Introduction to the carbon spinup

1. Scientific issue – Concepts
2. Mathematical solution – Estimation of carbon stocks
3. Code implementation
4. libIGCM configuration
5. New challenges and solutions for more complex cases

1. Scientific issue

i. Use of Land Surface Models?

ii. Steady state equilibrium

iii. Need for a Carbon Spinup

iv. Dynamics of **carbon pools**

v. Case with two carbon pools

vi. In ORCHIDEE

vii. The **CENTURY** model

1.I. Why do we use Land Surface Models?

→ Test our **understanding** of processes.

→ Lead **numerical experiments**, usually introduction of disturbances such as:

- Climate Change
- Increasing atmospheric CO_2 concentrations
- Land Use Change
- …

➲ A stable initialization state (with no trend) is required to study impacts.

1.II. Steady state equilibrium

- Without disturbances, the carbon cycle in terrestrial ecosystems and in LSMs reaches an equilibrium, with all variables at a steady state (constant mean value over a period).
- This steady state equilibrium is usually used as the initialization state of experiments with LSMs (convention in MIPs protocols).
- This ideal state is useful when you don't know the real history (plantation date, fires, LUC, …) so always with regional/global simulations.
- This equilibrium depends on the model (+ parameters), climate, vegetation type, soil.

1.III. Need for a Carbon Spinup

The carbon cycle is conceptually represented using **carbon pools** exchanging carbon.

The equilibrium is usually reached by running the carbon model **several thousands of years** to bring all carbon pools at equilibrium.

This operation is named as the **spinup** of the model.

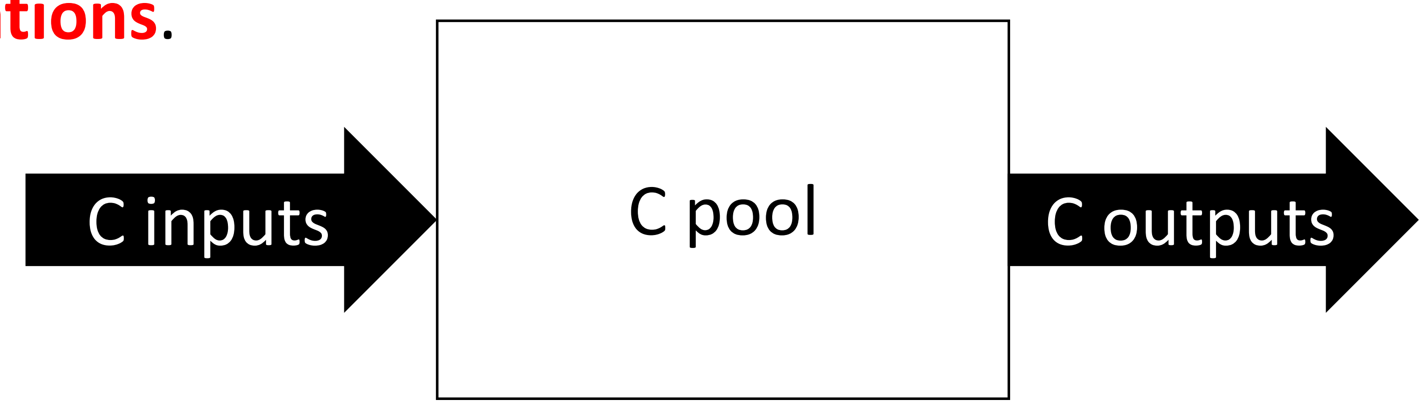
The computational cost is quite heavy as compared to the experiment itself (hundreds of years).

➲ We need to optimise the spinup.

➲ Analytical expression of the carbon stocks at the equilibrium state

1.iv. Dynamics of carbon pools

Carbon processes in terrestrial ecosystems can be represented by **linear first-order differential equations**.



