SECTION 3

MODELLING GLOBAL CHANGE IMPACTS ON THE SOIL ENVIRONMENT

3.1. INTRODUCTION

The modelling exercises and tools, which are explored here, deal with various levels and scales of models. They begin with a very broad and global concept of carbon budget based on a common carbon input-output in the atmosphere driven by human activities. The aim is to give general implications for the carbon balance when humans alter natural ecosystems to meet their needs. It involves conversion of land and the use of fossil fuels as the main energy source.

Detailed process-based models involving ecophysiological parameters where the cycling of substances plays important role were also exercised. They do not only deal with carbon but also other components such as nitrogen, water and light when vegetation interacts with its physical environment including soil and the atmosphere.

3.2. GLOBALC – A BEGINNER'S MODEL OF GLOBAL CARBON STOCKS AND FLOWS

By:

Meine van Noordwijk

The GlobalC model accounts for carbon stocks in the atmosphere, in terrestrial ecosystems, the ocean and fossil form, and the major exchanges between these. CO_2 and some other gasses (held constant in this model) have a 'greenhouse' effect, reducing the amount of long-wave radiation that can leave the planet earth, thus increasing its temperature. A change in atmospheric CO_2 can by this mechanism lead to a change in global temperature (global warming or global cooling). Temperature itself has an impact on a range of biological processes in C sequestration by plant growth and C dissipation by decomposer activity. The oceans contain by far the largest C stocks, but only a small part of this, in the upper ocean layers, interacts with the atmosphere. Potentially the oceans can absorb CO_2 brought into the atmosphere by changes in terrestrial stocks or use of fossil fuel, but the rate, at which such absorption can occur, is limited by the equilibration processes. In the terrestrial systems, the model distinguishes two types of vegetation 'forest' and 'agriculture'. The rate of photosynthesis depends on temperature and atmospheric CO_2 but does not differ between these two land-cover types. The stocks maintained in above-ground biomass, however, do differ between the two vegetation types, as does the rate of litterfall, leading to differences in soil organic matter storage in soils. Figure 3.1 shows the diagram of processes in GlobalC.

