

## Abstract

Interactions between the atmosphere and the biosphere were investigated with Simulation model of Carbon cYCLE in Land Ecosystems (Sim-CYCLE), which enables us to simulate atmosphere-biosphere CO<sub>2</sub> exchange and carbon (C) dynamics in terrestrial ecosystems. Sim-CYCLE is a mechanistic model (described in Chapter 2), on the basis of the dry-matter production theory established by Monsi and Saeki (1953). The atmosphere-biosphere CO<sub>2</sub> exchange is composed of physiological processes, such as photosynthesis (*GPP*), respiration (*AR*), and decomposition (*HR*), and then this simulator enables us to estimate the ecosystem C budget in a mechanistic way. Plant growth process was retrieved by the Monsi (1960) scheme, and C dynamics including soil organic matter was captured by the Oikawa's (1985) compartment model. Then, terrestrial ecosystems were conceptualized as a five-compartment system: foliage, stem and branch, root, litter, and mineral soil. In addition to *GPP*, *AR*, and *HR*, carbon flows such as litterfall, photosynthate allocation, and humus formation were properly formulated. *GPP* was regulated by a couple of physiological processes at a single-leaf scale (e.g. stomatal conductance and quantum yield), and scaled up to a canopy scale. *AR* consists of two functional components, i.e. maintenance respiration and growth respiration, each of which is regulated by environmental factors independently. The difference between *GPP* and *AR* is termed net primary production (*NPP*), and the difference between *NPP* and *HR* is termed net ecosystem production (*NEP*). Sim-CYCLE contains water and radiation subschemes to estimate physical environment in terrestrial ecosystems.

Sim-CYCLE was validated by comparing with a number of plot-scale observations at various biome types (Chapter 3). In four representative sites, growth pattern, *NPP*, biomass, and seasonal cycle were appropriately captured. In 21 worldwide sites, model estimations of *NPP*, *LAI*, plant and soil C storage showed satisfactory coincidence with field observations.

Using the 0.5°x0.5° longitude-latitude grid system (86,705 grid cells), a global simulation was performed to estimate the equilibrium carbon dynamics of terrestrial ecosystems at the global scale (Chapter 4). A long-term mean climate, stationary CO<sub>2</sub> level,

and Olson's (1983) actual vegetation mapping of 33 biome types were adopted (e.g. tropical rain forest, temperate evergreen forest, boreal deciduous forest, grassland, tundra, desert, and cropland). In consequence, global *NPP* and biospheric C storage were estimated as 61.8 Pg C yr<sup>-1</sup> and 2150 Pg C, respectively (1Pg =10<sup>15</sup> g). The contribution by C<sub>3</sub> and C<sub>4</sub> plants to global *NPP* was 79.8 and 20.2 %, respectively. Geographical distribution of carbon storage, seasonal and biome-to-biome variations of *NPP* were properly captured by Sim-CYCLE. Finally, the geographical distribution of *NPP* showed satisfactory correlations with other three model estimations ( $r=0.75\sim 0.84$ ).

Next, interannual change in the carbon budget of terrestrial ecosystems was assessed, in relation to perturbations of climatic factors (Chapter 5). The long-term climate data for 41 years was derived from the NCEP/NCAR-reanalysis dataset, whose spatial resolution is 94 x 192 grid cells latitude-longitude. The convenient vegetation mapping (12 biome types) was derived from Matthews (1983). During the experimental period from 1958 to 1998, global *NPP* increased from 59.3 to 63.5 Pg C yr<sup>-1</sup>, owing to atmospheric CO<sub>2</sub> increase from 316 to 367 ppmv. After removing the fertilization effect, the terrestrial carbon fluxes, especially *NEP*, exhibited a considerable degree of interannual change, induced by climatic perturbations. The anomaly of *NEP* ( $\Delta NEP$ ) was related to anomalies of climatic factors, and consequently it was found that  $\Delta NEP$  was firstly influenced by anomalies of temperature and secondarily by precipitation. The responsiveness of  $\Delta NEP$  to temperature was so strong that warming of 1°C would result in annually as much as 3.1 Pg of C emission from biosphere to atmosphere. This was exemplified by the largest negative  $\Delta NEP$  in 1998 (-2.5 Pg C), when a huge ENSO event took place and surface temperature was extremely high (+0.58°C). Through a series of detailed analyses, it was found that tropical rain forests and grasslands in lower latitudes responded most sensitively to climate change, and that the responses of *AR* and *HR* to temperature chiefly accounted for the  $\Delta NEP$  variation.

