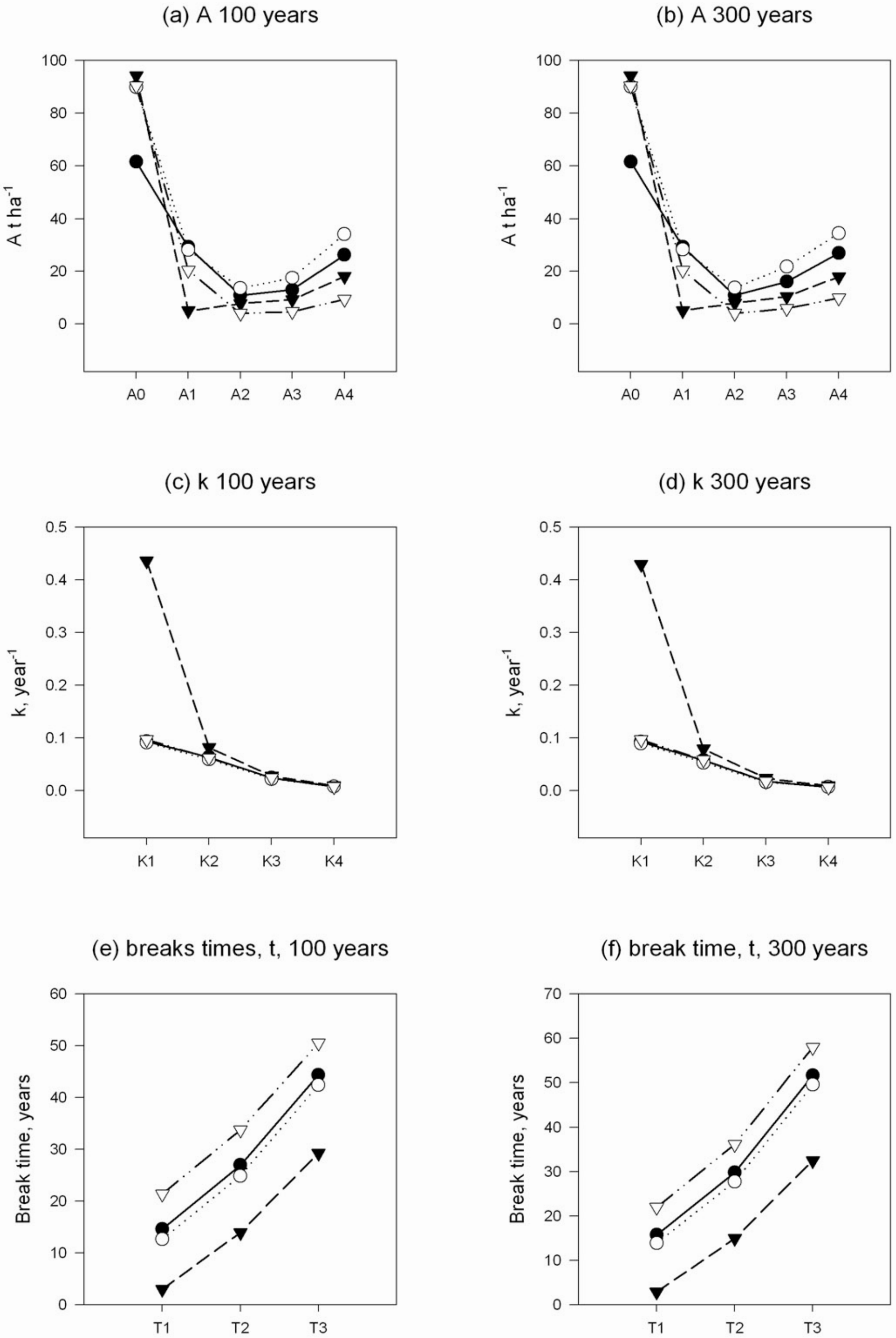

Figure 6-2 Sensitivity of the values of parameters of model [2c] to different land-use changes: (a, b) the A_i describing changes in carbon stocks, (c, d) the k_i describing the rate of turnover of carbon stocks, (e, f) the t_i describing the times over which the k_i are effective; for 100 years of comparisons between parameters (a, c, e) and 300 years of comparisons, (b, d, f), under land-use changes: —●—, arable to forest; · · ○ · ·, pasture to semi-natural; --▼--, pasture to arable; —— · · ▽ · · ——, pasture to forest. For SEs see Table 6-1 and Table 6-2

