SEIB–DGVM v3.10sasa description (Last modified on 13 Sep 2023)

Written by Hisashi SATO (JAMSTEC)

### Important notes for this update

(1) The update from ver. 3.03 to ver. 3.10 corresponds to Sato *et al*. (2023), in which the SEIB-DGVM was adapted to a cold-temperate forest in the Northmost part of Japan. In Sato *et al.* (2023), one grid cell comprises 10 virtual forests that differ in CTI (The Composite Terrestrial Index) and simulates horizontal water movement among these virtual forests. However, due to its complexity, this public code does not contain the extension. Researchers who want to get the original code with the CTI extension, please contact Hisashi SATO.

(2) Following six woody PFTs were newly added.

PFT number, Description of the PFT (Abbreviate name), *Life\_type* number

10, Cold-temperate needle-leaved evergreen, Late-succession, (CTeNE1), 7

11, Cold-temperate needle-leaved evergreen, Middle-succession, (CTeNE2), 7

12, Cold-temperate broad-leaved deciduous, Early-succession, drought-tolerant (CTeBS1), 8

13, Cold-temperate broad-leaved deciduous, Early-succession, drought-intolerant (CTeBS2), 8

14, Cold-temperate broad-leaved deciduous, Late-succession, drought-tolerant (CTeBS3), 8

15, Cold-temperate broad-leaved deciduous, Late-succession, drought-intolerant (CTeBS4), 8

(3) Leaf metabolic properties (*Pmax*, *SLA*, *PNf*) of the newly introduced PFT are given as functions of leaf longevity. This procedure is conducted once a simulation year (L838-890 in main\_point.f90 and L845-893 in main.f90) because the relative light environment for each tree would also control these properties in upcoming updates.

(4) Soil wetness regulation in photosynthesis was changed, and three PFT-specific parameters were introduced: *Statwater\_opt*, *Statwater\_opt*, and *Statwater\_opt*. They are, respectively, optimum, minimum, and maximum *statwater* for photosynthesis (fraction). See equation A35 for the new regulation.

(5) C3草本をササ(dwarf bamboo)としてモデリングした。この変更に関係する箇所は青字で記載している。

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# Overview

### 1-1. General Structure

The SEIB–DGVM simulation unit is a 30 × 30-m spatially explicit virtual forest (the size of the virtual forest is specified by a parameter, *Max\_loc*) in which individual trees establish, compete, and die. Grass layer cells, which divide the forest floor by 10 × 10, also exist in the forest under the tree canopy (this resolution is specified by a parameter, *DivedG*). Appendix B1 shows the input and output of the model. Appendix B2 summarizes the processes represented, classified into physical, physiological, and vegetation dynamics. The SEIB–DGVM utilizes three computational time steps: a daily time step for all physical and physiological processes and an annual time step for vegetation dynamics and disturbance. Appendix B3 lists the symbols used in the model’s equations. Those that begin with a capital letter are constants, while those that begin with a lowercase letter are variables. Plant species are classified into plant functional types (PFTs) to enable global-scale simulation (Table 1). These PFTs can coexist in the same virtual forest.

### 1-2. Plant Functional Types (PFTs)

Detailed descriptions for PFT-specific features and parameters can be found in the papers of the following list.

BoND (Boreal Needle-leaved Deciduous PFT): Sato *et al.* (2009)

TrBE1~4 (Tropical Broad-leaved Evergreen PFTs, South-East Asia) Sato (2009)

TrBE5 (Tropical Broad-leaved Evergreen PFT, Africa) Sato & Ise (2012)

TrBR (Tropical Broad-leaved Rain green PFT) Sato & Ise (2012)

TeH (C3-type photosynthesis grass, 本拡張版ではササ) 本マニュアル

TrH (C4-type photosynthesis grass) Sato & Ise (2012)

CTeNE1~2 (Cold-temperate needle-leaved evergreen, East Asia) Sato *et al.* (2023)

CTeBS1~4 (Cold-temperate broad-leaved deciduous, East Asia) Sato *et al.* (2023)

Other PFTs Sato *et al.* (2007)

TrBE5 can only establish in the African continent. Only TrBE5 and TrBR are allowed to establish woody PFT in the African continent.

### 1-3. Plant structures

Woody PFTs are represented by individual trees composed of three organs: the crown and the trunk, both of which are cylindrical, and the fine roots, which are formless (Fig. 1). The crown is defined by biomass (*massleaf*), leaf area (*la*), diameter (*crowndiameter*), and depth (*crowndepth*); the trunk, by biomass (*masstrunk*), height (*height*), and the diameters of sapwood (*dbhsapwood*) and heartwood (*dbhheartwood*); the fine roots, by biomass (*massroot*) only. Trunk biomass (*masstrunk*) includes both branch and coarse root biomass. Besides these variables, each tree has a reserve resource (*massstock*), which is used for foliation after the dormant phase (for deciduous PFTs) and after fires (for all PFTs). Non-Structural-Carbon as the currency for every expenditure of trees is also available (*massavailable*). The representation of Grass PFTs is much simpler, consisting of a leaf, fine root, coarse root, and reserve resource, all represented by biomass per unit area (gmassleaf, gmassroot, gmasscroot, gmassstock, and *gmassavailable*, respectively). The grass layer divides the forest floor by 10 × 10 (A parameter *DivedG* specifies this resolution). While each grass cell in a virtual forest shares a common pool of soil water, it receives different intensities of sunlight, depending on tree leaves’ horizontal distribution.

# Material and Energy balances

### 2-1. Carbon cycles

Figure 2 provides an overview of the carbon cycle in the SEIB–DGVM. The foliage of woody PFTs and grass PFTs assimilates atmospheric CO2. This assimilated carbon goes to all other organs, where maintenance and growth respiration occurs. All respired carbon goes to the atmosphere as CO2. At the same time, defoliation at the end of the growing season, regular turnover of leaves and fine roots, and tree death produce litter flux. When the litter pool decomposes, some portion of the carbon within it is recycled into the atmosphere, while the remaining carbon goes to pools of soil organic carbon 1 (fast decomposition rate) or 2 (slow decomposition rate). Finally, decomposed soil organic carbon goes to the atmosphere as CO2.

### 2-2. Water cycles

Figure 3 provides an overview of the water cycle as represented in the model. The ground comprises 20 soil layers, of which the depth is equally 0.1m. Hydrological and radiation properties of soil are given by four grid-specific parameters, AlbedoSoil0, Wsat, Wfi, and Wwilt. Each parameter indicates soil albedo, soil moisture at saturation point, field capacity, and wilting point. Values for these parameters are from soil texture data in BIOME3 (Haxeltine & Prentice, 1996), which is based on the FAO soil data set (Zobler, 1986) (FAO, 1991). Water is stored on land surfaces as snow (poolsnow) or as water in soil layers i (poolw(i)). Liquid state surface water that is not infiltrated within a day immediately goes runoff water.

#### Daily water flow (in the order of computation)

Precipitation (*prec*) is divided into rainfall (*precrain*) and snowfall (*precsnow*) using empirical function of the daily mean temperature of air (*tmpair*) (Ito & Oikawa, 2002):

*precsnow* = *prec*/[ 1 + exp( 0.75 × *tmpair* – 1.5 ) ] (1)

*precrain* = *prec* – *precsnow*.(2)

Snowfall goes to the snow pool (*poolsnow*), which melts as a function of temperature at top soil layer (*tmpsoil(1)*):

Δ*poolsnow* = *precsnow* – *tw* (3)

*tw* = *poolsnow*/[ 1 + exp (–0.3 ( *tmpsoil(1)* – 10 ) ) ], (4)

where *tw* is daily snow melting water. A portion of the rainfall is caught by leaves, and evaporates before reaching the soil surface. The fraction of this intercepted rainfall is a function of the leaf area index (*lai* in m2 m–2).

*ic* = min [*precrain* , 3.0 × *rain* × ( 1.0 – exp(–1.0 × *lai*) ) ], (5)

where *rain* is expected number of rain in a day, which is calculated using method in Neilson (1995). From the above equations, the daily liquid water to reach the soil surface can be obtained as *precrain* + *tw* − *ic*.

#### Daily changes of the soil water storages (in the order of computation)

Daily input of liquid water on the ground surface will penetrate the top soil layer until it fulfills its saturation point if the temperature at the top soil layer is more than 0°C. The remaining water immediately washes off the surface as runoff. For each soil layer, soil water above field capacity percolates to the next soil layer until it fulfills its saturation point, while the remaining stays in the current layer. This vertical soil water movement only occurs when soil temperature at the current or next layer is less than 0°C. Soil water in the bottom soil layer cannot penetrate or run off. Plants can absorb soil water from unfrozen top *RootDepth* soil layers (10×*RootDepth* cm depth) until these wilting points, and they transpire absorbed water. Here, *RootDepth* is a PFT-specific parameter. Evaporation occurs only from water at the top 5 soil layers (0-50cm depth). Daily amounts of transpiration and evaporation were calculated using the Penman–Monteith equation (Monteith & Unsworth, 1990) (see Appendix A6 for detail).

For regulating leaf phenology and the photosynthesis rate as a function of soil water availability, the physiological status of water availability is defined as follows (statwater, 0.0–1.0):

*statwater*=.

Soil layers whose temperature is less than 0 °C, are omitted for this calculation. If the temperature is less than 0 °C for all soil layers within the RootDepth, statwater is assumed to be zero. For a TOPMODL-implemented version of the SEIB-DGVM (Sato *et al.,* 2023), *statwater* is further regulated by the deviation of the Topographical Wetness Index (TWI, or CTI) of the simulation stand to the grid averaged TWI. Refer to Sato *et al.* (2023) for detail.

### 2-3. PAR Allocation

For each simulation day, the radiation module of the SEIB–DGVM calculates direct and diffuse components of photosynthetically active radiation at midday (*pardirect* and *pardiffuse*, respectively) (see Appendix A2 for the calculation). Allocations of PARs among trees and grass controls plant growth and competition.