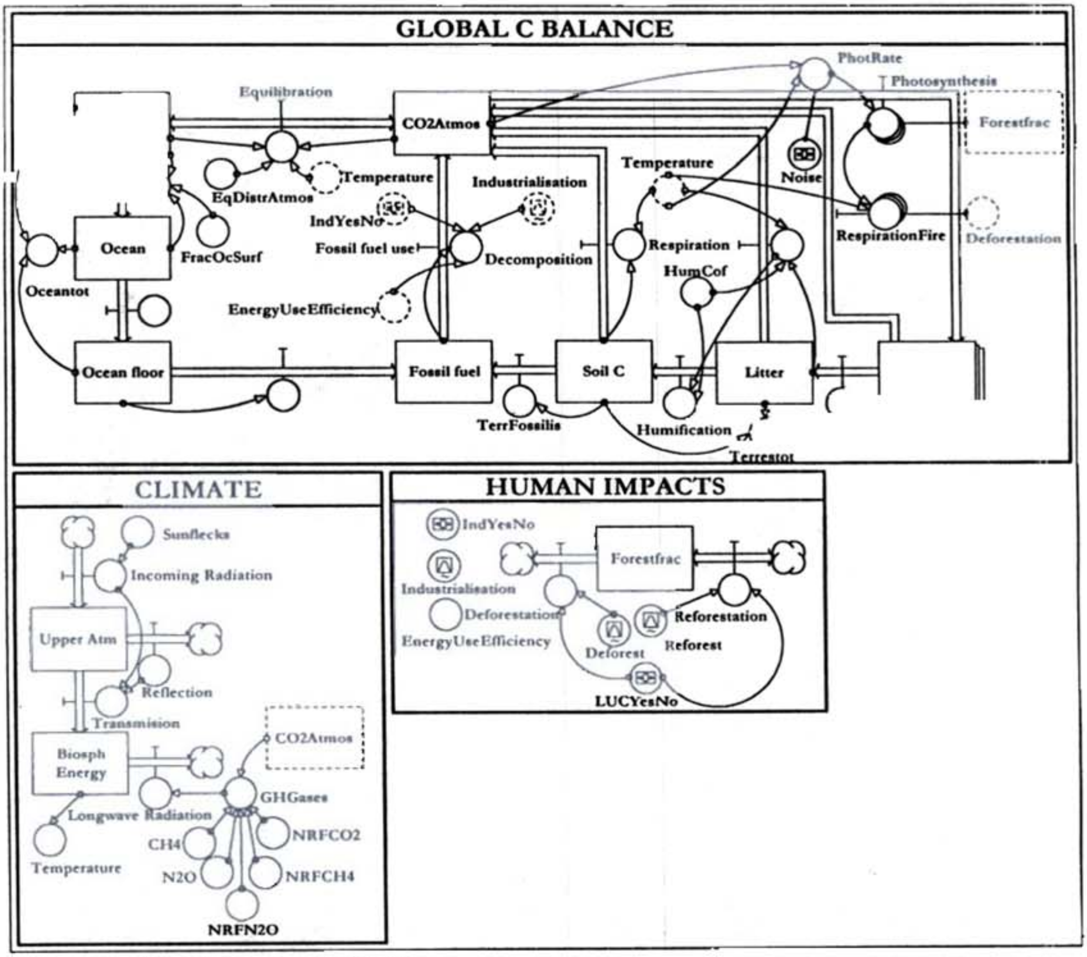


Figure 3.1. Model diagram of GlobalC

The model is obviously a strong simplification and does not incorporate many feedback loops and distinctions between climate zones and vegetation types (with the largest contrast between systems with below-ground storage in peat soils dominating in the subarctic and those with above-ground storage dominating in tropical forests on non-peat soils). Yet, for all its simplicity, the model suggests a number of conclusions (or hypotheses for further exploration):

- when left to itself, the very slow rate of fossil C production in oceans and terrestrial systems combined, leads to a gradual reduction of CO_2 in the atmosphere and cooling of the earth, but this trend is masked by 'natural' fluctuations;

- historical land-use change, leading to a gradual replacement of forests in the temperate zone and part of the tropics by agricultural land occurred at a speed that the oceans could dampen the effect; the fast deforestation of the second half of the 20th century leads to a recognisable increase in atmospheric CO_2, but not to dramatic impacts;

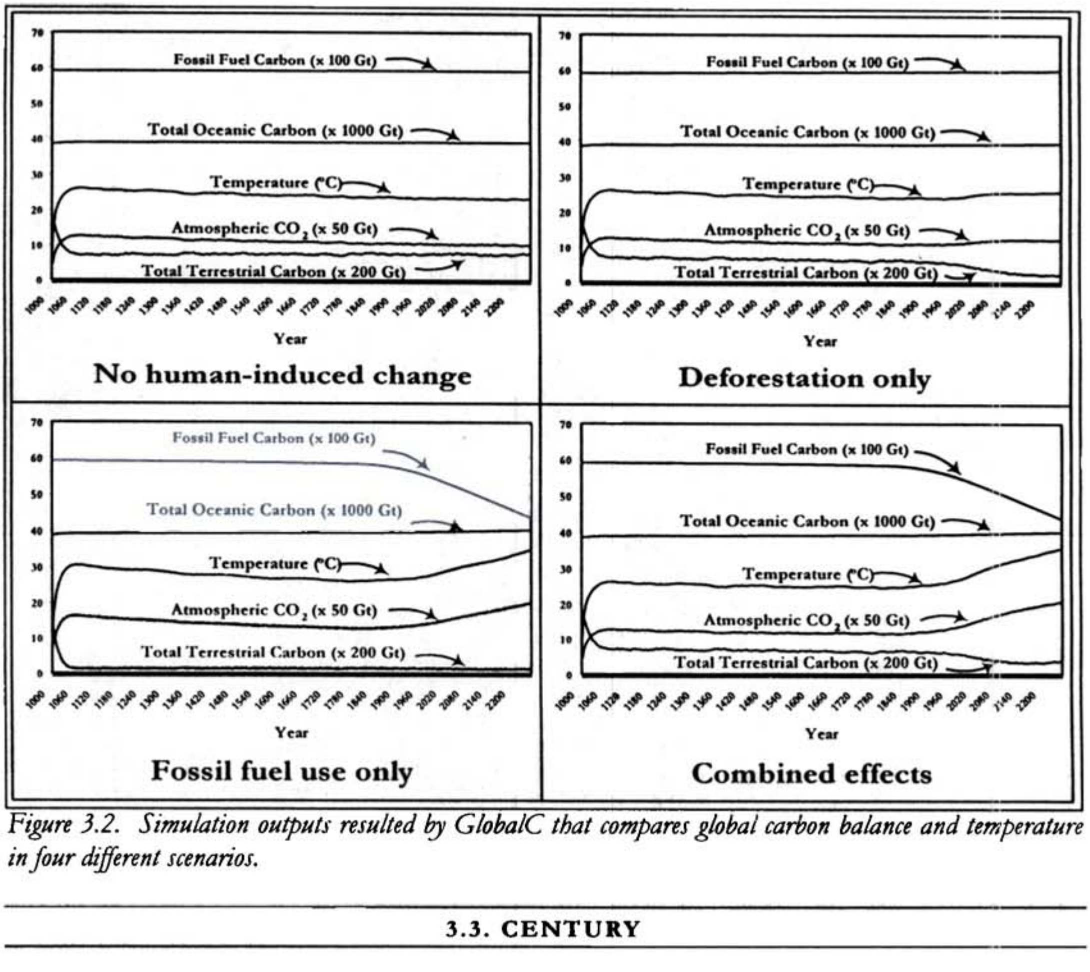
- fossil fuel use transfers CO_2 into the atmosphere at a rate beyond what the oceans can absorb and thus leads to global warming; if the globe remains forested, a small fraction of this atmospheric CO_2 can be stored in terrestrial stocks, but the effect is counteracted by increase in temperature and thus decomposition of soil C; and