Finally, Sim-CYCLE predicted the response of terrestrial carbon dynamics to global warming induced by atmospheric CO<sub>2</sub> increase (Chapter 6). The 0.5°-grid model coupled with Olson's biome mapping was adopted. Climate projection was derived from three GCM

experiments (GFDL, GISS, and MRI), assuming the gradual atmospheric CO<sub>2</sub> increase (+1 % yr<sup>-1</sup>). Two supplementary scenarios using the MRI-GCM were considered: MRIs including the effect of sulfate aerosols, and MRIh assuming a halved CO<sub>2</sub> growth rate. These scenarios predicted that global land temperature would rise by +1.9 to +2.5°C, and precipitation would more or less increase, when atmospheric CO<sub>2</sub> concentration becomes double. As a result of 70-year simulations, it was estimated that global *NPP* would increase by 27 to 30 %, and the terrestrial biosphere as a whole would act as a net carbon sink of 1 to 3 Pg C yr<sup>-1</sup>. The carbon sequestration was mostly attributable to the increased plant biomass, while soil carbon storage was lost from a part of boreal regions, due to the robust temperature rise. Although variability of estimations among GCM scenarios was substantially large, a consistent relationship was derived between atmospheric CO<sub>2</sub> concentration and global *NPP*, including the effect of climate change. The carbon sequestration into the biosphere was estimated as 74 to 128 Pg C yr<sup>-1</sup>, bringing about a negative feedback effect on the global warming.

Through these simulation experiments, the nature of terrestrial carbon dynamics in relation to atmospheric change was assessed at the global scale. The theme will be further explored in forthcoming researches, using an improved version of Sim-CYCLE.

# List of Abbreviations and Symbols

<b>Term</b>	<b>Definition (units)</b>
<i>AD</i>	air density (kg m <sup>-3</sup> )
<i>AE</i>	notation of aerobic condition
<i>AET</i>	actual evapotranspiration (mm mon <sup>-1</sup> )
<i>ALP</i>	albedo, reflectance to short-wave radiation, of leaf surface (dimensionless)
<i>ALS</i>	albedo of soil surface (dimensionless)
<i>AP</i>	air pressure (hPa)
<i>AP<sub>o</sub></i>	sea-level air pressure at 20°C (=1013.25 hPa)
<i>APAR</i>	absorbed PAR energy by canopy (MJ m <sup>-2</sup> yr <sup>-1</sup> )
<i>AR</i>	plant autotrophic respiration [= <i>ARM</i> + <i>ARG</i> ] (Mg C ha <sup>-1</sup> mon <sup>-1</sup> )
<i>ARG, ARG<sub>F.C.R</sub></i>	total and partial growth respiration (Mg C ha <sup>-1</sup> mon <sup>-1</sup> )
<i>ARM, ARM<sub>F.C.R</sub></i>	total and partial maintenance respiration (Mg C ha <sup>-1</sup> mon <sup>-1</sup> )
<i>ASH</i>	specific heat of air (=0.2813 J kg <sup>-1</sup> °C <sup>-1</sup> )
<i>AT</i>	altitude (m above sea level)
<i>BLF</i>	notation of boreal larch forest site
<i>CD<sub>ATM</sub></i>	atmospheric CO <sub>2</sub> concentration (ppmv)
<i>CD<sub>CPM</sub></i>	compensation CO <sub>2</sub> concentration for photosynthesis (ppmv)
<i>CD<sub>ICL</sub></i>	intercellular CO <sub>2</sub> concentration (ppmv)
<i>CL</i>	cloudiness (fraction of sky)
<i>CV</i>	convexity of water availability-evapotranspiration rate curve (dimensionless)
<i>DAY</i> (subscription)	notation of a dialy value
<i>DC</i>	daily cost to hold unit area of leaf (μ mol CO <sub>2</sub> m <sup>-2</sup> day <sup>-1</sup> )
<i>DI</i>	dryness index related to runoff (mm)
<i>DL</i>	day-length (hours)
<i>EC</i>	eccentricity of the Earth's orbit ( <i>EC</i> <sup>2</sup> =0.000669447)
<i>EP</i>	effective photosynthate for biomass growth [= <i>GPP</i> - <i>ARM</i> ] (Mg C ha <sup>-1</sup> mon <sup>-1</sup> )
<i>ESD</i>	earth-sun distance (km)
<i>ESD<sub>o</sub></i>	annual mean <i>ESD</i> (=1.46 x 10 <sup>8</sup> km)
<i>EV</i>	evaporation rate from soil surface (mm mon <sup>-1</sup> )
<i>EV<sub>PM</sub></i>	potential evaporation rate estimated by Penman-Monteith equation (mm mon <sup>-1</sup> )