#### Woody PFTs

Each tree crown is horizontally sliced into 10-cm-deep 'disks,' for which photosynthesis is calculated separately (Fig. 1). The midday PAR that enters disk *l* of individual *n*, *parwood(l,n)*, is calculated as follows, where *fpardirect(l,n)* and *fpardiffuse(l)* represent the relative intensity of direct and diffuse PAR of disk *l* of tree *n* compared to the forest top, respectively:

*parwood(l,n)* = *fpardirect(l,n)* × *par direct* + *fpardiffuse(l)* × *par diffuse*. (10)

To obtain *fpardirect(l,n)*, a virtual cylinder with a cross-section equal to disk *l*, was extended from the disk to the direction of the south with angle *slhgt*, where *slhgt* is midday solar angle (Fig. 4). Then, the total leaf area falling within the cylinder, *fpardirect(l,n)*, was summed using Beer’s law as follows, where *la(p)* (in m2) is the sum of the leaf area of PFT *p* within the cylinder, *crownarea(n)* is the cross-section of the crown area of tree *n*, and *eK(p)* is the solar-angle adjusted light-attenuation coefficient of PFT *p*:

. (11)

In this calculation, the virtual forest was assumed to repeat; i.e., if the cylinder exited the forest edge at a lower position than the tallest tree, the cylinder would reenter the forest from the opposite edge at the same position in a west–east vertical plane. The calculation of *fpardirect(l,n)* is the most computationally power-consuming process in the model. Thus, this factor is updated in 14-day intervals.

As diffuse PAR scatters in the sky, we ignored horizontal structures in the forest while calculating its distribution; all disks at the same height receive the same intensity of diffuse PAR. The relative intensity of diffuse PAR on the disk layer *l*, *fpardiffuse(l)*, is calculated every day as follows, where *lai(l,p)* is the leaf area index (in m2 m-2), which is calculated only for PFT *p* and for leaves above disk layer *l*:

. (12)

#### Grass PFTs

The midday PAR that reaches the grass cell *i* (*pargrass(i)*)is calculated every day as follows, where *lai(p,i)* is the leaf area index of woody PFT *p* in grass cell *i*:

. (13)

As shown in the equation below, *eK(p)* is the light attenuation coefficient for the direction of the sun at midday. It is calculated every day as a function of the solar angle at midday *slhgt* (see Appendix A2 for the calculation) and the light attenuation coefficient for vertical direction *EK(p)*:

*eK(p)*= *EK(p)* / sin(*slhgt*). (14)

### 2-4. Integration with the NOAH-LSM

In the update from ver.2.80 to ver. 3.00, the SEIB-DGVM integrates the NOAH-LSM for mechanistically simulating thermo-hydrology. When the parameter "Flag\_land\_physics" in the parameter.txt file is set to ".false.", the calculation will be performed without using NOAH-LSM as in previous versions.

The main body of the NOAH-LSM is the "SFLXALL\_SRC\_VER\_2.7.1.f90" in the distribution package. It is obtained from the Web Site and has only been partially modified (such as input/output-related changes). The following URL is the source of the file: <ftp://ftp.emc.ncep.noaa.gov/mmb/gcp/ldas/noahlsm/>. All the modifications in this file are annotated with "Inserted by H. Sato."

A schematic diagram of the integrated model is available on the Fig. 5. Refer to Sato *et al.* (2016) for details on this integration. The followings are only essential points of this integration.

Important notes concerning the NOAH-LSM

1. Inputted soil temperatures will be only utilized if the NOAH-LSM is not activated. The default setting is “activated”.
2. NOAH-LSM requires temperature at its bottom soil layer at 2m depth, which is constant throughout the year. When it was implemented into the SEIB-DGVM with the assumption that it is equal to the annual mean temperature (the constant “TBOT” in the main\_point.f90). This assumption must be revised, especially for snowing regions, because snowpack insulates heat exchange between the atmosphere and ground.
3. The “DF1\_given”, thermal conductivity of the top soil layer, is calculated as a function of litter density. This function results from calibration for Eastern Siberia so that readjustment may be necessary for other biomes in the circum-Arctic region.
4. NOAH-LSM employs Zobler's soil types (GLOBAL SOIL TYPES, 1-DEGREE GRID); hence, Zobler's soil types are added in the global parameter file land\_prop.txt.

# 3. Physiology

### 3-0. Parameters

According to previous studies of vegetation modeling (Fisher *et al.* 2015), we relied on the spectrum for reducing arbitrariness in the parameter settings: *TOf*, determined *SLA* (m2 g DM−1), *PNf* (N gDM−1), and *Pmax* (μmol CO2 m−2 s−1) in line with the following empirical relationships (Reich *et al.* 1997).

### 3-1. Photosynthesis

To compute photosynthesis, the SEIB–DGVM assumes that environmental conditions other than PAR intensity (e.g., air temperature, CO2, and water) are equal among all the leaves all day. The single-leaf photosynthetic rate is formulated as a simple Michaelis-type function of the intensity of PAR, *par*:

. (15)

, where *psat* and *lue* are the light-saturated photosynthetic rate and light-use efficiency, respectively (see Appendix A4 for the calculation).

Woody PFTs

According to Kuroiwa (1979), a daily change in PAR can be approximated by a square sine function as follows, where *x* is PAR on crown disk *l* at time *t* (hours from sunrise), *parl* is the intensity of PAR at midday, and *dlen* is day length (hour):

. (16)

By combining equations 16 and 15 and integrating the resultant equation into day length, the daily photosynthetic production on crown disk *l*, *gpp(l)*, is obtained as follows, where constant 12∙10–6∙3600/0.41505 is the unit converter from [μmol CO2 m−2 s−1] to [g DM m−2 hour] and *lal* is the leaf area within crown disk *l*:

. (17)

Equation 17 delivers the daily photosynthetic production for each crown disk of each individual. These values are summed for each tree and then added to the NSC (available resource) of the tree, massavailable.

Grass PFTs

Grass leaves are assumed to be uniformly distributed within the grass cell. Thus, PAR of time *t* (hour from sunrise) at cumulative grass LAI *y* (m2 m–2) is calculated as follows, where *pargrass(i)* is PAR at the surface of the grass cell *i* at midday:

. (18)

By combining equations 18 and 15, and integrating the resultant equation into *t* and *y*, the daily gross primary production of the grass cell *i*, *gppg(i)*, is calculated as follows (Kuroiwa, 1979), where *laig(i)* is the leaf area index of the grass cell *i* (m2 m–2):

. (19)

The daily photosynthetic production piles up on the NSC (available resource) of grass cell *i*, *gmassavailable(i)*.

### 3-2. Canopy Conductance

To compute single-leaf stomatal conductance *gs*, the SEIB–DGVM adopts a semi-empirical model by Ball *et al.* (1987), modified by Leuning (1995), where *co2atm* is atmospheric CO2 concentration, *co2cmp* is the CO2 compensation point, and *vpd* is the vapor pressure deficit between saturated and actual vapor pressures:

. (20)

Here, GSb1, GSb2, and GSb3 are PFT-specific parameters. The model updates vpd, co2atm, and co2cmp daily, according to Appendix A1 and A4. For each crown disk *l* of each tree *n*, mean daytime stomatal conductance (*gsmean(l,n)* in mol H2O m−2 s−1) is obtained by combining equations 15, 16, and 20, and integrating the resultant equation into time *t*, averaged over the daytime:

 (21)

Thus, the mean daytime and whole forest stomatal conductance of woody PFTs, *cconwood* (in mol H2O m–2 s–1), is calculated as follows, where *AREA* is the area of the simulation plot (m2):

. (22)

The mean daytime stomatal conductance for grass PFTs, *ccongrass* (in mol H2O m–2 s–1), is obtained by combining equations 15, 18, and 20, and integrating the resultant equation into daytime and cumulative LAI.

 (23)

*ccongrass* is calculated for each grass cell and averaged for the plot. We defined the sum of cconwood and ccongrass as this plot's mean daytime stomatal conductance (ccon in mol H2O m−2 s−1).

### 3-3. Growth Respiration

For plants to grow, they require carbohydrates for their plant-body construction and biosynthesis. We define construction cost as the required biomass per actual growth (g DM g DM–1). Thus, the amount of growth respiration of organ o is (RGo − 1.0)∙Δmasso, where RGo is the construction cost of organ o, and Δmasso is the biomass increment of organ o. Construction cost can be estimated by combining data on the biochemical composition of organs with knowledge on the biochemical costs of synthesis of all the major compounds, including cellulose, hemicellulose, lignin, protein, lipids, and organic acids (Lambers *et al.*, 1998). Applying this method, Poorter (1994) collected biochemical composition data on various plant species and then estimated the construction cost of leaves (1.56, mean value of 123 species), stems (1.44, mean value of 38 species), and roots (1.34, mean value of 35 species). Our model employs these parameters with the following two modifications: for grass PFTs, ~~leaves and stems are grouped together as a 'leaf' and thus the two values are averaged (i.e., their collective construction cost is 1.50)~~ rods and coarse root are grouped together as stem (i.e., their construction cost is 1.44); the above parameters of Poorter (1994) are estimated mainly from grass species, so we employ 1.68 as the construction cost of a woody stem because lignin synthesis requires a high expenditure of energy. This value is from Penning de Vries (1975) but modified by changing the nitrogen source to NO3, as in Poorter (1994).

Individual tree and grass cells have stock resources, which are used for foliation after the dormant phase and after disturbance. In the model, 7% of the photosynthetic carbon is required for forming a unit amount of stock resource (RGstockin = 1.07). This conversion efficiency is from the calculation 1.19 × (0.400 / 0.444), where 1.19 is the primary photosynthetic product (as glucose) required for producing a unit amount of starch (Tanaka, 1983) and 0.400 and 0.444 are carbon mass within a unit mass of glucose and starch, respectively. However, no extra carbon is required when the stock resource is used (RGstockout = 1.00) because producing glucose from starch is simple enzymatic hydrolysis (Penning de Vries *et al.*, 1983).

### 3-4. Maintenance Respiration

In our simulations, maintenance respiration occurs every day irrespective of phenology phase. The carbohydrates required for maintenance respiration is first charged to the NSC and then the remaining requirements are charged to the stock resource. When the sum of these two resources of carbohydrate is not enough to cover the amount charged, 1% of the biomass of all of the living organs is removed. The removed biomass of sapwood changes to heartwood, while the removed biomass of other organs enters the litter pool. Note that maintenance respiration does not occur in heartwood or the stock resource.

