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_2 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_2 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_2 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^{-1} and 2150 Pg C, respectively (1Pg =10^{15} g). The contribution by C_3 and C_4 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=0.75~0.84).

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^{-1}, owing to atmospheric CO_2 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* (ΔNEP) was related to anomalies of climatic factors, and consequently it was found that ΔNEP was firstly influenced by anomalies of temperature and secondarily by precipitation. The responsiveness of ΔNEP 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 ΔNEP 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 ΔNEP variation.

Finally, Sim-CYCLE predicted the response of terrestrial carbon dynamics to global warming induced by atmospheric CO_2 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_2 increase (+1 % yr^{-1}). Two supplementary scenarios using the MRI-GCM were considered: MRIs including the effect of sulfate aerosols, and MRIh assuming a halved CO_2 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_2 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^{-1}. 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_2 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^{-1}, 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

Term	Definition (units)
AD	air density (kg m^{-3})
AE	notation of aerobic condition
AET	actual evapotranspiration (mm mon^{-1})
ALP	albedo, reflectance to short-wave radiation, of leaf surface (dimensionless)
ALS	albedo of soil surface (dimensionless)
AP	air pressure (hPa)
AP_0	sea-level air pressure at 20°C (=1013.25 hPa)
$APAR$	absorbed PAR energy by canopy (MJ m^{-2} yr^{-1})
AR	plant autotrophic respiration [$=ARM+ARG$] (Mg C ha^{-1} mon^{-1})
ARG, $ARG_{F,C,R}$	total and partial growth respiration (Mg C ha^{-1} mon^{-1})
ARM, $ARM_{F,C,R}$	total and partial maintenance respiration (Mg C ha^{-1} mon^{-1})
ASH	specific heat of air (=0.2813 J kg^{-1} $°C^{-1}$)
AT	altitude (m above sea level)
BLF	notation of boreal larch forest site
CD_{ATM}	atmospheric CO_2 concentration (ppmv)
CD_{CPM}	compensation CO_2 concentration for photosynthesis (ppmv)
CD_{ICL}	intercellular CO_2 concentration (ppmv)
CL	cloudiness (fraction of sky)
CV	convexity of water availability-evapotranspiration rate curve (dimensionless)
DAY (subscription)	notation of a dialy value
DC	daily cost to hold unit area of leaf (μ mol CO_2 m^{-2} day^{-1})
DI	dryness index related to runoff (mm)
DL	day-length (hours)
EC	eccentricity of the Earth's orbit ($EC^2=0.000669447$)
EP	effective photosynthate for biomass growth [$=GPP-ARM$] (Mg C ha^{-1} mon^{-1})
ESD	earth-sun distance (km)
ESD_0	annual mean ESD (=1.46 x 10^8 km)
EV	evaporation rate from soil surface (mm mon^{-1})
EV_{PM}	potential evaporation rate estimated by Penman-Monteith equation (mm mon^{-1})

F_{C3}, F_{C4}	fractional land coverage by C_3 and C_4 plants (fraction)
GA	aerodynamic conductance (mmol H_2O m^{-2} s^{-1})
GC	canopy conductance (mmol H_2O m^{-2} s^{-1})
GCM	General Circulation Model
GFDL	Geophysical Fluid Dynamics Laboratory (U.S.)
GG	ground conductance for evaporation from non-saturated soil (mm H_2O m^{-2} s^{-1})
GH	soil hydraulic conductivity (day^{-1})
GISS	Goddard Institute for Space Studies (U.S.)
GPP	gross primary production (Mg C ha^{-1}, yr^{-1} or mon^{-1} or day^{-1})
GS	leaf stomatal conductance (mmol CO_2 m^{-2} s^{-1})
HA	hour angle from sunrise to midday (degree)
HF	humus formation rate (Mg C ha^{-1} mon^{-1})
HR, $HR_{L,H}$	total and partial soil heterotrophic respiration (Mg C ha^{-1} mon^{-1})
HT	height of wind velocity data (m)
IBP	International Biological Programme
IC	rain interception by canopy (mm mon^{-1})
INS (subscription)	notation of an instantaneous value
IR	ratio of canopy intercepion (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 (ha ha^{-1})
LAI_{CML}	cumulative leaf area index, downward from the canopy-top (ha ha^{-1})
LAI_{OPT}	theoretically optimum leaf area index (ha ha^{-1})
LAT	site latitude (degree)
LF, $LF_{F,C,R}$	total and partial plant litterfall (Mg C ha^{-1} mon^{-1})
LH	specific latent heat of water vaporization (=2.5 MJ kg^{-1} H_2O)
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 mositure content (mm)
NCB	net carbon balance [=*NEP* - crop harvest] (Mg C ha^{-1} mon^{-1})
ND	day-number from the beginning of the year (days)