$F_{C3}, F_{C4}$	fractional land coverage by $C_3$ and $C_4$ plants (fraction)
$GA$	aerodynamic conductance ( $\text{mmol H}_2\text{O m}^{-2} \text{s}^{-1}$ )
$GC$	canopy conductance ( $\text{mmol H}_2\text{O m}^{-2} \text{s}^{-1}$ )
GCM	General Circulation Model
GFDL	Geophysical Fluid Dynamics Laboratory (U.S.)
$GG$	ground conductance for evaporation from non-saturated soil ( $\text{mm H}_2\text{O m}^{-2} \text{s}^{-1}$ )
$GH$	soil hydraulic conductivity ( $\text{day}^{-1}$ )
GISS	Goddard Institute for Space Studies (U.S.)
$GPP$	gross primary production ( $\text{Mg C ha}^{-1}, \text{yr}^{-1}$ or $\text{mon}^{-1}$ or $\text{day}^{-1}$ )
$GS$	leaf stomatal conductance ( $\text{mmol CO}_2 \text{m}^{-2} \text{s}^{-1}$ )
$HA$	hour angle from sunrise to midday (degree)
$HF$	humus formation rate ( $\text{Mg C ha}^{-1} \text{mon}^{-1}$ )
$HR, HR_{LH}$	total and partial soil heterotrophic respiration ( $\text{Mg C ha}^{-1} \text{mon}^{-1}$ )
$HT$	height of wind velocity data (m)
IBP	International Biological Programme
$IC$	rain interception by canopy ( $\text{mm mon}^{-1}$ )
$INS$ (subscription)	notation of an instantaneous value
$IR$	ratio of canopy interception (fraction)
$KA$	light attenuation coefficient (dimensionless)
$KC$	von Karman's constant ( $=0.41$ , dimensionless)
$KM_x$	parameter in Michaelis-type equation [ $X = AE, CD, SW, WA$ ]
$LAI$	leaf area index ( $\text{ha ha}^{-1}$ )
$LAI_{CML}$	cumulative leaf area index, downward from the canopy-top ( $\text{ha ha}^{-1}$ )
$LAI_{OPT}$	theoretically optimum leaf area index ( $\text{ha ha}^{-1}$ )
$LAT$	site latitude (degree)
$LF, LF_{F.C.R}$	total and partial plant litterfall ( $\text{Mg C ha}^{-1} \text{mon}^{-1}$ )
$LH$	specific latent heat of water vaporization ( $=2.5 \text{ MJ kg}^{-1} \text{ H}_2\text{O}$ )
LPF	notation of warm-temperate evergreen broad-leaved [lucidophyllus] forest site
LSP	Land Surface Parameterization
$MD$ (subscription)	notation of the value at midday
MRI	Meteorological Research Institute (Japan)
$MS_{UP}, MS_{LW}$	upper and lower soil moisture content (mm)
$NCB$	net carbon balance [ $=NEP - \text{crop harvest}$ ] ( $\text{Mg C ha}^{-1} \text{mon}^{-1}$ )
$ND$	day-number from the beginning of the year (days)