For many plant organs, the maintenance respiration rate linearly correlates to the nitrogen content of living tissue (Ryan, 1991). Incorporating this tendency into our model, we calculate the daily maintenance respiration of an organ *o* as follows, where constant *RM* is the specific respiration rate at 15.0°C (g DM g N–1 day–1), *PNo* is the nitrogen content per biomass of organ *o*, *tmp* is air temperature for aboveground organs and soil temperature for underground organs (average soil temperature for soil layers at 0~0.50m depth), and *qt* represents the temperature sensibility:

. (24)

The temperature sensibility was formulated according to Yokota and Hagihara (1996) as follows:

*qt* = 2.0 × exp [–0.009 (*tmp* – 15.0)]. (25)

First, we estimated the nitrogen content of the leaves *PNf* for each PFT (Appendix B6) based on a data set from Wright *et al.* (2004). Then, assuming that the relative proportions of nitrogen in each organ for any particular PFT are linearly correlated, we calculated *PNs* and *PNr* as follows, where the coefficients 0.145 and 0.860 are employed by Friend *et al.* (1997):

*PNs* = 0.145 × *PNf* (26)

*PNr* = 0.860 × *PNf.*(27)

In the case of boreal needle-leaved deciduous trees (BoND), PNf was taken from an empirical regression equation by Reich *et al.*, (1997) assuming leaf longevity of three months because the data set of Wright *et al.*, (2004) does not contain a value of BoND. For PNs of BoNS, an actual measurement of 0.0014 was used (Schulze, 1995).

### 3-5. Turnover

To account for the turnover of organic matter, constant fractions of leaves and fine roots are transformed into the litter, while those of sapwood are transformed into the heartwood. This turnover occurs every simulation day, irrespective of the phenology phase. Appendix B6 shows the PFT-specific turnover rates of leaves TOf; the data set, which is from Wright *et al.*, (2004), does not contain a value for boreal needle-leaved deciduous trees (BoND), so the leaf turnover rate of BoND is assumed to be 4 year–1 (i.e., leaf longevity of three months). The fine roots turnover rate of (TOr) is taken from Gill & Jackson (2000). ササの粗根バイオマス(*gmasscroot*)は一斉枯死までTurnoverしないと仮定した。ササの稈バイオマスは、通常のturnoverに加えて、積雪深による制御も受けると仮定した：稈高が前年の最大積雪深を超えた部分を枯死させる（こちらはまだ未実装）。The turnover rate of sapwood TOs is assumed to be 0.05 year–1 for all PFTs, except for TrBE and BoNS. In the case of TrBE, a constant fraction of dbh (ALM5) was assumed to be sapwood, and the remaining fraction was considered heartwood. In the case of BoNS, sapwood diameter is assumed to be min[dbh, 0.0188] (in m).

### 3-6. Phenology

Every deciduous PFT in the model has two phenology phases: a growth phase and a dormant phase. Foliation and growth of deciduous PFTs only occur during the growth phase. The criteria for switching between the two phases and the procedure of phase change are followings.

#### From Dormant Phase to Growth Phase

Each PFT is classified into the following phenology types, which differ in sub-models. The computation time step for all sub-models is daily.

* Summer green broad-leaved woods (TeBS, CTeBS1, CTeBS2, CTeBS3, CTeBS4, BoBS)

One of the phenology control variables is gdd5Jan, which sums the daily mean air temperature above 5°C starting on 1 January (for the northern hemisphere) and 1 July (for the southern hemisphere). Trees change from the dormant phase to the growth phase when gdd5Jan exceeds −68 + 638 × exp(−0.01 × i), where i is the sum of the days for which the mean air temperature is below 5°C, starting on 1 November (for the northern hemisphere) and 1 May (for the southern hemisphere). Thus, the number of cold days affects the days required for phenology change. This sub-model is from Botta *et al.*, (2000), which is based on the distribution of leaf onset date estimated from remote sensing data. We also assumed that the day of the year (doy) of the switch is within the range of ‘latitude + 30’ to ‘latitude + 130’ for the northern hemisphere and ‘212 − latitude’ to ‘312 − latitude’ for the southern hemisphere.

One of the phenology control variables is *gdd5Jan*, which sums the daily mean air temperature above 5°C starting on 1 January (for the northern hemisphere) and 1 July (for the southern hemisphere). Trees change from the dormant phase to the growth phase when *gdd5Jan* exceeds −68 + 638 × exp(−0.01 × *i*), where *i* is the sum of the days for which the mean air temperature is below 5°C, starting on 1 November (for the northern hemisphere) and 1 May (for the southern hemisphere). Thus, the number of cold days affects the number of days required for phenology change. This sub model is taken from Botta *et al.*, (2000), which is based on the distribution of leaf onset date estimated from remote sensing data. We also assumed that the day of the year (*doy*) of the switch is within the range of ‘latitude + 30’ to ‘latitude + 130’ for the northern hemisphere, and ‘212 − latitude’ to ‘312 − latitude’ for the southern hemisphere.

* Summer green needle-leaved woods (BoNS)

The foliation phase starts when the conditions are satisfied: “soil temperature at 10cm becomes greater than 5°C” and “accumulated daily mean air temperature becomes greater than 100°C the day after the daily mean air temperature is beyond 0°C”. We took this parameterization from the following literature from Yamazaki *et al.*, (2007).

* Raingreen woody PFT (TrBR)

When 10 day running average of *statwater* exceeds 0.0, the dormant phase changes into the growth phase.

* Grass PFTs (TeH, TrH)

When the optimum leaf area index (*laiopt*; formulas described in the section titled 'Growth Procedure of Grass PFTs') exceeds 0 for preceding 7 days, the dormant phase changes into the growth phase. For the first 14 days (7 days for BoNS, 30 days for TrH) of the growth phase, all stock resources are consumed and transformed into available resources at a constant rate. For grass PFTs, this transformation paused when the optimal leaf area index, laiopt, is attained.

From Growth Phase to Dormant Phase

At 60 days after the leaf onset date, leaf phenology can change to the dormant phase. At the beginning 14 days of the defoliation phase, all leaves transform into litter at a constant rate. When plants lose all leaves, the deficit is supplemented from the litter pool if the stock resource does not satisfy the minimum value (100 g individual–1 for woody PFTs, 50 g m–2 for grass PFTs). Each deciduous PFT has a distinct condition to change from the growth phase to the dormant phase. Irrespective of these conditions, all deciduous woody PFTs enter to dormant phase after 300 days from the first leafing day. When a grass PFT does not satisfy the condition, it acts as a de facto evergreen PFT.

* Temperate and Cold-temperate summer green broad-leaved woods (TeBS, CTeBS1, CTeBS2, CTeBS3, CTeBS4)

The phenology phase is declared dormant if the 10-day running mean of air temperature falls below 9°C or below the 10-year running mean of the coldest month temperature + 5°C.

* Boreal summer green broad-leaved woods (BoBS)

The phenology phase is declared dormant if the soil temperature falls below 2°C. This criterion is from Arora & Boer (2005).

* Boreal summer green needle-leaved woods (BoNS)

When 10 days of running average mean air temperature becomes less than 7 °C, and the leaf defoliation phase occurs, which lasts 14 days. During the defoliation phase, all leaves transform into litter at a constant rate.

* Raingreen woody PFT (TrBR)

The phenology phase is declared dormant when 10 day running average of statwater falls below 0.0.

* Grass PFTs (TeH, TrH)

The phenology phase is declared dormant if the optimum leaf area index (laiopt) falls below 0 for the preceding 7 days. ササは休眠期に入らないと仮定した。

### 3-7. Soil Respiration

The decomposition of litter and soil organic carbon occurs every simulation day. The SEIB–DGVM employs the soil respiration module of the DEMETER-1 (Foley, 1995) with some simplifications. The mean turnover rate of litter at 20°C and ample soil moisture is assumed to be 3/10 year−1. 70% of the decomposed litter carbon goes to the atmosphere as CO2, and the remaining 30% becomes soil organic carbon. The partitioning coefficients for soil organic carbon flowing into the fast and slow decomposition pools are 0.985 and 0.015, respectively. According to Foley (1995), the mean turnover rates for the fast and slow soil organic carbon (*TOfast*, *TOslow*) at 20°C and ample soil moisture are 1/15 year−1 and 1/750 year−1, respectively.

Actual daily turnover rates (*kn* day−1), which are adjusted by soil environment, are approximated as follows, where g and f are functions of the monthly mean soil temperature (averaged for 0~0.50m depth) and moisture, respectively:

 (42)

These functions are defined as follows:

(43)

 (44)

In Foley (1995), the temperature effect g (*tmpsoil*) is an exponential function. However, this underestimates the soil turnover rate for cold regions, and thus we employ the function of Lloyd & Taylor (1994). All decomposed soil organic carbon goes to the atmosphere as CO2.

# 4. Plant population dynamics

### 4-1. Establishment of Woody PFTs

The model establishes new individual trees on the last day of each simulation year. Tree establishment only occurs if the total precipitation of the current year (in mm) exceeds 20 times the annual mean temperature (in °C) (Köppen, 1936). Each woody PFT has a distinct climatic range for the establishment, following the LPJ–DGVM (Sitch *et al.*, 2003): the maximum coldest-month temperature (TCmax), and the minimum growing-degree day (GDDmin), as shown in Appendix B5. All climatic limitations are applied to the running means of the last 20 years. All climatic limitations are multiplied by a random factor that uniformly distributes 0.9-1.1 for reducing the sharpness of the climatic envelopes.

For some PFTs, we assumed that they could only establish when the midday photosynthetically active radiation (PAR, hereafter) that is computed for each grid cell on the surface of the grass layer and averaged for the previous year exceeded PARmin (in μmol photon m–2 s–1). For some PFTs, we additionally assumed that they could not establish when drought month (monthly potential evapotranspiration is more than monthly actual precipitation) existed more than DMmax month in the previous year. For BoNS, we assumed that the establishment could only occur within 50 years after wildfire.

We calibrated bioclimatic limits for reproducing the geographical distribution of woody PFTs in the African continent. TrBE5 and TrBR can only establish if the dry months in the previous year are more than 4 and 9 months, respectively. Here, the dry month is defined as the month whose precipitation is less than potential evapotranspiration calculated by the Priestley-Taylor model with a coefficient of 1.26 (Rosenberg *et al.*, 1983).

All newly established trees have 0.01 m of dbhsapwood, 0.00 m of dbhheartwood, and 0 m of lowest-branch height (i.e., height = crowndepth). From these properties, tree height (height), crown diameter (crowndiameter), and stem biomass (masstrunk) are calculated using allometric and allocation formulas described in the section titled 'Tree growth.' These newly established trees initially lack leaves and fine roots, but have 250 g DM of reserve resource (massstock) and 250 g DM of available resource (massavailable). The available and stock resources, respectively, presume sucrose (soluble carbon-hydrate) and polysaccharide (non-soluble carbon-hydrate). Convert efficiency from available to the stock resource is defined by RG\_stock\_in, and that from stock to available resource is defined by RG\_stock\_out. The biomass of newly established trees is taken from the litter pool of the same forest so that the total carbon storage of the forest remains the same.