b influx

$$\frac{dC}{dt} = -aC + b$$

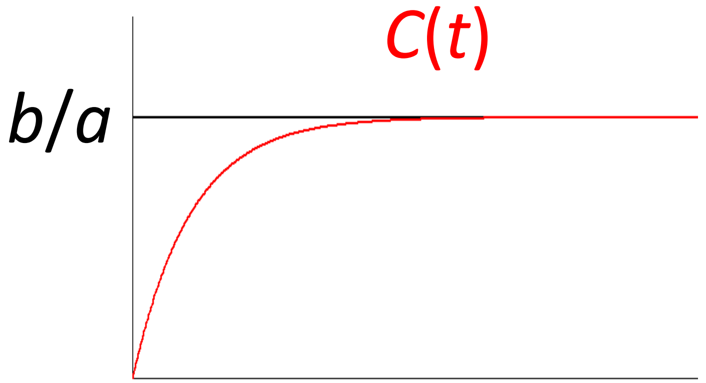
a decomposition rate (a>0)

$a = a_{max}\rho_T\rho_W$

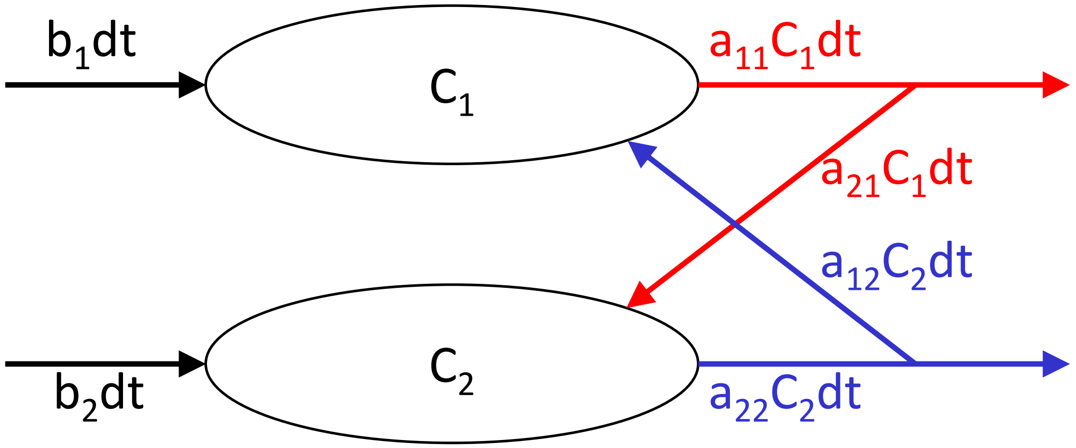
$\tau = 1/a$ residence time

Simple case: one pool, *a* and *b* constants, *C(0)*=0

$$\Rightarrow \quad C(t) = \frac{b}{a}(1 - e^{-at})$$



1.v. Case with two carbon pools



$$\frac{dC_1}{dt} = -a_{11}C_1 + a_{12}C_2 + b_1$$

$$\frac{dC_2}{dt} = a_{21}C_1 + a_{22}C_2 + b_2$$

$$\frac{d}{dt}\begin{bmatrix} C_1 \\ C_2 \end{bmatrix} = \begin{bmatrix} -a_{11} & a_{12} \\ a_{21} & -a_{22} \end{bmatrix}\begin{bmatrix} C_1 \\ C_2 \end{bmatrix} + \begin{bmatrix} b_1 \\ b_2 \end{bmatrix}$$