<i>ND<sub>VE</sub></i>	day-number of the vernal equinox (=80 days)
<i>NDVI</i>	normalized difference vegetation index
<i>NEP</i>	net ecosystem production [= <i>NPP</i> - <i>HR</i> ] (Mg C ha <sup>-1</sup> mon <sup>-1</sup> )
<i>NPP</i>	net primary production [= <i>GPP</i> - <i>AR</i> ] (Mg C ha <sup>-1</sup> mon <sup>-1</sup> )
<i>PAR</i>	notation of photosynthetically active radiation
<i>PC</i>	single-leaf photosynthetic rate ( $\mu$ mol CO <sub>2</sub> m <sup>-2</sup> s <sup>-1</sup> )
<i>PC<sub>SAT</sub></i>	light-saturated photosynthetic rate ( $\mu$ mol CO <sub>2</sub> m <sup>-2</sup> s <sup>-1</sup> )
<i>PET</i>	potential evapotranspiration (mm mon <sup>-1</sup> )
<i>PN</i>	soil water penetration from upper to lower layer (mm mon <sup>-1</sup> )
<i>PPFD<sub>IN</sub></i>	incident photosynthetic photon flux density at leaf surface ( $\mu$ mol photons m <sup>-2</sup> s <sup>-1</sup> )
<i>PPFD<sub>TOP</sub></i>	photosynthetic photon flux density at the canopy-top ( $\mu$ mol photons m <sup>-2</sup> s <sup>-1</sup> )
<i>PR, PR<sub>RAIN, SNOW</sub></i>	total, rain, and snow precipitation (mm mon <sup>-1</sup> )
<i>PSC</i>	psychrometer constant (=0.667 Pa K <sup>-1</sup> )
<i>PT, PT<sub>F,C,R</sub></i>	total and partial photosynthate translocation (Mg C ha <sup>-1</sup> mon <sup>-1</sup> )
<i>QE</i>	quantum yield, photochemical light-use efficiency (mol CO <sub>2</sub> mol <sup>-1</sup> photon)
<i>QT</i>	temperature sensitivity of respiration, <i>Q<sub>10</sub></i> (dimensionless)
<i>RDG</i>	direct short-wave radiation at the ground surface (W m <sup>-2</sup> )
<i>RN</i>	total net radiation [= <i>RNC</i> + <i>RNG</i> = <i>RN<sub>L</sub></i> + <i>RN<sub>S</sub></i> ] (W m <sup>-2</sup> )
<i>RNP</i>	net radiation at plant canopy (W m <sup>-2</sup> )
<i>RNS</i>	net radiation at soil surface (W m <sup>-2</sup> )
<i>RN<sub>LN</sub>, RN<sub>ST</sub></i>	long- and short-wave fractions of net radiation (W m <sup>-2</sup> )
<i>RO</i>	runoff (mm mon <sup>-1</sup> )
<i>RFG</i>	diffuse short-wave radiation at the ground surface (W m <sup>-2</sup> )
<i>RTG</i>	total solar radiation at the ground surface (W m <sup>-2</sup> )
<i>RTT</i>	total solar radiation at the atmosphere-top (W m <sup>-2</sup> )
<i>RUE</i>	radiation use efficiency of dry-matter production (g C MJ <sup>-1</sup> )
<i>SA</i>	seasonal angle of the Earth's orbit (degree)
<i>SARG<sub>F,C,R</sub></i>	specific growth respiration coefficient (Mg C Mg C <sup>-1</sup> )
<i>SARM<sub>F,C,R</sub></i>	specific maintenance respiration rate (Mg C Mg C <sup>-1</sup> day <sup>-1</sup> )
<i>SBC</i>	Stefan-Boltzmann constant (=5.67 x 10 <sup>-8</sup> W m <sup>-2</sup> K <sup>-4</sup> )
<i>SE</i>	angular solar elevation (degree)
<i>SHM</i>	specific humidity of air (kg kg <sup>-1</sup> )
<i>SHR<sub>L,H</sub></i>	specific heterotrophic respiration rate (Mg C Mg C <sup>-1</sup> day <sup>-1</sup> )
<i>SLC</i>	solar constant (=1365 W m <sup>-2</sup> )