A grid of 1.0 × 1.0–m mesh (A parameter Dived specifies this resolution) composes the floor of the virtual forest, and each tree monopolizes one of the mesh boxes. The SEIB–DGVM assumes that crowns of different trees cannot occupy the same space, and thus mesh boxes in which a newly established tree interacts with existing trees are not available for further establishment. The same establishment rate, Pestablish, was assumed for each available mesh box.

There are four scenarios to allocate available mesh boxes to woody PFT that can establish under the given climate. For changing the establishment scenario, modify Est\_scenario in the parameter file.

**Scenario 1** (one specific PFT establish): Only one woody PFT, which is specified by *Est\_pft\_OnOff* in the parameter file, can monopolize the available mesh box.

**Scenario 2** (infinite seed dispersal): All woody PFTs that can establish at the given climatic conditions share the available mesh box equally.

**Scenario 3** (no seed dispersal): Same as scenario two until specific year Est\_year\_change in the parameter file. After that, allocate available mesh boxes among each woody PFTs in proportion to existing biomass at the forest stand.

**Scenario 4** (Scenario 3 + long migrated seed): Same as the scenario 2 until year Est\_year\_change. After that time, available boxes are allocated to deterministic and stochastic establishment components in proportion to 1.0−EstRandom and EstRandom, respectively. EstRandom determines the fraction of establishment cells allocated to the stochastic establishment. The deterministic establishment only occurs when the mean biomass of woody PFT in the virtual forest was more than 100g dry mass (DM) m−2: It implies that we assumed that the deterministic establishment only occurs when a certain amount of seed production is expected in the virtual forest: Available mesh boxes for deterministic establishment were allocated in proportion to the biomass of each woody PFT. Available mesh boxes for stochastic establishment were equally allocated to all woody PFTs that can establish under the given environment.

### 4-2. Establishment of Grass PFTs

For grass PFTs, establishment processes are not treated explicitly. A small amount of grass 'seed' is always assumed to be present, even if the environment is unfavorable to grass survival; densities of grass biomass (gmassleaf, gmassroot, gmasscroot, and gmassstock) never decrease below their minimum limits (0.1 g m-2 for each pool).

One of the two grass PFTs, namely C3 or C4 grass, monopolizes the floor of the virtual forest. At the end of each year, the dominant grass type is determined as follows: For each grass growing month (mean air temperature is more than 5.0 C °, and precipitation is more than 25 mm month-1), the advantageous grass type is decided. C4 grass type is advantageous if the monthly mean air temperature is more than 1.0 / [1.0 / (x-10.0) + 1 / 68.0], where x is the partial pressure of atmospheric CO2 (Pa). C3 grass type is advantageous in other cases. The source of this equation is the Figure 1b of Collatz et al., (1998). If the C4 advantageous month is more extensive than the C3 advantageous month, the C4 grass type will dominate the following year, and *vice versa*. ササ拡張版の場合は常にC3草本が優占すると仮定した。

When the dominant PFT changes, the biomass properties (gmassleaf, gmassroot, and gmassstock) of the previously dominated grass PFT are assigned those of the newly dominated grass PFT so that the total grass biomass of the plot remains the same.

### 4-3. Growth procedure of woody PFTs

The growth process of woody PFTs consists of four procedures, which differ in computation time steps.

Dynamic carbon allocation (daily computation)

During the growth phase, while resource availability (*massavailable*) is greater than 0, the following procedures are executed for each individual tree every simulation day.

(1) If the fine root biomass (*massroot*) is less than is required by the functional balance (*massleaf*/*FRratio*), the deficit is supplemented from *massavailable*. *FRratio* is the ratio of leaf biomass to fine root biomass satisfying the functional balance.

(2) The stock resource (*massstock*) is supplemented until it becomes equal to the existing leaf mass (*massleaf*). However, this step is skipped for the first 30 days of the growing season.

(3) Foliation. There are three constraints on the maximum leaf biomass for each individual: crown surface area (*max1*), cross-sectional area of sapwood (*max2*), and available resource (*max3*). These maximum values (in g DM) are defined as follows:

*max1* = (*crownarea* + π × *crowndiameter* × *crowndepth* ) × *LAmax*/*SLA* (default, 28)

*max1* = *crownarea* × *LAmax*/*SLA* (for TrBE, 28`)

*max1* = ∞ (for BoNS, 28``)

*max2* =  (Default, 29)

*max2* = ∞ (for TrBE1~5, TrBR, 29`)

*max2* = 330 × 50580 *dbh*2 (for BoNS, 29``)

*max3* = *massavailable*/*RGf*,(30)

where the constant *SLA* is the PFT-specific leaf area per unit biomass (Appendix B4).  SLA is primarily from data of Wright *et al.,* (2004), but it does not include a value for boreal needle-leaved deciduous trees (BoND); thus, the SLA value for this type is derived from an empirical regression equation from Reich *et al.,* (1997), assuming a leaf longevity of three months. LAmax is the PFT-specific maximum leaf area per unit crown surface area, excluding the bottom soffit. ALM1 is a constant representing the required area of transport tissue per unit leaf area (Shinozaki *et al.,* 1964a,b). If the current leaf area is less than the min[max1, max2, max3], the deficit is supplemented from massavailable. However, the maximum daily increment of leaf area is assumed to be 10% of the crown surface area.

In the case of TrBE1~5, TrBR, and BoNS, a negative-daily-NPP (net primary production) at the lowest crown layer suspends new foliation.

(4) The remaining daily computations (procedure 5~6) continue unless satisfying the following conditions.

* Annual NPP is less than 10 gDM/tree per year in the previous year.
* Available resource is less than 10.0 gDM/tree.

(5) Reproduction: If total woody biomass is more than 10 kg DM (which defines the minimum tree size for reproduction), 10% of the available resource (massavailable) is transformed into the litter.

(6) The final step of the daily growth procedure is trunk growth. All of the remaining resource (except 10g DM/tree, which is for a ‘buffer’ resource for other daily metabolic costs) goes to the growth of sapwood biomass (masssapwood). There is no direct allocation to heartwood, which is produced indirectly by slowly converting sapwood. In the case of TrBE and BoNS, the resource for producing trunk is diminished by multiplying the following diminishing factor:

, [for TrBE1~4]

, [for BoNS]

where *gppmonth* is monthly GPP for each individual treeand *DBHlimit* is the PFT-specific maximum *dbh* (m). This equation assumes that the stem growth efficiency decreases when *dbh* approaches its maximum limits. The reduced resource goes to maintenance respiration.

Increments in sapwood biomass accompany growth in sapwood diameter (dbhsapwood) and trunk height (height). These increments (∆dbhsapwood and ∆height) must satisfy the following two trunk mechanics.

(A) Trunk mechanics 1: A relationship between trunk biomass and trunk geometry. Trunk biomass, a function of tree height (*height*) and trunk diameter, is calculated as follows, where *ALM3* is dry mass per unit timber volume (in g DM m–3):

*masstrunk* =  [Default]

 [for TrBE1~4]

 [for TrBE5, TrBR]

 [for BoNS]

The value of ALM3 for TrBE and BoNS are from Huth & Ditzer (2000) and Schulze *et al.,* (1995), respectively. Other broad-leaved PFTs and evergreen needle-leaved PFTs were calculated by averaging 46 broad-leaved woody species and 24 needle-leaved woody species from Japan; the data were from a table in The Handbook of Wood Industries (FFPRI, 1982). It should note that the table excluded pioneer woody species, which typically produce low-density timber, and that the SEIB–DGVM assumes that the trunk has a cylindrical shape that extends to the top of the crown (Fig. 1). Thus, the estimated trunk biomass (from default equation) should exceed the actual biomass for the same trunk diameter at the bottom with tapered trunk shape; however, because the model includes branches and coarse roots as trunk biomass, this simplification might be justified.

(B) Trunk mechanics 2: a relationship between trunk diameter and maximum tree height for that diameter, calculated as follows, where the parameters *HGTs* and *HGTmax* are the initial growth slope and the maximum tree height for an infinite trunk diameter, respectively:

. (32)

In the model, the crowns of different trees cannot occupy the same space. Thus, when the crowns of neighboring trees interfere with tree height, only the trunk diameter expands.

Expansion of a cross-section area of the crown (daily computation)

Crown expansion occurs under the following constraints:

[Default]

[for TrBE1~4 (*dbh*<0.2)]

[for TrBE1~4 (*dbh*≥0.2)]

[for TrBE5, *TrBR*]

[for Cold-temperate trees]

[for BoNs]

These equations for default, BoNS, and TrBE are based on inversion of Reineke's rule (Zeide, 2001), forest inventory data (Yabuki personal communication), and Köhler & Huth (1998), respectively. The crown size has additional constraints: it can neither (1) exceed its maximum limit (*CDmax*) nor (2) expand into neighboring crowns nor (3) increased its horizontal area more than 50% within a year.

Crown depth adjustment (annual computation)

On the last day of each year, the height of the lowest branch increases due to purging crown disks, or self-pruning of branches, at the bottom of the crown layer. This procedure occurs even if the tree is in the dormancy phase. A maximum of 10 crown disks can be pruned at one time, each at a depth of 10 cm.

We first calculate the annual GPP for each crown disk to determine the number of crown disks to purge. First, the mean of the GPP for each of the 10 crown groups (1–10 successive disks from the crown bottom) for each tree is calculated. Then, these values are divided by the GPP of the top crown disk of each tree, and then the fraction is used to select disks for purging. Those with fractions less than ALMcrown2 are to prune; of these, the group that includes the largest number of crown disks is to prune. Besides, pruning is also under the control of crowndepth, which must always exceed 10 (i.e., >100 cm). Once a crown disk prunes, it cannot be restored (i.e., the height of the lowest branch cannot decrease).

In the case of TrBE1~5 and TrBR, crown depth (m) is proportional to tree height. The crown depth to tree height (m) ratio, *ALMcrown3*, was from Huth (1998) for TrBE1~4. While *ALMcrown3* of TrBE5 and TrBR are assumptions. In the case of BoNS, crown depth (m) is assumed to be min [10, *height*]. In the case of BoNS, a crown vertical depth was assumed to be 10 m. For trees less than 10m tall, a crown starts from 1.3m aboveground height.

Crown horizontal location adjustment (annual computation)

On the last day of each year, the crown center moves horizontally toward the most open direction. This crown movement represents trees extending their branches into open and bright spaces. Without introducing this plasticity, interference among crowns severely limits the number of tall trees because crowns of different trees cannot occupy the same space in the SEIB–DGVM. The maximum speed of crown movement is assumed to be 20 cm year−1, and the maximum distance of the movement is equal to half of the crown radius (i.e., the distance between the bole and crown centers is less than half of the crown radius).