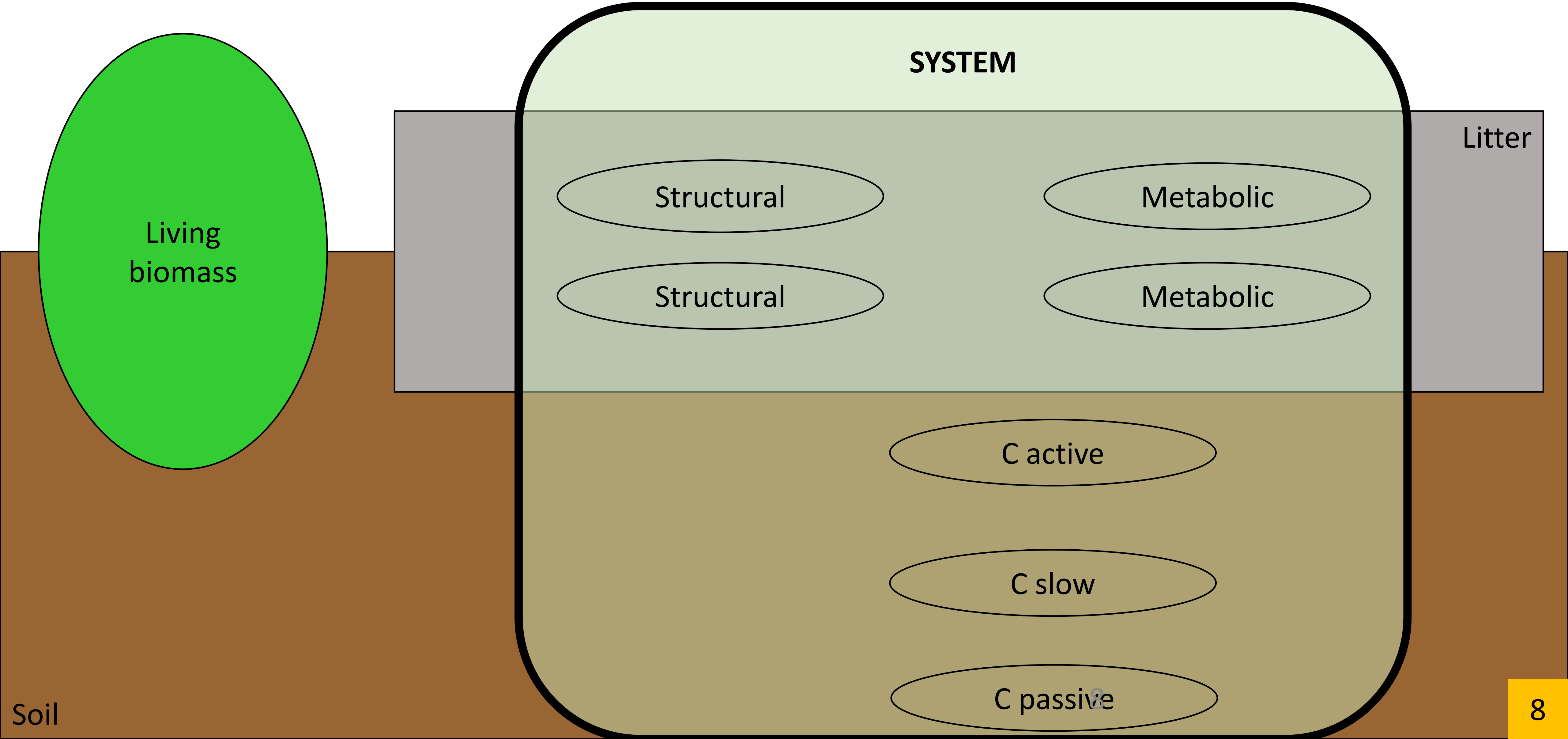
Matrix formulation

Same equation as in the one pool case

$$\frac{dC}{dt} = AC + B$$

➲ Generalization to a vector *C* of any number of carbon pools

1.VI. IN ORCHIDEE



1.VII. THE CENTURY MODEL

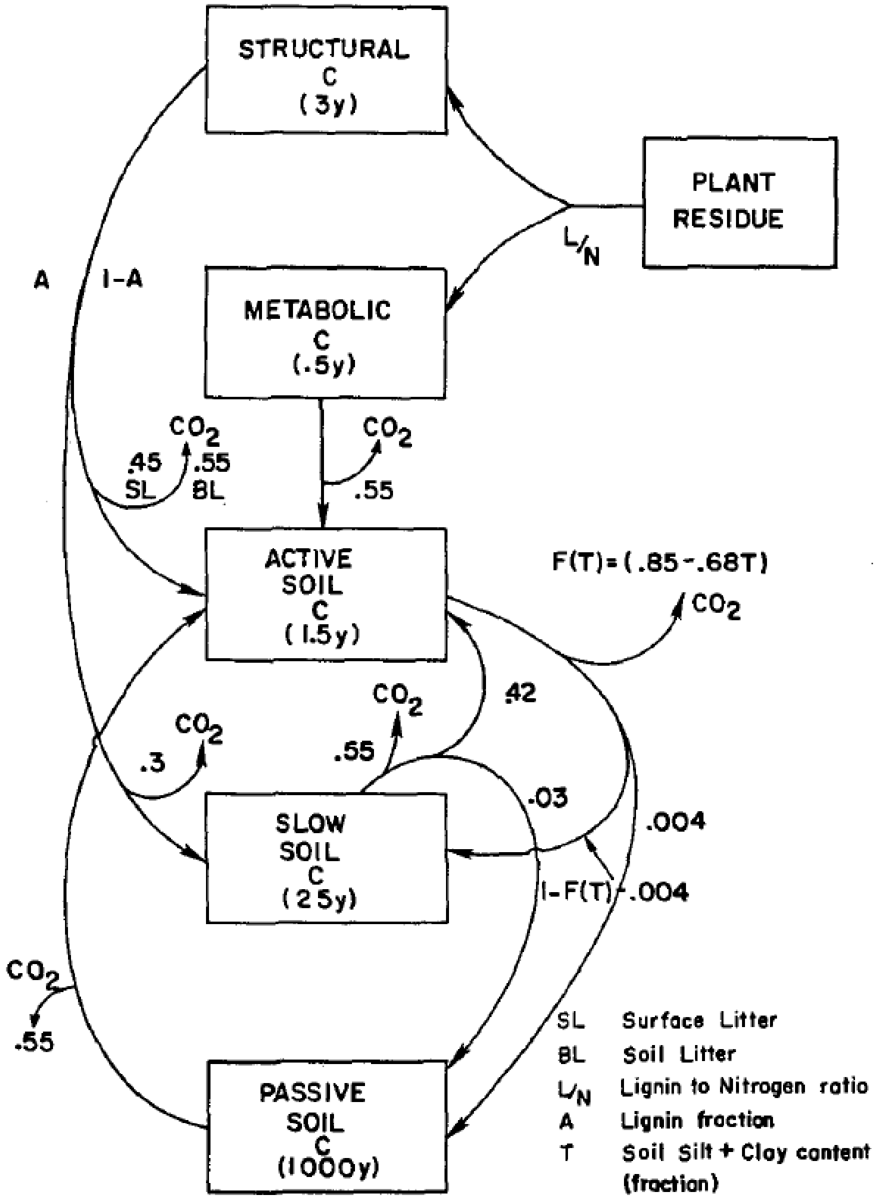


Fig. 1. Flow diagram for the C flows in the Century model.

Parton et al. (1987)

2. Mathematical implementation

i. System dynamics

ii. Mathematical manipulations

iii. Steady-state analytical expression

Implementation done by D. Solyga, N. Vuichard and J. Ghattas

2.I. SYSTEM DYNAMICS

Lardy et al. (2011)

C is the vector of carbon stocks.

The system dynamics is represented as:

$$C'(t) = \rho_t A_t C_t + B_t \quad (1)$$

with:

$$C'(t) = \frac{C_{t+1} - C_t}{dt} \quad (2)$$

ρ_t represents the temperature and water stresses.

A_t is the matrix of the maximum decomposition rates.

B_t is the vector of inputs.

We rearrange (1) and (2) in:

$$C_{t+1} = (I + \rho_t dt A_t) C_t + B_t dt \quad (3)$$

and define:

$$D_t = (I + \rho_t dt A_t) \quad (4)$$

2.II. Some mathematical manipulations

$$C_{t+1} = (I + \rho_t dtA_t)C_t + B_t dt \quad (3)$$

$$D_t = (I + \rho_t dtA_t) \quad (4)$$

Equation (3) may thus be rewritten:

$$C_{t+1} = D_t C_t + B_t dt \quad (5)$$

By induction we have:

$$C_t = \sum_{i=t_0}^{t-1} (\prod_{j=i+1}^{t-1} D_j) B_i dt + (\prod_{i=t_0}^{t-1} D_i) C_{t_0} \quad (6)$$