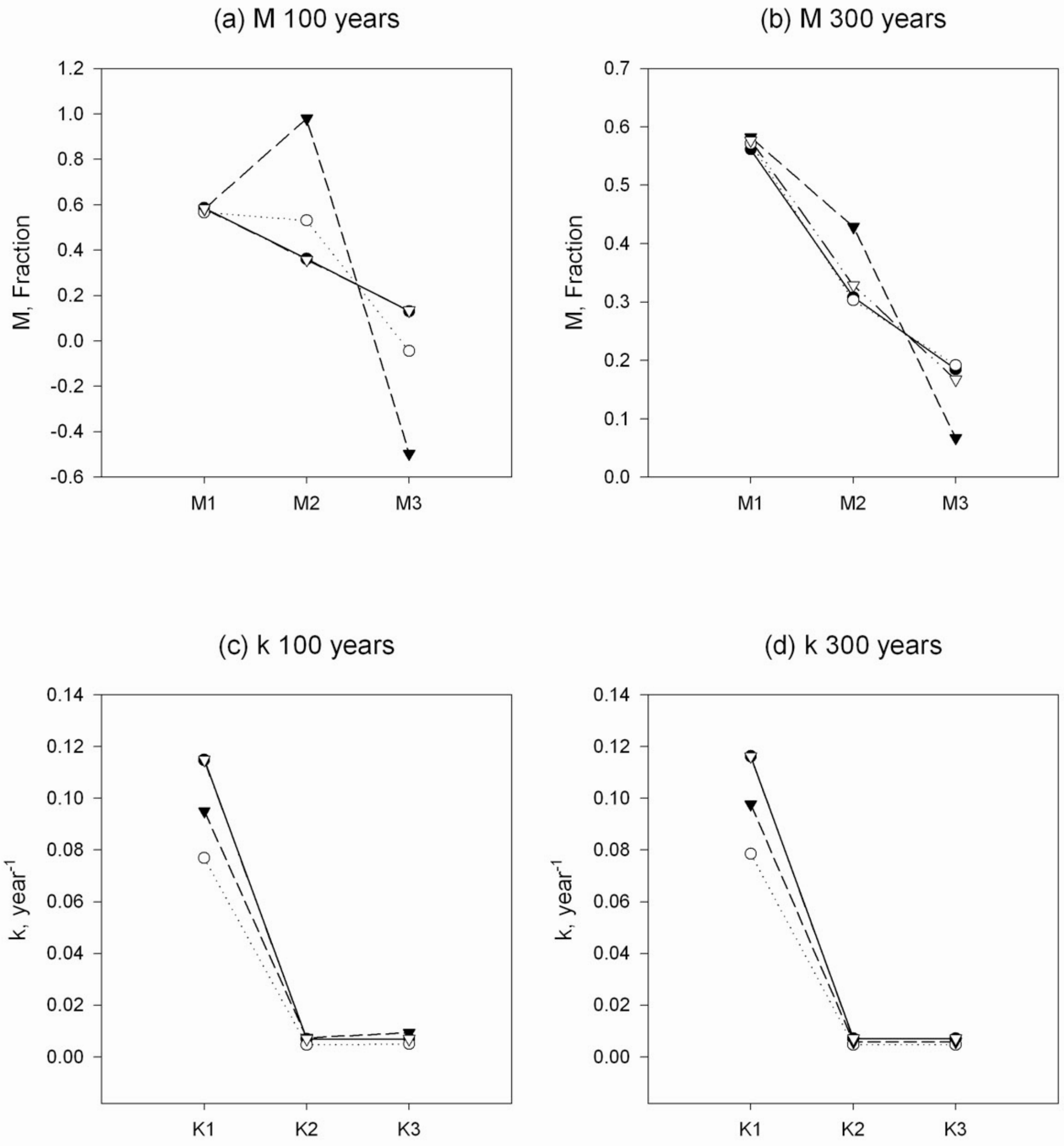

Figure 6-3 Sensitivity of the values of parameters of model [3c] to different land-use changes: (a, b) the Mi describing fractional extent of change of the carbon stocks under LUC, (c, d) the ki describing the rate of turnover of carbon stocks; for 100 years of comparisons between parameters (a, c) and 300 years of comparisons, (b, d), under land-use changes: —●—, arable to forest; · · ○ · ·, pasture to semi-natural; --▼--, pasture to arable; —— · ·▽· · ——, pasture to forest. For SEs see Table 6-1 and Table 6-2.