### 4-4. Growth Procedures of Grass PFTs (Daily Computation)

While resource availability (*gmassavailable*) is greater than 0 during growth phase, the following procedures are executed every simulation day.

(1) If root biomass (*gmassroot*) is less than that required by the functional balance (*gmassleaf*/*FRratio*), the deficit is supplemented.

(2) The stock resource (*gmassstock*) is supplemented until it becomes 1.3 (a tuning parameter) times the existing leaf biomass (*gmassleaf*). This step starts after the first 30 days of the growing season.

(3) The leaf biomass (*gmassleaf*) is supplemented until the leaf area index of the PFT (*laig*) reaches a weekly running mean equal to the optimal leaf area index *laiopt*, which maximizes daily net primary production, *gppg* – *cost* × *laig*/*SLA* (derived from equations 19 and 34). This variable is calculated as follows, where *cost* is the cost of maintaining leaves per unit leaf mass per day (see equation 34 for the definition):

. (36)

(4) All remaining resource (*gmassavailable*) is used for reproduction and then transformed into the litter pool. This step starts after the first 30 days of the growing season if the stock resource exceeds 100 g DM m–2.

(5) ササ版の場合は上記ステップ4を実施せずに、*gmasscroot* / *gmassrod* = 0.55 となるまでcoarse root (*gmasscroot*)が生産され、その時点の余剰資源（*gmassavailable*）を全てrod (*gmassrod*)の生産に割り当てる。

### 4-5. Mortality (except death by fire and gap formation)

Mortality is explicitly modeled only for woody PFTs. On the last day of each simulation year, each tree's overall death rate is calculated as a sum of mortality components: background mortality, heat stress, and bioclimatic limit. Most of these components are from the LPJ–DGVM (Sitch *et al.*, 2003). In addition, if the annual NPP of the previous year is negative, (1) background mortality is multiplied by 10 times for African woody PFTs, (2) the same background mortality will be applied for BoNS, while (3) other woody PFTs will die by 10% year-1. Besides, a 5% year-1 death rate is assumed for trees whose annual NPP per crown cross-section area is less than 10gDM/yr/m2. A tree dies if the trunk diameter exceeds the PFT-specific limitation, defined as the DBH limit in the parameter.txt. Finally, newly established trees do not die in their first 2 years to stabilize the establishment process.

Background mortality is related to growth efficiency, a sensitive indicator of resistance to environmental stress (Warning, 1983). Although there is no standard formula for background mortality, the model assumes the following, where anpp is the annual sum of net primary production (g DM), lamean is the mean leaf area of the previous year (m2), and M1 (≤1.0) and M2 (≥1.0) are PFT-specific mortality coefficients:

. [Default]

In the case of TrBE1~4, background mortality is modeled as a function of the annual incremental increase of *dbh* (*∆dbh* in m yr-1), which was regressed from Table 3 of Huth & Ditzer (2000) (r2 = 0.98) as follows:

 [for TrBE]

This carbon balance mortality is multiplied by 8.0 for TrBE3.

Mortality by bioclimatic limit restricts the climate range in which each woody PFT can survive. If the 20-year mean of the coldest month temperature is less than the PFT-specific limit *TCmin*, all individuals of the PFT die at the probability of 10% per year. Boreal needle-leaved summergreen trees (BoNS) have an additional bioclimatic limit: if the 20-year mean of (warmest–coldest monthly air temperature) is less than 43°C, all trees of the PFT die at the probability of 10% per year. Biomass of dead trees is forming new litter.

### 4-6. Disturbance by Fire (default, daily computation)

We employed the global fire model of Thonicke *et al.*, (2001), which was developed for the LPJ–DGVM. On the last day of each simulation year, if the fuel load (litter + aboveground biomass) satisfies the minimum threshold (200 g C m–2), the probability of fire is calculated as a function of moisture fraction in the fuel, *θ*, as follows:

’ (39)

, where variable *s* is

. (40)

Variable *me*, considering the difference in fire extinction efficiency between woody and grass PFTs, is defined as 0.3 × (aboveground biomass of trees/total aboveground biomass) + 0.2 × (leaf biomass of grass/total aboveground biomass). Here, the moisture fraction of the fuel, *θ*, is assumed to be half of the moisture fraction in the top soil layer (0-50cm depth). The model also assumes that fire cannot occur in two consecutive years.

The fraction of individuals killed in a fire depends on PFT fire resistance (M3, Appendix B5). During a fire, all leaf biomass of grass, all leaf biomass of dead and surviving trees, half of the trunk biomass of dead trees, and half of the litter pool are released into the atmosphere as CO2, while the remaining biomass of dead trees goes to the litter pool. In response to fire, the phenology phase of all grass PFTs changes to dormant (they reenter the growth phase as described previously in the section titled ‘Phenology’). If the stock resource of grass PFTs (gmassstock) does not satisfy the minimum value (50 g DM m–2) after a fire, the litter pool supplements the deficit.

### 4-7. Disturbance by Fire (for African continent, daily computation)

Wildfire frequently occurs in African savannas, leading to tree and grass death and litter consumption. For simulations of the African continent, we introduced a fire sub-model of aDGVM (Scheiter, 2009) with some simplifications. This sub-model is a semi-empirical model based mainly on data from southern African studies of savanna.

The litter pool comprises three pools: a standing dead mass of tree leaves, a standing dead mass of grass, and a lying dead mass. The litter flux from tree leaves was first added to the “standing dead mass of tree leaves,” and the litter flux from grass aboveground biomass was first added to the “standing dead mass of grass.” Both standing-dead pools convert into “lying dead mass” at 0.075% per day. Besides reclassifying litter pools with different combustibility, all litter pools decompose with the same function of soil moisture and air temperature (Sato, 2007).

For each grass cell, the potential energy intensity on the fire line (*ifire* in J s−1m−1) is estimated as a function of the fuel load in the grass cell (*fuel* in gDM m−2), the fraction of fuel moisture (*θ*), and the wind speed (*wind* in m s−1):

*ifire*(*fuel*, *θ, wind*) = 16890 ×

Here, 16890 is the typical heat yield when fuel is consumed (in J g−1); 119.7 and 301 are coefficients; and 2.6 × 103 and 1.61× 105 are the preignition heat of moisture and fuel (in J g−1), respectively. The first parenthetic term is the weight of fuel consumed (in gDM m−2), and the second is the rate of fire spread (in m s−1). These coefficients and fuel preignition heat are estimated from field observations during data collection campaigns conducted in grassland and savanna in South Africa.

For estimating the *fuel* and *θ*, the fuel load was divided into living (moist) fuel *fuelliving* and dead (dry) fuel *fueldead*.

*fuel* = *fuelliving* + *fueldead*

Living fuel, *fuelliving*, is the sum of the aboveground grass biomass, *gmassleaf*, and one-half of the standing dead mass of grass, . Dead fuel, *fueldead*, is the sum of lying dead mass, *fuellying*, and one-half of the grass standing dead mass, .

*fuelliving* = *gmassleaf* + 0.5 × 

*fueldead* = *fuellying* + 0.5 × 

The moisture content of living fuel is assumed to be equal to the relative air humidity, *rh*. The moisture content of dead fuel is assumed to be 0% because it quickly decreases with an exponential function (Higgins, 2000). Hence, average fuel moisture, *θ*, is given as follows:



For the occurrence of a fire, the stand average of the potential fire intensity, ifire, must exceed a minimum intensity of 300 kJ s−1 m−1 (van Wilgen, 1997). When this condition is satisfied, the probability of fire in a day is 0.0015 (Scheiter & Higgins, 2009). This probability is reduced by 80% and 100% if the fraction of the tree canopy coverage of the stand (0.0–1.0) is 0.40–0.65 and 0.65, respectively (Archibald *et al.*, 2009). This reduction imitates a phenomenon where the fuel load in tree stands with high canopy coverage is shaded and dries out more slowly. The fire sub-model works every simulation day.

Fire consumes all the aboveground grass biomass, standing dead mass of grass and tree leaves, lying dead mass, and half of the trunk litter. Fire changes grass phenology to dormant. Fire also causes tree mortality. Following (Higgins, 2000), tree mortality due to wildfire is an empirically derived function of tree height, height (m), and fire intensity, ifire, of the tree standing grass cell.

*mortfire*(*height*, *ifire*) =,

where the coefficients *d1*, *d2*, and *d3* are 4.3, 5.003, and 0.004408, respectively.

### 4-8. Disturbance by Gap formation

When the biome type is tropical rainforest, the following computation is conducted. When a large tree (height > 25 m) dies, gap formation (falling trees knock over healthy trees) occurs at a probability of 0.20. This incident kills trees within the gap at the tree height-specific probabilities: 0.3 for trees of 1.3~15 m height, 0.6 for trees of 15~25 m height, 0.8 for trees of 25~36 m height, and 0.4 for trees >36 m height. These formulations are based on those of FORMIX3 (Huth & Ditzer, 2000). Hence, to match the 20 × 20-m square gap size in FORMIX3, a circular-shaped gap of 11.3-m radius was assumed to appear in a random location within the virtual forest.