We introduce the following series:

$$\begin{cases} V_{t_0} = D_{t_0} \\ V_t = D_t V_{t-1} \end{cases} \quad (7)$$

and

$$\begin{cases} U_{t_0} = B_{t_0} dt \\ U_t = D_t U_{t-1} + B_t dt \end{cases} \quad (8)$$

$$V_t = D_t V_{t-1} = \prod_{i=t_0}^{t} D_i \quad (9)$$

$$U_t = \sum_{i=t_0}^{t} (\prod_{j=i+1}^{t} D_j) B_i dt \quad (10)$$

2.III. Steady-state analytical expression

$$C_t = \sum_{i=t_0}^{t-1} \left(\prod_{j=i+1}^{t-1} D_j\right) B_i dt + \left(\prod_{i=t_0}^{t-1} D_i\right) C_{t_0} \quad (6)$$

$$V_t = D_t V_{t-1} = \prod_{i=t_0}^{t} D_i \quad (9)$$

$$U_t = \sum_{i=t_0}^{t} \left(\prod_{j=i+1}^{t} D_j\right) B_i dt \quad (10)$$

Thus:

$$C_t = U_{t-1} + V_{t-1} C_{t_0} \quad (11)$$

At equilibrium:

$$C_t = C_{t_0} = C^* \quad (12)$$

$$C^* = U_{t-1} + V_{t-1} C^* \quad (13)$$

$$(I - V_{t-1}) C^* = U_{t-1} \quad (14)$$

$$C^* = (I - V_{t-1})^{-1} U_{t-1} \quad (15)$$

3. Code implementation

i. Initialisation part

ii. Loop part

iii. Final inversion

3.I. Initialisation part

constantes_var.f90

global variable spinup_analytic initialised to FALSE

constantes.f90::activate_sub_models

SPINUP_ANALYTIC KEYWORD read

stomate.f90::stomate_initialize

KEYWORDs read: SPINUP_PERIOD, EPS_CARBON

stomate.f90::stomate_init

allocation of variables

IF spinup_analytic

stomate_io.f90::readstart

Specific variables are read from the restart file: ‘Global_years’, ‘nbp_sum’, ‘nbp_flux’, ‘ok_equilibrium’, ‘MatrixV’,’VectorU’,’previous_stock’, ‘current_stock’

3.II. Loop part

At each sechiba time step

stomate_io.f90::write_restart

IF (lstep_last) specific variables are written in the restart file.

stomate_litter.f90::littercalc

filling of MatrixA and VectorB with fluxes related to litter pools

stomate_soilcarbon.f90::soilcarbon

filling of MatrixA with fluxes related to soil carbon pools; $A = A + I$ (= D)

At each stomate time step

lpj_fire.f90::fire

update of the terms of MatrixA related to above ground litter pools using firefrac

stomate.f90::stomate_main

nbp is accumulated.

stomate.f90::stomate_main

$$V_t = D_t V_{t-1} \qquad U_t = D_t U_{t-1} + B_t dt$$

3.III. FINAL INVERSION

stomate.f90::stomate_main

IF LastTsYear

Increment the years counter (global_years).

IF global_years is a multiple of SPINUP_PERIOD

- $C^* = (I - V_{t-1})^{-1} U_{t-1}$ is computed using the Gauss-Jordan method (gauss_jordan_method.f90::gauss_jordan_method).
- Compute the relative error over the passive carbon pool (sum over all PFTs for each grid cell, gauss_jordan_method.f90::error_L1_passive).
- For grid cells where relative error <= EPS_CARBON

  ok_equilibrium=TRUE
- Update all pools to new values.
- **IF all pixels at equilibrium: END OF THE ANALYTICAL SPINUP**

ENDIF

ENDIF

4. The libIGCM SPINUP_ANALYTIC configuration

i. Configuration files

ii. Expected evolution of CARBON_PASSIVE & NBP

4.I. CONFIGURATION FILES

config.card

```
....
#----- ExperimentName : Short Name of Experiment
ExperimentName=spinup
#============================
#-- leap(gregorian), noleap, 360d
CalendarType=noleap
#-- Start and End of Job
#-- "YYYY-MM-DD"
DateBegin=1901-01-01
DateEnd=2240-12-31
# Forcing data between 1901 and 1920
CyclicBegin=1901
CyclicEnd=1910
#============================
#-- 1Y, 1M, 5D, 1D
PeriodLength=1Y
...
```

4.I. CONFIGURATION FILES (BIS)

COMP/orchidee_ol.card

```
[BoundaryFiles]
List=  (${R_IN}/SRF/METEO/CRUJRA/v2.2.2/twodeg/crujra_twodeg_v2.2.2_${CyclicYear}.nc, forcing_file.nc)
```