combined effects of fossil fuel use and land-use change lead to a marked increase of atmospheric CO_2 during the 20th century and into the third millennium.

The model presented here is in the STELLA modelling shell, which allows users to make runs, look at output, change parameters or scenario's (especially the time pattern of deforestation, reforestation and fossil fuel use) and add structural complexity to the model. Figure 3.2 shows example of simulation outputs resulted by GlobalC, in which global carbon balance and temperature in four different scenarios can be compared. Without human-induced changes, there is no significant temperature increase. It also shows that fossil fuel use will increase the temperature more drastically rather than deforestation.

The GlobalC model can help to see the relevance in a global perspective of the land-use questions discussed in this course:

- How do terrestrial C stocks differ between land-cover types?
- Which part of the total stock is in above-ground vegetation (biomass, litter, dead wood on the soil surface), and how much is below-ground (roots, soil organic matter, peat) and how can we measure the various stocks?
- What are the dynamics of these pools and how rapid is their response to change in land-use, temperature or atmospheric CO_2 concentration?
- What is the relationship between soil carbon pools and the functioning of agro-ecosystems from the farmers' perspective, via processes of mineralisation and functional aspects of below-ground biodiversity?
- What about the other greenhouse gasses (especially N_2O and CH_4) and their relations with land-use?



No human-induced change

Deforestation only

Fossil fuel use only

Combined effects

Figure 3.2. Simulation outputs resulted by GlobalC that compares global carbon balance and temperature in four different scenarios.

3.3. CENTURY

3.3.1. INTRODUCTION

The first widely used Soil Organic Matter (SOM) model was developed by Jenkinson and Reyners (1977) who divided soil C into active, slow and passive pools with different turnover times (1 y, 30 y, and 1,500 y respectively). Van Veen and Paul (1981) then improved this model by including concepts of physical and chemical protection, and factors such as soil erosion and soil cultivation. Parton *et al.* (1987) added the impact of soil texture on SOM dynamics and eventually developed a relatively complete model called Century Model.