### 4-\*.ササの一斉開花

70年に1度、ササの一斉開花が生じる。この場合、全ての草本バイオマスがリターに変換される。

# Appendix A

### A1. Atmospheric environments (computed daily)

Atmospheric conditions were calculated daily based on input climate data. Air pressure (*ap* in hPa) was approximated by site altitude (*ALT* in m) and air temperature (*tmpair* in °C ):

, (A1)

where the multiplier 1013.25 is the control air pressure (in hPa) at sea level at 15°C, and the multiplier 8.3144 is the universal gas constant (in J mol−1 K−1). Actual vapor pressure (*vp* in hPa) was a function of air pressure *ap* and humidity *humid* (g g–1):

, (A2)

The saturated vapor pressure *vpsat* (hPa) was given by Tetens' equation:

 ( *tmpair* > 0.0 ) (A3)

 ( *tmpair* ≤ 0.0 ). (A4)

The vapor pressure deficit *vpd* (hPa) is the difference between saturated and actual vapor pressures:

*vpd* = *vpsat* – *vp*. (A5)

The slope of saturated vapor pressure *slopevps* (hPa ºC−1) is:

 (*tmpair* > 0.0) (A6)

 (*tmpair* ≤ 0.0) (A7)

The density of air *dnsa* (kg m−3) is:

. (A8)

### A2. Solar radiation (computed daily)

Angular solar elevation above the horizontal at midday (*slhgt*) was calculated by the following equations:

sin(*slhgt*) = sin(*LAT*) × sin(*sldec*) + cos(*LAT*) × cos(*sldec*), (A9)

where *LAT* is the site latitude (−90 ≤ *LAT* ≤ 90 in degree) and *sldec* is the solar declination of the earth's orbit in degrees. *sldec* has a maximum value of 23.4 on the summer solstice, and a minimum value of −23.4 on the winter solstice, and a value of 0 on equinox days; thus, it can be approximated by the following equation:

*sldec* = 23.4 sin( 360×(*doy*−81)/365 ), (A10)

where *doy* is the days of the year (1–365, ignoring leap years). Using *sldec*, the hourly angle of the sun from sunrise to midday can be calculated as arccos( −tan(*LAT*) × tan(*sldec*) ); thus, the day length in hours (*dlen*) will be:

*dlen* = 2 [ arccos(−tan(*LAT*) × tan(*sldec*) )/15 ]. (A11)

Incoming shortwave radiation at the top of the atmosphere at midday (*radintact* in W m–2) is a function of *slhgt*:

*radintact* = 1367 × sin(*slhgt*) × (*ESDmean*/*ESD*)2, (A12)

where the multiplier 1367 is a solar constant (in W m–2), *ESD* is the distance between the sun and the earth (in km), and *ESDmean* represents the annual mean *ESD* (=1.46∙108 km). (*ESDmean*/*ESD*)2 can be approximated by:

(*ESDmean*/*ESD*)2 = 1.000111 + 0.034221 cos(*x*) + 0.00128 sin(*x*) + 0.000719 cos(2*x*) + 0.000077 sin(2*x*), (A13)

where *x* is the seasonal angle of the earth's orbit ( *x* = 360 × *doy*/365 ). In the troposphere, the incident solar radiation *radintact* (W m−2) is attenuated by clouds and airborne particles. Fraction of *rad* (downward shortwave that reaches to the biosphere, in W m−2) to *radintac*t alters the ratio between direct and diffuse radiation:

*rad diffuse* = *rad* × [ 0.958 − 0.982 (*rad*/*radintact*) ] (A14)

*rad direct* = *rad* − *rad diffuse*, (A15)

where *raddiffuse* and *raddirect* are diffuse radiation and direct radiation within *rad*, respectively. Diffuse and direct radiation differ in their fractional content of photosynthetically active radiation (PAR: 400–700 nm) in the total spectrum; diffuse radiation contains 57%, while direct radiation contains 43%. Thus, photosynthetic photon flux density of PAR is given by the following:

*par diffuse* = 4.2 × 0.57 × *rad diffuse* (A16)

*par direct* = 4.6 × 0.43 × *rad direct* (A17)

*par* = *par diffuse* + *par direct* (A18)

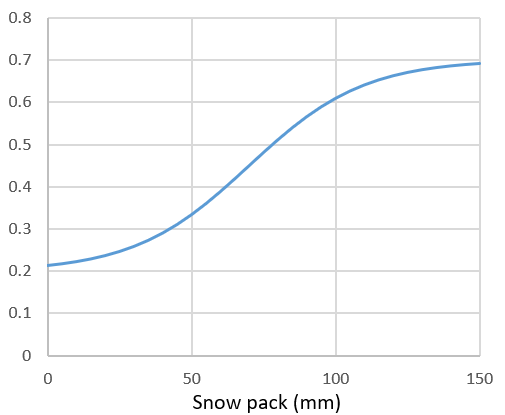
where *par* is photosynthetically active radiation at midday (in μmol photon m–2 s–1), and *par diffuse* and *par direct* are the diffused and direct radiation components of *par*. The multipliers 4.2 and 4.6 are for unit conversion from [W m–2] to [μmol photons m–2 s–1] for diffuse and direct radiation, respectively (Larcher, 1995).

### A3. Net Radiation (Computed Daily)

To estimate the transpiration rate of leaves and the evaporation rate of soil, the net radiation at vegetation (*radnetveg* in W m–2) and at the soil surface (*radnetsoil* in W m–2) were calculated as:

*radnet veg*= [*rad* × (1 − *albedo leaf*) + *radnet long*] × (1 − *ir*) (A19)

*radnet soil*= [*rad* × (1 − *albedo soil*) + *radnet long*] × *ir*, (A20)

where *ir* is the shortwave interception by leaves. *albedoveg* and *albedosoil* are the albedo of vegetation and the soil surface, respectively; *albedoveg* was assumed to be 0.107 for larch forest (Fukuda, personal observation), 0.15 for other forest biome, and 0.24 for other biome (Jones 1992). On the other hand, *albedoveg* and *albedosoil* were adjusted by snow packs on the ground:

*albedoleaf* = *AlbedoLeaf0* + (0.7 − *AlbedoLeaf0*)/[1 + exp(−0.05(*poolsnow*−70.0))]. (A21)

*albedosoil* = *AlbedoSoil0* + (0.7 − *AlbedoSoil0*)/[1 + exp(−0.05(*poolsnow*−70.0))]. (A22)

A21 and A22 were taken from Ito & Oikawa (2002) and gave a diminishing curve for albedo as a function of the snowpack. An example of albedo change with snow pack is in the above figure.

The *radnetlong* is net long-wave radiation, which is estimated by the following formula:

*radnetlong* = 5.67 × 10−8 × (*tmpair* + 273.15)4 − *radlong*, (A24)

where the constant 5.67 × 10−8 is Stefan–Boltzmann's constant (in W m−2 K−4), and *radlong* is downward longwave radiation.

### A4. Parameters of Photosynthesis and Stomatal Conductance (Computed Daily)

Appendix B7 shows the definition of PFT-specific photosynthesis parameters. To estimate photosynthesis and stomatal conductance, daily averages of photosynthetic rates (*pave* in μmol CO2 m−2 s−1) was calculated for each PFT of each scale of one to ten relative PAR intensity (10%, 20%,…, 100% relative PAR intensity to the top of the forest canopy of the day), using equation (15):

, (A25)

where *psat* is single-leaf photosynthetic rate under light saturation (in μmol CO2 m−2 s−1). *x* is the daily average of PAR receiving for grass layer (for grass PFTs) or for crown disk of trees (for woody PFTs) (in μmol photon m−2 s−1). *lue* is the light-use efficiency of photosynthesis (in mol CO2 mol photon−1), which is formulated to conform to the data in Osmond *et al.* (1980) as follows:

 (for C3 PFTs) (A26)

 (for C4 PFTs), (A27)

where *LUE* is the potential maximum value, and *co2cell* is the intercellular CO2 concentration (in μmol mol−1). The single-leaf photosynthetic rate, *psat*, under light saturation (in μmol CO2 m−2 s−1), is calculated by multiplying its potential maximum of photosynthetic rate (*PMAX*) by the coefficients of temperature, CO2 level, and soil water effects (*cetmp*, *ceco2*, and *cewater*, respectively):

. (A28)

*cetmp*, the temperature-dependent function of *psat*, is a bell-shaped curve that reaches the maximum (1.0) at the optimum temperature and tapers off in warmer or cooler temperatures (Raich et al., 1991):

, (A29)

where *Tmax*, *Tmin*, and *topt* are the PFT-specific maximum, minimum, and optimum temperature for photosynthesis, respectively (in °C). *topt* increases with the intercellular CO2 concentration because of photorespiration:

*topt* = *Topt0* + 0.01 *co2cell* (A30)

where *Topt0* is the minimum value of *topt* at a very low *co2cell*. For grass PFTs, *topt* is assumed to be a 20-year running mean of air temperature in the growth phase (maximum range 10°C–30°C for TeH and 20°C–40°C for TrH) because grass PFTs include a variety of species adapted to a wide range of climatic zones.

The *ceco2*, the CO2-dependent function of *psat*, is expressed by a Michaelis-type function:

 (for C3 PFTs) (A31)

 (for C4 PFTs), (A32)

where *KM* is the coefficient of CO2 concentration sensitivity; *co2cmp* is the CO2 compensation point, which is adjusted by temperature for C3 species (Brooks & Farquhar, 1985).

(for C3 PFTs) (A33)

(for C4 PFTs), (A35)

where *CO2cmp* is the control value of *co2cmp* at 20°C; *cewater*, the water availability effect coefficient of *psat*, is calculated as follows:

, (A35)

where *θ* is the efficient soil water available for plants, which varied linearly with soil moisture content within the root zone from 0.0 (wilting point) to 1.0 (field capacity). *θmax*, *θmin*, and *θopt* were, respectively, the PFT-specific maximum, minimum, and optimum *θ* for photosynthesis (0.0–1.0). All *θ* are represented as *statwater* in this manuscript, and *stat\_water* in the code.

This function reconstructs a generally observed phenomenon in which the ratio of actual evaporation to potential evaporation has a high sensitivity to soil water content near the wilting point, while sensitivity is reduced near field capacity (Dunne & Leopold, 1978)

The mean daytime crown stomatal conductance of H2O *gsave* (mol H2O m−2 s−1), is obtained by equation 20:

, (A36)

where *GSb1*, *GSb2*, and *GSb3* are PFT-specific parameters; *gsave* affects the intercellular CO2 concentration (*co2cell* in μmol mol−1) following Leuning (1990):

, (A37)

where 1.56 is a factor to convert *gs* into CO2 conductance. Using equations A25 through A37, we calculated *pave*, *lue*, and *gsave* of each PFT every simulation day. Because these values have interactions, which is interact mediated by intercellular CO2 (Figure 6), five iterations of calculations are conducted to converge these values.

### A5. Evapotranspiration (Computed daily)

The potential evaporation (*evpm*) and transpiration (*trpm*) are estimated by the Penman–Monteith method (Monteith & Unsworth, 1990), assuming an abundant water supply:

, (A44)

, (A45)

where *dlen* is day length (in hour), *slopevps* is saturated vapor pressure (in hPa ºC−1), *dnsa* is density of air (in kg m−3), *vpd* is vapor pressure deficit (in hPa), and *ic* is intercepted precipitation (in mm day−1). 0.5 × *radnetveg* and 0.5 × *radnetsoil* are the daytime averages of net radiation on leaves and soil surface when a daily change of radiation was approximated by sin2. The constant 24 is the day length (in hour day−1), 1012 is the specific heat of air (in J kg−1 K−1), and 0.667 is the psychrometer constant (in hPa K−1). *lh* is the latent heat of water (in Wh kg−1 H2O), given by an empirical function of Fritschen & Gay (1979).

,

where 1000 and 3600 are, respectively, unit converter from g to kg and unit converter from second to hour.

*caero*, *csoil*, and *cleaf* are aerodynamic conductance, soil surface conductance, and canopy conductance, respectively.