COMP/sechiba.card

```
[UserChoices]
# VEGET_UPDATE=0Y : no change in vegetation map. PFTmap.nc should be set only in InitialStateFiles/List.
VEGET_UPDATE=0Y

# Specify output level for output files
output_level_sechiba_history = 4
output_level_sechiba_out_2 = NONE
output_level_sechiba_history_4dim = 4

# Specify output frequency for each file [1y, 1mo, 1d, 10800s, 1ts]
output_freq_sechiba_history = 1y
output_freq_sechiba_history_4dim = 1y

[InitialStateFiles]
List=     (${R_IN}/SRF/ROUTING/routing.nc, .),     \
        (${R_IN}/SRF/PFTMAPS/CMIP6/ESA-LUH2v2/historical/15PFT.v1/PFTmap_1860.nc, PFTmap.nc), \
…
```

4.I. CONFIGURATION FILES (TER)

COMP/stomate.card

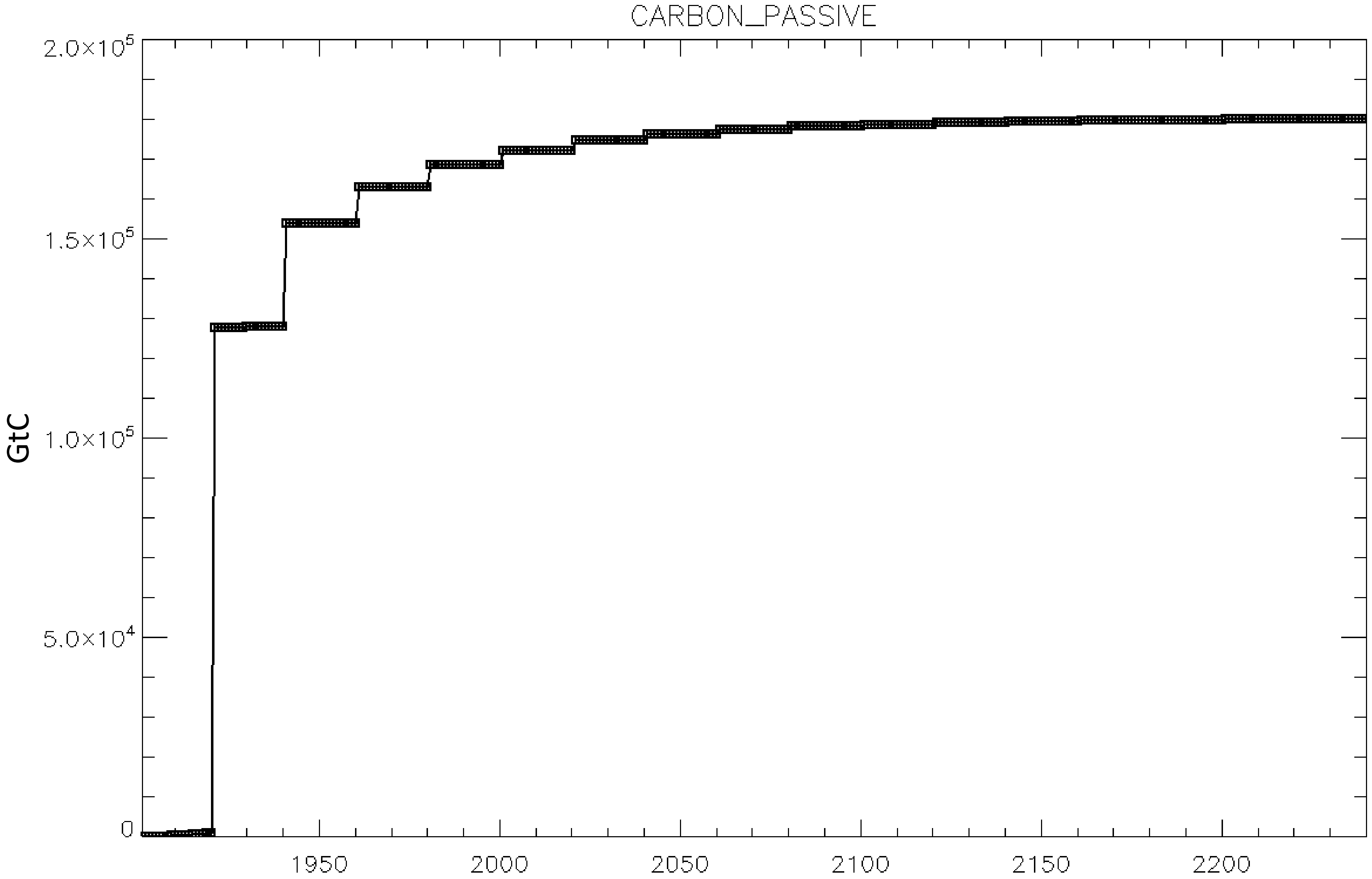
```
[UserChoices]
# SPINUP_ANALYTIC=y/n : Activate the spinup analytic option to solve the carbon in soil balance
SPINUP_ANALYTIC=y

# Specify output level for output files
output_level_stomate_history = 5
output_level_stomate_ipcc_history = 1

# Specify output frequency for each file [1y, 1mo, 1d]
output_freq_stomate_history = 1y
output_freq_stomate_ipcc_history = 1y

[InitialStateFiles]
List=   ()
…
[ParametersFiles]
#List=   (${R_IN}/SRF/CO2_1860_2012_TRENDY2.txt, CO2.txt)
List=   ()
…
```