In the Century Model, the fractionation of soil organic matter is based on the rate of decomposition or turnover time and results in three fractions or pools (Figure 3.3). The fraction of SOM with a short turnover time (1-5 y) is called active SOM (SOM1C), which consists of live microbes and microbial products along with soil organic matter. The fraction with an intermediate turnover time (20-40 y) is called slow SOM (SOM2C), which is physically and/or chemically protected and more biological resistant to decomposition. The third fraction has the longest turnover time (200-1500 y) and is called passive SOM (SOM3C), which is chemically recalcitrant and may be also physically protected. The source of soil organic matter is confined to plant residue, which is divided into components based on lignin to nitrogen ratio. The component with a high lignin/nitrogen ratio is considered to be the structural part with 1-5 y turnover time, and the one with a low ratio is considered to be the metabolic part with 0.1-1 y turnover time. The lignin/nitrogen ratio is used to split plant residue into structural and metabolic components and to allocate all plant residue lignin flows into the structural component.

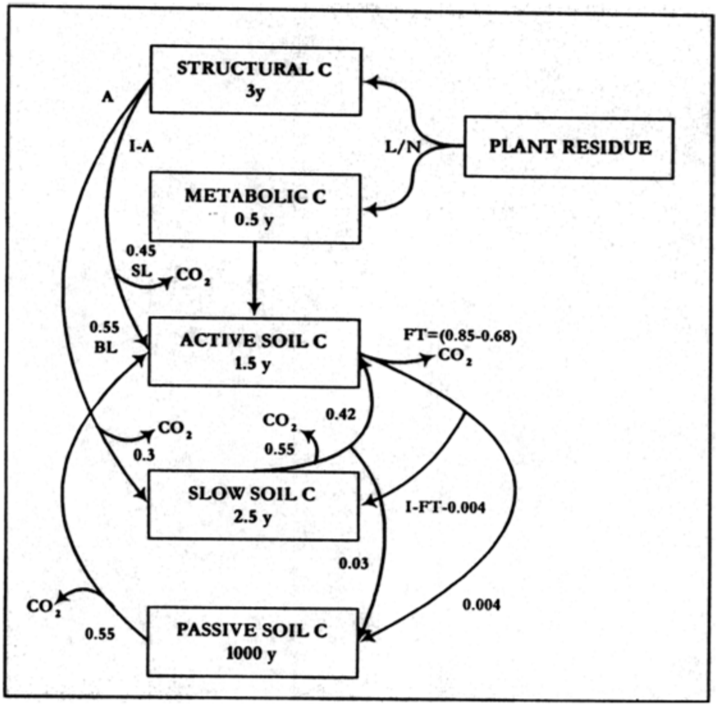


Figure 3.3. Flow diagram for the carbon flow model (SL = Surface Litter, BL = Soil Litter, L/N = Lignin to Nitrogen ratio, A = Lignin fraction, FT = Fraction of Soil Silt + Clay content.

It is also assumed that the rate of structural material decomposition is controlled by its lignin content and that the lignin fraction is directly incorporated into slow SOM. The critical point of the Century Model is that the decomposition of each pool is a result of microbial activity, and hence some organic matter will be lost in every step through respiration.

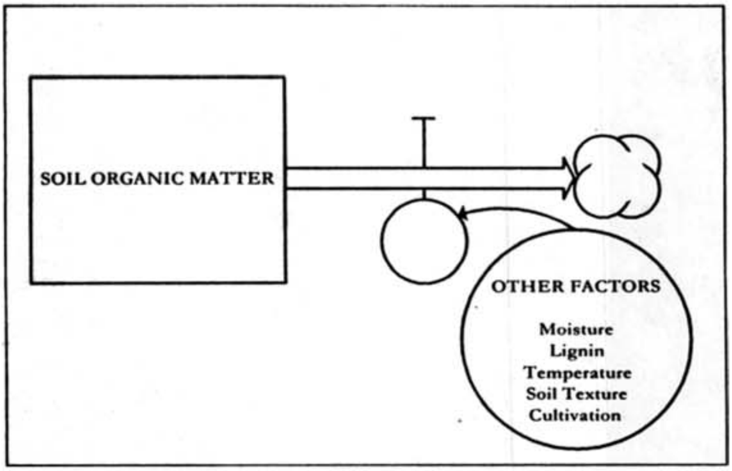


Figure 3.4. The model of SOM decomposition following first order equation.