<i>SLD</i>	solar declination of the Earth's orbit (degree)
<i>SLF</i> <sub>F,C,R</sub>	specific litter fall rate (Mg C Mg C <sup>-1</sup> day <sup>-1</sup> )
<i>SLGS</i>	initial slope of the irradiance- <i>GS</i> curve (mol H <sub>2</sub> O mol <sup>-1</sup> photon)
<i>SLVP</i> <sub>SAT</sub>	slope of the saturated vapor pressure-temperature curve (hPa °C <sup>-1</sup> )
<i>SNA</i>	snow accumulation (mm)
<i>t</i>	time from sunrise (hours)
<i>T</i> <sub>OPT,MIN,MAX</sub>	optimum, minimum, and maximum temperature for photosynthesis (°C)
<i>TG</i>	ground surface temperature (°C)
<i>TNE</i>	annual total net CO <sub>2</sub> exchange (Pg C yr <sup>-1</sup> )
<i>TR</i>	plant transpiration rate (mm mon <sup>-1</sup> )
<i>TR</i> <sub>PM</sub>	potential transpiration estimated by Penman-Monteith equation (mm mon <sup>-1</sup> )
<i>TRF</i>	notation of tropical rain forest site
<i>TS</i> <sub>10</sub> , <i>TS</i> <sub>200</sub>	soil temperature at 10 cm and 200 cm depth (°C)
<i>TW</i>	snow thawing rate (mm mon <sup>-1</sup> )
<i>UGC</i>	universal gas constant (=8.3144 J mol <sup>-1</sup> K <sup>-1</sup> )
<i>VP</i>	vapor pressure of air (hPa)
<i>VP</i> <sub>SAT</sub>	saturated vapor pressure (hPa)
<i>VPD</i>	vapor pressure deficit of air (hPa)
<i>WA</i>	notation of water availability
<i>WE</i>	ecosystem carbon storage [= <i>WP</i> + <i>WS</i> ] (Mg C ha <sup>-1</sup> )
<i>WHC</i>	water holding capacity of soil (mm)
<i>WND</i>	wind velocity at 10 m height (m s <sup>-1</sup> )
<i>WP</i> , <i>WP</i> <sub>F,C,R</sub>	total, foliage, stem, and root biomass (Mg C ha <sup>-1</sup> )
<i>WS</i> , <i>WS</i> <sub>L,H</sub>	total, litter, and mineral soil carbon storage (Mg C ha <sup>-1</sup> )
<i>WTG</i>	notation of warm tall prairie site
<i>WUE</i>	water use efficiency of dry-matter production (g C kg <sup>-1</sup> H <sub>2</sub> O)
<i>ZAT</i>	absolute temperature at 0 °C (=273.15 K)
$\alpha$ <sub>1,2,3,4</sub>	parameters for <i>ALS</i> calculation
$\beta$ <sub>1,2,3</sub>	parameters for <i>SLVP</i> <sub>SAT</sub> and <i>VP</i> <sub>SAT</sub> calculation
$\chi$ <sub>1,2,3</sub>	parameters for <i>GS</i> calculation
$\delta$ <sub>1,2</sub>	parameters for <i>CD</i> <sub>CMP</sub> calculation
$\epsilon$	unit converter from $\mu$ mol CO <sub>2</sub> m <sup>-2</sup> s <sup>-1</sup> to Mg C ha <sup>-1</sup> day <sup>-1</sup> (=4.32x10 <sup>-4</sup> )
$\phi$ <sub>1,2,3,4,5</sub>	parameters for <i>SARM</i> <sub>C,R</sub> calculation

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