4.I. CONFIGURATION FILES (QUATER)

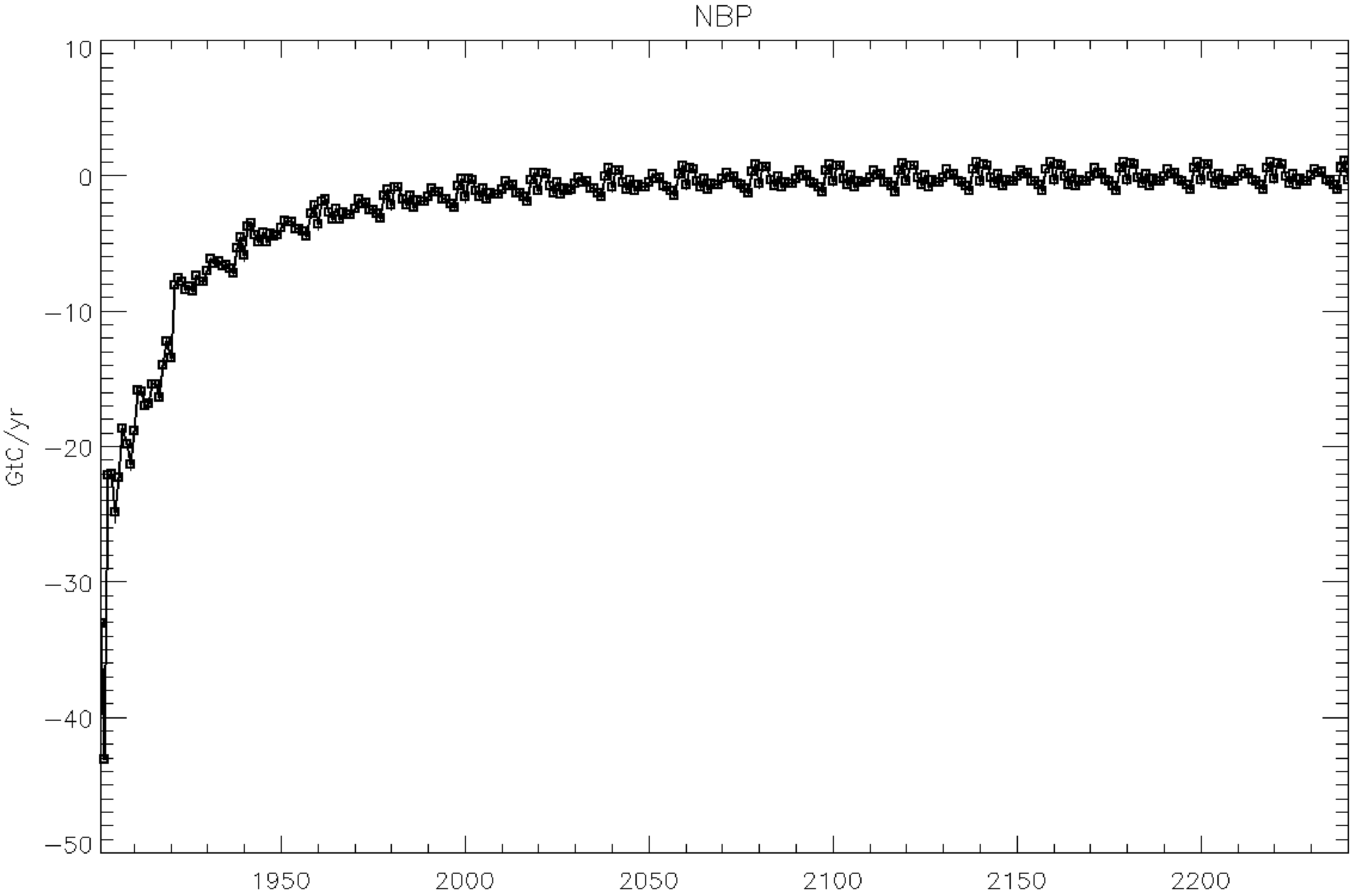
```
…

# OK_EXPLICITSNOW :  Activate explict snow scheme (default y)
OK_EXPLICITSNOW=y

# Carbon related parameters
#**************************************************************************
# Analytic spinup (default n)
SPINUP_ANALYTIC = _AUTO_
SPINUP_PERIOD = _AUTO_

# Value for atmospheric CO2 (default=350)
# ATM_CO2=287.14 : Year 1860 specified for TRENDY2 spinup
ATM_CO2 = _AUTO_: DEFAULT = 287.14

# Activate harvest of wood (default y)
DO_WOOD_HARVEST=y

# Deactivate fire (default FIRE_DISABLE=y)
FIRE_DISABLE=y
…
```