The rate of decomposition is calculated using first order equation as shown in Figure 3.4, which means that the change of SOM with time, or the amount of organic matter loss through decomposition, is not constant, but dependent upon the amount of SOM and other factors. It can be written in the form of a differential equation as follows:

$$\frac{\delta(SOM)}{\delta t} = k.SOM.f$$

This equation can be easily solved with analytical means as shown below

$$\frac{\delta(SOM)}{SOM} = k.f.\delta t$$

$$\int_{SOMo}^{SOMt} \frac{\delta(SOM)}{SOM} = kf\int_{0}^{t}\delta t$$

$$\ln (SOMt/SOMo) = kft$$

$$SOMt = SOMo.e^{kft}$$

However, complex differential equations cannot be always easily solved analytically, so that the numerical integration, such as Euler's Method and Second Order Method (Runge-Kutta), will be used. Equations used to calculate a change in each component of organic matter in the Century Model are shown below:

$$\frac{\delta C_i}{\delta t} = K_i.Lc.A.C_i \qquad i = 1, 3$$

$$\frac{\delta C_i}{\delta t} = K_i . A . Tm . C \qquad i = 5$$

$$\frac{\delta C_i}{\delta t} = K_i . A . C_i \qquad i = 2, 4, 6, 7, 8$$

i = POOL	K_i	i = POOL	K_i
1. Structural Surface Litter	3.90	5. Active SOM (Microbial Biomass, SOM1)	7.30
2. Metabolic Surface Litter	14.80	6. Slow SOM (Particulate Fraction, SOM2)	0.20
3. Structural Soil Litter	4.90	7. Surface Microbial Biomass	6.00
4. Metabolic Soil Litter	18.50	8. Passive SOM Fraction (SOM3)	0.0068

K_i = maximum decomposition rate (yr^{-1}) for fraction-i
A = the combined effect of abiotic impact of soil moisture and soil temperature on decomposition
Tm = is the effect of soil texture (T) on active SOM turnover
= $1 - 0.75(T)$ where T = silt + clay
Lc = impact of lignin content of structural material (Ls) on structural decomposition
= $e^{(-3.Ls)}$

3.3.2. MAJOR VARIABLES

The model runs using a monthly time step and the major input variables for the model include:

- monthly average maximum and minimum air temperature;
- monthly precipitation;

- lignin content of plant material;
- plant N, P and S content;
- soil texture;
- atmospheric and soil N inputs; and
- initial soil C, N, P and S level.

The model can be run for C and N only by setting NELEM = 1, otherwise set NELEM = 2 or 3 to simulate C, N and P or C, N, P and S respectively. In addition to these elements, numerous outputs can be obtained from the model (Metherell, 1993).

3.3.3. AN EXAMPLE OF CENTURY APPLICATION

Century Model version 4.0 was used to simulate SOM dynamics after forest conversion into plantations, such as oil palm and sugarcane. This type of land-use change is considered to be major cause of deforestation. In Lampung, secondary forest having grown for about 30 years is the available area of forest converted to plantations. The outputs of simulation model show that this forest may accumulate >11,6 kg C.m^{-2} equivalent to a total biomass (TBM) of >255 Mg.ha^{-1}, and >80% of which (208 Mg.ha^{-1}) is large wood component. The above-ground biomass of this forest is about 226 Mg.ha^{-1}, which agrees with field estimates of secondary forest at the same site, based on tree diameter at breast height (dbh), that vary between 115.9 and 355.3 Mg. ha^{-1} of above-ground biomass (Sitompul *et al.*, 1996; Hairiah, 1997).

Sugarcane cultivated after forest removal without external application of fertiliser has a TBM of 2,3 kg C.m^{-2} in the first year which then declines rapidly in the following years. A parallel trend is exhibited by sugarcane yield which is 40 Mg.ha^{-1} in the first year and then falls to less the half after 5 years. The effect of fertiliser application of 150, 250 and 350 kg Urea.ha^{-1} successively in the first, second and following years in addition to 350 TSP ha^{-1}.year^{-1} may maintain a sufficiently high yield. This yield is close to that observed in the field and comparable with the average productivity of upland sugarcane in Indonesia during the period of 1981-1991 (*Anonymous*, 1992).