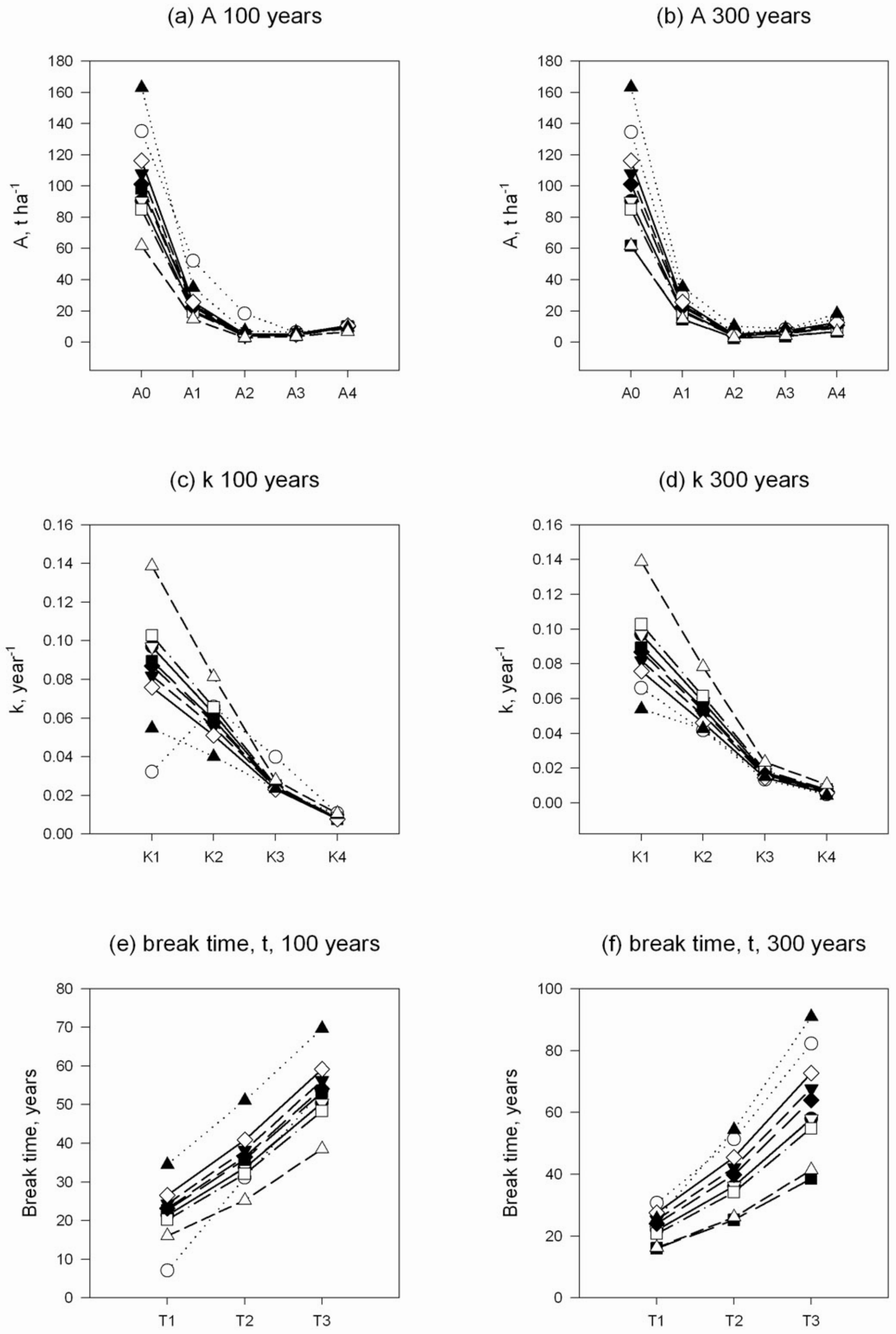

Figure 6-4 Sensitivity of the values of parameters of model [2c] to changes in weather data: (a,b) the Ai describing changes in carbon stocks, (c, d) the ki describing the rate of turnover of carbon stocks, (e, f) the ti describing the times over which the ki are effective; for 100 years of comparisons between parameters (a, c, e) and 300 years of comparisons, (b, d, f). For details of the conditions see text and Table 6-3.