ND_{VE}	day-number of the vernal equinox (=80 days)
NDVI	normalized difference vegetation index
NEP	net ecosystem production [$=NPP - HR$] (Mg C ha^{-1} mon^{-1})
NPP	net primary production [$=GPP - AR$] (Mg C ha^{-1} mon^{-1})
PAR	notation of photosynthetically active radiation
PC	single-leaf photosynthetic rate (μ mol CO_2 m^{-2} s^{-1})
PC_{SAT}	light-saturated photosynthetic rate (μ mol CO_2 m^{-2} s^{-1})
PET	potential evapotranspiration (mm mon^{-1})
PN	soil water penetration from upper to lower layer (mm mon^{-1})
$PPFD_{IN}$	incident photosynthetic photon flux density at leaf surface (μ mol photons m^{-2} s^{-1})
$PPFD_{TOP}$	photosynthetic photon flux density at the canopy-top (μ mol photons m^{-2} s^{-1})
PR, $PR_{RAIN, SNOW}$	total, rain, and snow precipitation (mm mon^{-1})
PSC	psychrometer constant (=0.667 Pa K^{-1})
PT, $PT_{F,C,R}$	total and partial photosynthate translocation (Mg C ha^{-1} mon^{-1})
QE	quantum yield, photochemical light-use efficiency (mol CO_2 mol^{-1} photon)
QT	temperature sensitivity of respiration, Q_{10} (dimensionless)
RDG	direct short-wave radiation at the ground surface (W m^{-2})
RN	total net radiation [$=RNC + RNG = RN_L + RN_S$] (W m^{-2})
RNP	net radiation at plant canopy (W m^{-2})
RNS	net radiation at soil surface (W m^{-2})
RN_{LN}, RN_{ST}	long- and short-wave fractions of net radiation (W m^{-2})
RO	runoff (mm mon^{-1})
RFG	diffuse short-wave radiation at the ground surface (W m^{-2})
RTG	total solar radiation at the ground surface (W m^{-2})
RTT	total solar radiation at the atmosphere-top (W m^{-2})
RUE	radiation use efficiency of dry-matter production (g C MJ^{-1})
SA	seasonal angle of the Earth's orbit (degree)
$SARG_{F,C,R}$	specific growth respiration coefficient (Mg C Mg C^{-1})
$SARM_{F,C,R}$	specific maintenance respiration rate (Mg C Mg C^{-1} day^{-1})
SBC	Stefan-Boltzmann constant ($=5.67 \times 10^{-8}$ W m^{-2} K^{-4})
SE	angular solar elevation (degree)
SHM	specific humidity of air (kg kg^{-1})
$SHR_{L,H}$	specific heterotrophic respiration rate (Mg C Mg C^{-1} day^{-1})
SLC	solar constant (=1365 W m^{-2})

SLD	solar declination of the Earth's orbit (degree)
$SLF_{F,C,R}$	specific litter fall rate (Mg C Mg C^{-1} day^{-1})
$SLGS$	initial slope of the irradiance-GS curve (mol H_2O mol^{-1} photon)
$SLVP_{SAT}$	slope of the saturated vapor pressure-temperatur curve (hPa $°C^{-1}$)
SNA	snow accumulation (mm)
t	time from sunrise (hours)
$T_{OPT,MIN,MAX}$	optimum, minimum, and maximum temperature for photosynthesis (°C)
TG	ground surface temperature (°C)
TNE	annual total net CO_2 exchange (Pg C yr^{-1})
TR	plant transpiration rate (mm mon^{-1})
TR_{PM}	potential transpiration estimated by Penman-Monteith equation (mm mon^{-1})
TRF	notation of tropical rain forest site
TS_{10}, TS_{200}	soil temperature at 10 cm and 200 cm depth (°C)
TW	snow thawing rate (mm mon^{-1})
UGC	universal gas constant (=8.3144 J mol^{-1} K^{-1})
VP	vapor pressure of air (hPa)
VP_{SAT}	saturated vapor pressure (hPa)
VPD	vapor pressure deficit of air (hPa)
WA	notation of water availability
WE	ecosystem carbon storage [$= WP + WS$] (Mg C ha^{-1})
WHC	water holding capacity of soil (mm)
WND	wind velocity at 10 m height (m s^{-1})
WP, $WP_{F,C,R}$	total, foliage, stem, and root biomass (Mg C ha^{-1})
WS, $WS_{L,H}$	total, litter, and mineral soil carbon storage (Mg C ha^{-1})
WTG	notation of warm tall prairie site
WUE	water use efficiency of dry-matter production (g C kg^{-1} H_2O)
ZAT	absolute temperature at 0 °C (=273.15 K)
$\alpha_{1,2,3,4}$	parameters for ALS calculation
$\beta_{1,2,3}$	parameters for $SLVP_{SAT}$ and VP_{SAT} calculation
$\chi_{1,2,3}$	parameters for GS calculation
$\delta_{1,2}$	parameters for CD_{CMP} calculation
ε	unit converter from μ mol CO_2 m^{-2} s^{-1} to Mg C ha^{-1} day^{-1} (=4.32x10^{-4})
$\phi_{1,2,3,4,5}$	parameters for $SARM_{C,R}$ calculation

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