The dynamic of soil organic matter alters with changes in land-cover from forest to sugarcane. Under forest, the active pool of SOM either at soil surface (SOM1C1) or in soil (SOM1C2) reaches a level which fluctuates around 30 and < 50 g C.m^{-2} respectively after 10 years old (Figure 3.5). The slow pool of SOM (SOM2C) tends to increase slightly which is the opposite of passive pool (SOM3C) trend. As a whole, the total organic matter (SOMTC) increases slightly with time and reaches 5281 g C.m^{-2} (2%) in the last month before forest removal. This SOMT level is around the common values observed in the field at 0-20 cm depth under secondary forest of about 30 years old in Lampung (Van der Heide, 1992; *Anonymous*, 1995). This also assumed to be the level required for maintaining favourable soil physical conditions in the humid tropics (Young, 1989).

When forest is removed and replaced by sugarcane, SOM1C1 drops immediately to a very low level, then fluctuates slightly around a constant level. In turn, SOM1C2 characterised by high fluctuation increases initially then tends to decline after a few years. An immediate and a slow decrease with time following forest removal is exhibited by SOM2C, while SOM3C declining very slowly with time has no response to the land-cover change.

The SOM outputs of simulation model indicate the depletion of soil organic matter as forest is replaced by sugarcane and a low-input management causes a larger drop than a high-input management does. This trend is comparable with that of yields, which suggests the significant role of SOM in soil fertility and hence crop productivity. Century Model may give good estimates of SOM.

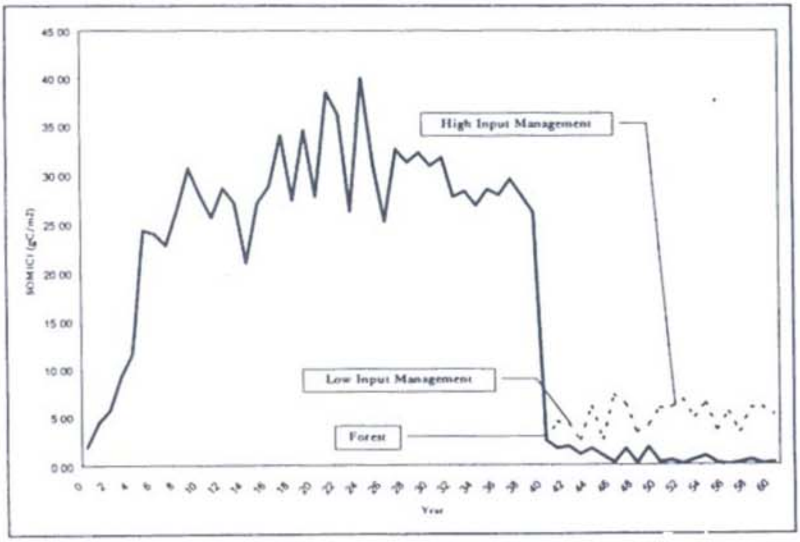


Figure 3.5. The dynamics of active SOM at soil surface (SOM1C1) under forest and sugarcane with low-input management or high-input management.

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3.4. CENW

By:
Miko Kirschbaum

3.4.1. INTRODUCTION

The Carbon, Energy, Nutrients and Water (CENW) model combines and links fluxes of soil carbon, nutrients, atmospheric CO_2 and water. Plants grow by fixing CO_2 from the atmosphere. However, the need to open a diffusion path for CO_2 inevitably leads to water loss in the diffusive exchange of CO_2 and water through stomatal pores. Water can be replenished from the soil provided adequate soil water is available. Otherwise, further plant CO_2 fixation is prevented by stomatal closure.

As shown in Figure 3.6, to meet their nitrogen requirements, plants must take up nitrogen from the mineral nitrogen pool. Nitrogen can be supplied by external sources or from the decomposition of organic matter. Plants utilise part of their carbon and nitrogen in new growth, and some carbon and nitrogen is lost in death or senescence of plant components. This returns carbon and nitrogen to the soil to form organic matter. Organic matter is decomposed by organisms in the soil, releasing CO_2 to the atmosphere. Any excess nitrogen can enter the pool of mineral nitrogen from where it can be taken up by plants.