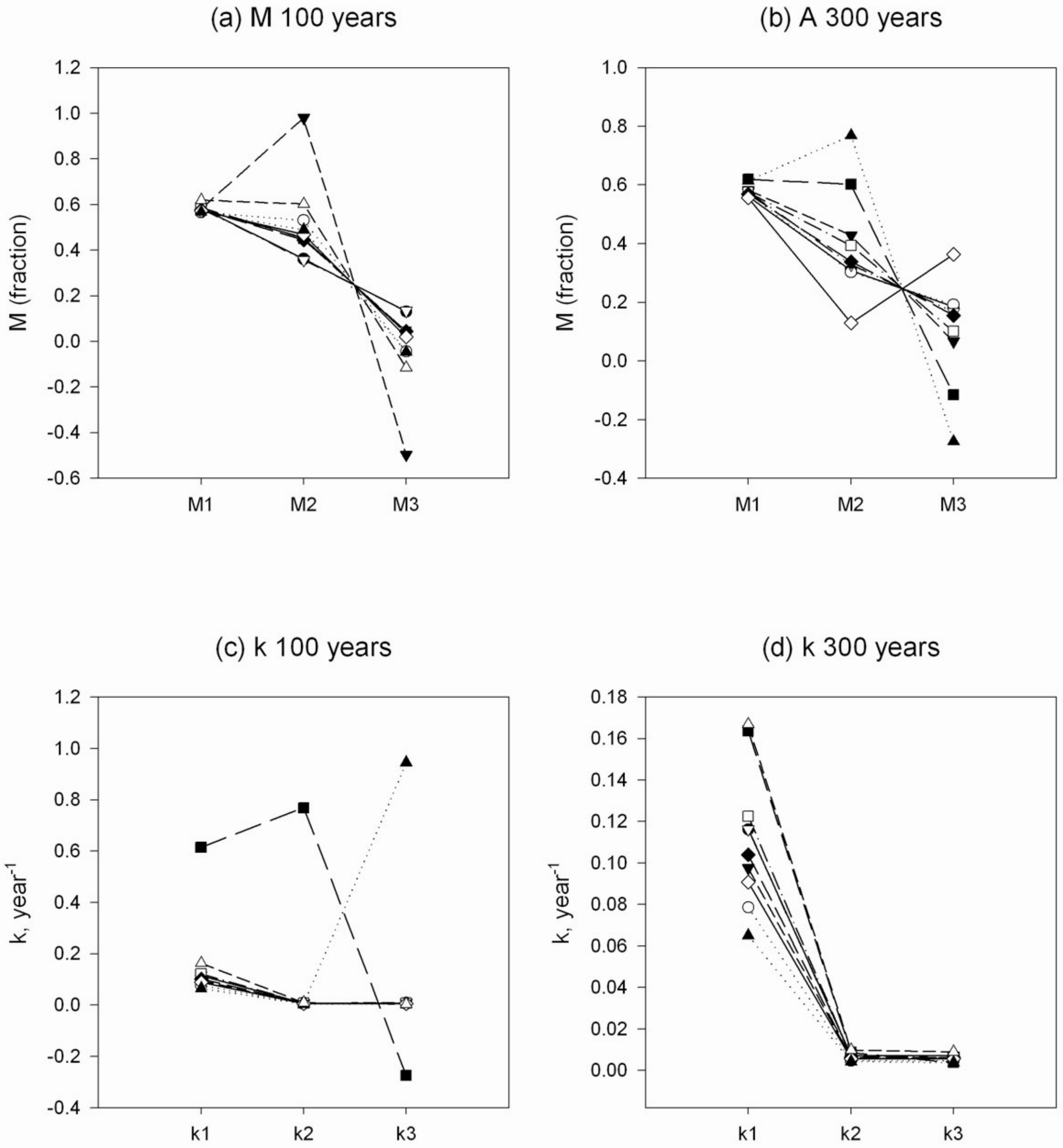

Figure 6-5 Sensitivity of the values of parameters of model [3c] to changes in weather data: (a,b) the M_i describing changes in carbon stocks, (c, d) the k_i describing the rate of turnover of carbon stocks; for 100 years of comparisons between parameters (a, c) and 300 years of comparisons, (b, d). For details of the conditions see text and Table 6-3.

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