. (A46)

This equation was delivered by substituting the empirical formulation of Penman (1948) into equation A44. *csoil*, soil surface conductance, is in proportion to the fraction of soil layer 1 that is saturated with water:

, (A47)

where the multiplier 0.0015 (this is just only a tuning parameters) is water-saturation conductance, which is a tuning parameter. Finally, *cleaf* is

, (A48)

where *ccon* is mean daytime stomatal conductance of the simulated forest (in mol H2O m−2 s−1), and the multiplier 0.0224 is the unit converter from [mol H2O m−2 s−1] to [m3 H2O m−2 s−1].

Due to the limited water availability, evapotranspiration rates were reduced from their potential values, *evpm* and *trpm*, to their actual values, *ev* and *tr*, as approximated by the quadratic functions:

0.1 *ev*2 – (*a* + *evpm*) *ev* + *a* × *evpm* = 0, (A49)

0.1 *tr*2 – (*b* + *trpm*) *tr* + *b* × *trpm* = 0, (A50)

where 0.1 is the empirical convexity of the available water to the actual evapotranspiration curves; *a* and *b* are available water for evaporation and transpiration, respectively; *a* = *poolw(1)*, *b* = . These equations can be transformed as follow:

, (A51)

, (A52)

Actual evaporation, *ev*, is charged only for topsoil layer. Actual transpiration, *tr*, is charged for soil layers 1 to maximum *RootDepth* among existing PFT in the stand.

# Appendix B (Tables)

### B1. Inputs and outputs of the SEIB–DGVM

Input

(1) Location

Latitude, Altitude

(2) Soil (fixed in time)

Albedo. Soil moisture at Saturation point, Field capacity, Wilting point.

(3) Climatic data (daily)

Air temperature, Soil temperature, Downward shortwave radiation at midday, Downward longwave radiation, Precipitation, Relative humidity, Wind velocity

Outputs

(1) Carbon dynamics (daily–yearly)

Terrestrial carbon pool (Woody biomass, Grass biomass, Litter, Soil organic matter), CO2 absorption, and emission fluxes.

(2) Water dynamics (daily)

Soil moisture content (0~3mm depth at 0.1m interval), Interception rate, Evaporation rate, Transpiration rate, Interception rate, Runoff rate

(3) Radiation and heat cycles (daily)

Land surface albedo. Bowen ratio.

(4) Properties of vegetation (daily–yearly)

Biome type, Dominant plant functional type, Leaf area index, Tree density, Size distribution of trees, Age distribution of trees, Woody biomass for each tree, and Grass biomass per unit area.

### B2. Processes in the SEIB–DGVM, and the approaches used to represent each process

|  |  |  |
| --- | --- | --- |
| Process | Approach | Source |
| *Physical process* |  |  |
| Radiation | Beer's Law within spatially explicit virtual forest |  |
| Evapotranspiration | Penman–Monteith evapotranspiration | Monteith & Unsworth (1990) |
| Soil water process | Analogs of simple bucket model |  |
| Physiology |  |  |
| Photosynthesis | Michaelis-type function |  |
| Maintenance respiration | The respiration rate is in proportion to the nitrate content of each organ. | Ryan (1991) |
| Growth respiration | The respiration rate is based on the chemical composition of each organ. | Poorter (1994) |
| Stomatal conductance | A semi-empirical model | Ball *et al.* (1987) modified by Leuning (1995) |
| Phenology | A set of semi-empirical models; parameters were estimated from satellite NDVI data. | Botta *et al*. (2000) except for BoNS |
| Decomposition | Three carbon sources: litter and soil organic carbon with slow and fast decomposition rates | Foley (1995) and Lloyd & Taylor (1994) |
| Vegetation dynamics |  |  |
| Establishment | Climatically favored PFTs establish as small individuals. |  |
| Mortality | Annual NPP per leaf area, heat stress, bioclimatic limit, and fire | Sitch *et al*. (2003) |
| Fire | An empirical function of soil moisture and aboveground biomass | Kistler *et al*. (2001) |
| Gap formation | An empirical function. This only occurs in tropical rain forest | Huth & Ditzer (2000) |

### B3. Parameters and constants in the model’s equations

Fixed parameters (begins with a capital letter)

**Soil properties (Grid specific)**

*Wsat* : soil moisture at saturation point (m m–1)

*Wfi* : soil moisture at field capacity (m m–1)

*Wwilt* : soil moisture at wilting point (m m–1)

*AlbedoSoil0* : soil albedo (fraction)

*Depth* : depth of soil layer (= 100 mm)

**Location**

*LAT* : latitude (degree)

*ALT* : altitude (m)

**Allocation and Allometry (PFT-specific)**

*HGTmax* : maximum tree height (m)

*HGTs* : initial value of relative growth rate, height to diameter (m m–1)

*LAmax* : maximum leaf area per canopy surface (m2 m–2)

*CDmax* : maximum crown diameter (m)

*SLA* : specific leaf area (one sided m2 g DM–1)

*ALM1, 2* : allometric parameter 1, 2 (dimensionless)

*ALM 3* : allometric parameter 3 (g DM m–3)

*ALM 4, 5, 6* : allometric parameter 4, 5, 6 (fraction)

*FRratio* : ratio of foliage mass to fine root mass for woody PFTs , and ratio of abovegournd biomass to belowground biomass for grass PFTs (ratio)

**Respiration and turnover (PFT-specific)**

*PNf, s, r* :nitrogen mass per biomass for foliage, sapwood, root (g N g DM–1)

*RM*  :maintenance respiration rate at 15°C for unit nitrogen mass (g C g N–1 day–1)

*RGf, s, r* :specific growth respiration rate for foliage, sapwood, and root (g DM g DM–1)

*RGstockin* :growth respiration rate from available resource to stock resource (g DM g DM–1)

*RGstockout*:growth respiration rate from stock resource to available resource (g DM g DM–1)

*TOf, s, r*:turnover rates of foliage, sapwood, and fine root for woody PFTs, while turnover rates of aboveground biomass, NA, and belowground biomass for grass PFTs (DM–1 year–1)

*TOfast, slow*:turnover rates for fast and slow soil organic matter (SOM) (DM–1 yr–1)

**Photosynthesis (PFT-specific)**

*PMAX* : maximum photosynthesis rate (μmol CO2 m–2 s–1)

*EK* : light attenuation coefficient for vertical direction (dimensionless)

*LUE* : control value of light-use efficiency for photosynthesis (mol CO2 mol photon–1)

*Topt0* :optimum temperature for photosynthesis at very low intercellular CO2 concentration (ºC)

*Tmin* : minimum temperature for photosynthesis (ºC)

*Tmax* : maximum temperature for photosynthesis (ºC)

*GSb1* : parameters for stomatal conductance (mol H2O m–2 s–1)

*GS b2* : parameters for stomatal conductance (dimensionless)

*GSb3* : parameters for stomatal conductance (hPa)

*KM* : dependence of photosynthesis on intercellular CO2 concentration (μmol mol–1)

*CO2cmp* : CO2 compensation point at 20°C (μmol CO2 mol–1 air)

*RootDepth* : Soil depth that plant can absorb soil water (10cm)

**Establishment (PFT-specific)**

*Pestablish* : establishment probability at vacant patch (m–2 year–1)

*GDDmin* : minimum growth-degree-day sum (5 ºC base)

*TCmax* : maximum coldest-month temperature (ºC)

*PARmin* : minimum annual average of midday PAR for establishment (μmol photons m–2 s–1)

**Mortality (PFT-specific)**

*M1*: parameter for background mortality (dimensionless)

*M2* : parameter for background mortality (dimensionless)

*M3* : probability of survival after fire (varying 0.0–1.0)

*TCmin* : minimum coldest-month temperature for survival (ºC)

**Other fixed parameters**

*ESD*: distance between sun and earth (km)

*ESDmean*: annual mean of *ESD* (km)

Variables (Begins with a lowercase letter)

**Daily climatic data**

*tmpair* : air temperature (ºC)

*tmpsoil(i)* : temperature at soil layer *i* (ºC)

*cloud* : total cloud cover (fraction)

*prec* : daily precipitation (mm day–1)

*humid* : air humidity (g g–1)

*wind* : wind velocity (m s–1)

**Woody biomass (for each individual tree)**

*massleaf*  : leaf biomass (g DM)

*masstrunk* : trunk biomass (g DM)

*massroot* : fine root biomass (g DM)

*massstock* : stock biomass (g DM)

*massavailable* : available biomass (g DM)

**Grass biomass**

*gmassleaf* : leaf biomass density of grass (g DM m–2)

*gmassroot* : root biomass density of grass (g DM m–2)

*gmassstock*: stock biomass density of grass (g DM m–2)

*gmassavailable* : available biomass density of grass (g DM m–2)

**Morphology and characteristics for woody PFTs (for each individual tree)**

*height* : tree height (m)

*crowndiameter* : crown diameter (m)

*crowndepth* : crown depth (m)

*crownarea* : cross sectional crown area (m2)

*dbhsapwood* : sapwood diameter (m)

*dbhheartwood* : heartwood diameter (m)

*la* : leaf area (m2)

*lamean* : annual mean leaf area in the previous year (m2)

**Photosynthesis conditions**

*pave* : daily average of photosynthetic rates for each woody individual (μmol CO2 m–2 s–1 )

*psat* : light saturated photosynthetic rate (μCO2 m–2 s–1 )

*lue* : light-use efficiency of photosynthesis (mol CO2 mol photon–1)

*co2cmp* : CO2 compensation point (μmol CO2 mol air–1)

*co2cell* : intercellular CO2 concentration (μmol CO2 mol air–1)

*topt* : optimum temperature for photosynthesis (ºC)

*gs* : single leaf stomatal conductance of H2O (mol H2O m–2 s–1)

*gsave* : mean daytime leaf stomatal conductance of H2O (mol H2O m–2 s–1)

*cconwood* : stomatal conductance of H2O of tree canopy, day time mean (mol H2O m–2 s–1)

*ccongrass* : stomatal conductance of H2O of grass leaves, day time mean (mol H2O m–2 s–1)

*ccon* : stomatal conductance of H2O, day time mean (=cconwood+ ccongrass, mol H2O m–2 s–1)

**Production**

*gpp* : gross primary production of each tree (g DM day–1)

*gppl* : gross primary production of each crown layer (g DM day–1)

*gppg* : gross primary production of grass layer (g DM day–1 m–2)

*anpp* : annul net primary production of the previous year (kg DM year–1)

*statleaf* : benefit per cost of maintaining leaf mass (g g–1 day–1)

**Other metabolic variables**

*lai* : leaf area index of each PFT (m2 m–2)

*laig* : leaf area index of grass layer (m2 m–2)