PARAM/run.def

4.II. CARBON_PASSIVE TIME-SERIES GLOBAL SCALE



4.II. NBP TIME-SERIES GLOBAL SCALE



5. New challenges and solutions for more complex cases

• **N cycle (branch V3)**
Lardy et al. (2011); Vuichard et al. (2019)
Same principles apply, additional code lines to compute steady-state N stocks

• **TRUNK (V4, including stand structure and forest management)**
The Analytical Spinup configuration is used.
Various options were tested regarding forest management.
More information may be found here:
https://forge.ipsl.jussieu.fr/orchidee/wiki/Documentation/TrunkFunctionality4

5. New challenges and solutions for more complex cases (bis)

- **N & P cycles (branch ORCHIDEE-CN-P, D. Goll)**

Machine learning for accelerating process-based computation of land biogeochemical cycles (Sun, Goll et al., 2023)
https://onlinelibrary.wiley.com/doi/full/10.1111/gcb.16623

- **Carbon permafrost**

Ad-hoc protocol developed during the IMBALANCE-P project
On-going developments within the PhD of Rémy Gaillard (B. Guenet, P. Peylin)

USEFUL REFERENCES / LINK

• Odum, E.P., 1969. The strategy of ecosystem development, Science, 164, 262-270.

• Parton, W.J., Schimel, D.S., Cole, C.V. and 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.

• Thornton, P.E. and Rosenbloom, N.A., 2005. Ecosystem model spin-up: Estimating steady state conditions in a coupled terrestrial carbon and nitrogen cycle model. Ecological Modelling, 189:25-48.

• Lardy, R., Bellocchi, G. and Soussana, J.F., 2011. A new method to determine soil organic carbon equilibrium. Environmental Modelling & Software, 26:1759-1763.

• Luo, Y.Q. and Weng, E.S., 2011. Dynamic disequilibrium of the terrestrial carbon cycle under global change. Trends in Ecology & Evolution, 26:96-104.

• Xia, J.Y., Luo, Y.Q., Wang, Y.P., Weng, E.S. and Hararuk, O., 2012. A semi-analytical solution to accelerate spin-up of a coupled carbon and nitrogen land model to steady state. Geoscientific Model Development, 5:1259-1271.

• Sun, Y., Goll, D. S., Huang, Y., Ciais, P., Wang, Y. P., Bastrikov, V. and Wang, Y., 2023. Machine learning for accelerating process-based computation of land biogeochemical cycles. Global Change Biology, 29(11), 3221-3234.

Work of D. Solyga:
http://forge.ipsl.jussieu.fr/orchidee/wiki/DevelopmentActivities/AccelerationSpinup