*statwater* : state of water availability for each PFT (varying 0.0–1.0)

*statwater\_opt* : optimum *statwater* for photosynthesis (varying 0.0–1.0)

*statwater\_min* : minimum *statwater* for photosynthesis (varying 0.0–1.0)

*statwater\_max* : minimum *statwater* for photosynthesis (varying 0.0–1.0)

*qt* : temperature sensitivity of respiration

**Soil water cycle**

*precrain* : precipitation, rain (mm day–1)

*precsnow* : precipitation, snow (mm day–1)

*rain* : expected number of rain in a day (day–1)

*poolw(n)* : water content at soil layer *n* (mm)

*poolsnow* : water-equivalent snow depth (mm)

*tw* : snowmelt rate (mm day–1)

*pn (n)* : penetration rate for soil layer *n* (mm day–1)

*ev* : actual evaporation rate from soil layer 1 (mm day–1)

*evpm* : potential evaporation rate from soil layer 1 (mm day–1)

*tr(n)* : actual transpiration rate from soil layer *n* (mm day–1)

*trpm* : potential transpiration rate (mm day–1)

*ic* : intercepted rainfall by plants (mm day–1)

*aet* : actual evapotranspiration of the previous year (mm year–1)

*caero* : aerodynamic conductance of evaporation

*csoil* : soil conductance of evapotranspiration

*cleaf* : canopy conductance of transpiration

**Radiation conditions at midday**

*radintact* : shortwave radiation at top of atmosphere (W m–2)

*rad* : shortwave radiation entering biosphere (W m–2)

*radlong* : longwave radiation entering biosphere (W m–2)

*raddirect* : direct radiation within *rad* (W m–2)

*raddiffuse* : diffused radiation within *rad* (W m–2)

*radnetveg* : net radiation at vegetation surface (W m–2)

*radnetsoil* : net radiation at soil surface (W m–2)

*radnetlong* : net long wave radiation (W m–2)

*par* : midday PAR (μmol photon m–2 s–1)

*pardirect* : direct radiation component of *par* (μmol photon m–2 s–1)

*pardiffuse* : diffused radiation component of *par* (μmol photon m–2 s–1)

*parwood (l, n)* : midday PAR on crown layer *l* of individual tree *n* (μmol photon m–2 s–1)

*pargrass* : midday PAR at the grass layer (μmol photon m–2 s–1)

*fpardirect(l, n)* : relative intensity of direct PAR of crown disk *l* of tree *n* at midday compared to the forest top (dimensionless)

*fpardiffuse(l)* : relative intensity of diffused of forest layer *l* at midday compared to the forest top (dimensionless)

*fpardirect* :relative intensity of direct PAR of crown disk *l* of tree *n* at midday compared to the forest top (dimensionless)

*slhgt* : solar angle at midday (degree)

*sldec* : solar declination of the Earth’s orbit (degree)

*dlen* : day length (hour)

*eK* : light attenuation coefficient at midday (dimensionless)

*ir* : shortwave interception by leaves (fraction)

*albedoveg* : albedo of vegetation surface corrected by snow pack (fraction)

*albedosoil* : albedo of soil surface corrected by snow pack (fraction)

**Air characteristics**

*ap* : air pressure (hPa)

*vp* : actual vapor pressure (hPa)

*vpsat* : saturated vapor pressure (hPa)

*vpd* : vapor pressure deficit between saturated and actual vapor pressures (hPa)

*co2atm* : ambient (canopy) CO2 concentration (μmol CO2 mol–1 air)

*slopevps* : slope of saturated vapor pressure (hPa ºC–1)

*dnsa* : density of air (kg m–3)

**Wild fire parameters for African continent**

*ifire* : potential fire intensity (kJ s–1 m–1)

*θ* : fraction of fuel moisture

*tc* : fraction of tree canopy

*fuel* : fuel load (gDM m–2)

*fuelliving* : living (moist) fuel load (gDM m–2)

*fueldead* : dead (dry) fuel load (gDM m–2)

*fuellying* : lying dead (dry) mass (gDM m–2)

: grass standing dead (dry) mass (gDM m–2)

### B4. PFT-specific allocation and allometric parameters

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| PFT | *ALM1* | *ALM3* | *ALM5* | *HGTmax* | *HGTs* | *DBHlimit* | *FRratio* | *SLA* | *LAmax* | *CDmax* |
|  | - | (g DM cm–3) | (ratio) | (m) | (m m–1) | (m) | (ratio) | (m2 g–1) | (m2 m–2) | (m) |
| TrBE1 | - | 0.62 | 0.2 | 68 | 140 | 1.56 | 4.00 | 0.010 | 5.0 | 39.0 |
| TrBE2 | - | 0.57 | 0.2 | 68 | 100 | 0.66 | 4.00 | 0.010 | 5.0 | 16.5 |
| TrBE3 | - | 0.37 | 0.2 | 54 | 95 | 0.45 | 4.00 | 0.010 | 5.0 | 11.3 |
| TrBE4 | - | 0.78 | 0.2 | 42 | 95 | 0.24 | 4.00 | 0.010 | 5.0 | 6.0 |
| TrBE5 | - | 0.56 | 0.1 | 60 | 172 | 1.00 | 4.00 | 0.010 | 3.0 | 15.0 |
| TrBR | - | 0.56 | 0.1 | 60 | 172 | 1.00 | 1.50 | 0.013 | 3.0 | 15.0 |
| TeNE | 4800 | 0.374 | *-* | 43 | 65 | 1.00 | 1.50 | 0.004 | 4.0 | 15.0 |
| TeBE | 4800 | 0.492 | *-* | 17 | 154.3 | 1.00 | 1.50 | 0.007 | 4.0 | 15.0 |
| TeBS | 14500 | 0.492 | *-* | 37 | 159 | 1.00 | 1.50 | 0.015 | 2.0 | 15.0 |
| CTeNE1 | 4800 | 0.400 | *-* | 75 | 90 | 1.00 | 1.50 | 0.0054 | 2.0 | 15.0 |
| CTeNE2 | 4800 | 0.380 | *-* | 75 | 90 | 1.00 | 1.50 | 0.005 | 2.0 | 15.0 |
| CTeBS1 | 14500 | 0.540 | *-* | 39 | 170 | 1.00 | 1.50 | 0.021 | 2.0 | 15.0 |
| CTeBS2 | 14500 | 0.550 | *-* | 39 | 170 | 1.00 | 1.50 | 0.021 | 2.0 | 15.0 |
| CTeBS3 | 14500 | 0.560 | *-* | 39 | 170 | 1.00 | 1.50 | 0.021 | 2.0 | 15.0 |
| CTeBS4 | 14500 | 0.630 | *-* | 39 | 170 | 1.00 | 1.50 | 0.021 | 2.0 | 15.0 |
| BoNE | 6000 | 0.374 | *-* | 35.0 | 130 | 1.00 | 1.50 | 0.004 | 2.0 | 10.0 |
| \*1 | 6000 | 0.420 | *-* | 31.7 | 165 | 0.50 | 1.50 | 0.003 | 4.0 | 8.0 |
| \*2 | 6000 | 0.460 | *-* | 31.7 | 165 | 1.90 | 1.50 | 0.004 | 4.0 | 8,0 |
| BoNS | - | 0.700 | *-* | 31.7 | 165 | 0.40 | 0.35 | 0.010 | 4.0 | 8.0 |
| BoBS | 8500 | 0.670 | *-* | 31.7 | 165 | 0.60 | 0.88 | 0.025 | 4.0 | 8.0 |
| TeH | - | - | *-* | - | - | - | 0.12 | 0.020 | - | - |
| TrH | - | - | *-* | - | - | - | 0.10 | 0.010 | - | - |

### \*1: *Pice obovata* (East Siberia): This tree species is not used in the simulation

### \*2: *Pinus sylvestris* (East Siberia): This tree species is not used in the simulation

### B4.1. PFT-specific crown-allometric-parameters

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| PFT | *ALMcrown1* | *ALMcrown2* | *ALMcrown3* | *ALMcrown4* | *ALMcrown5* | *ALMcrown6* | *ALMcrown7* |
|  | - | (Fraction) | (Fraction) | - | - | - | - |
| TrBE1 | - | - | 0.37 | - | - | - | - |
| TrBE2 | - | - | 0.28 | - | - | - | - |
| TrBE3 | - | - | 0.28 | - | - | - | - |
| TrBE4 | - | - | 0.28 | - | - | - | - |
| TrBE5 | - | - | 0.30 | - | - | - | - |
| TrBR | - | - | 0.30 | - | - | - | - |
| TeNE | 100 | 0.38 | - | - | - | - | - |
| TeBE | 200 | 0.38 | - | - | - | - | - |
| TeBS | 200 | 0.38 | - | - | - | - | - |
| CTeNE1 | 100 | 0.38 | - | 0.53 | 0.55 | 0.59 | 1.01 |
| CTeNE2 | 100 | 0.38 | - | 0.53 | 0.55 | 0.59 | 1.01 |
| CTeBS1 | 200 | 0.38 | - | 0.62 | 0.58 | 0.54 | 0.95 |
| CTeBS2 | 200 | 0.38 | - | 0.62 | 0.58 | 0.54 | 0.95 |
| CTeBS3 | 200 | 0.38 | - | 0.62 | 0.58 | 0.54 | 0.95 |
| CTeBS4 | 200 | 0.38 | - | 0.62 | 0.58 | 0.54 | 0.95 |
| BoNE | 100 | 0.20 | - | - | - | - | - |
| \*1 | 100 | - | - | - | - | - | - |
| \*2 | 100 | - | - | - | - | - | - |
| BoNS | - | - | - | - | - | - | - |
| BoBS | 200 | - | - | - | - | - | - |

### B5. PFT-specific dynamic parameters

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| PFT | *M1* | *M2* | *M4* | *M5* | *Pestablish* | *TCmin* | *TCmax* | *GDDmin* | *PARmin* |
|  | (no dimension) | (no dimension) | (no dimension) | (no dimension) | (m–2 year–1) | (ºC) | (ºC) | (5 ºC base) | (μmol photons m–2 s–1) |
| TrBE1 | - | - | 1.0 | 0.04 | 0.020 | 15.5 | - | 3000 | 20 |
| TrBE2 | - | - | 1.0 | 0.04 | 0.004 | 15.5 | - | 3000 | 20 |
| TrBE3 | - | - | 8.0 | 0.08 | 0.048 | 15.5 | - | 3000 | 1000 |
| TrBE4 | - | - | 1.0 | 0.04 | 0.002 | 15.5 | - | 3000 | 1000 |
| TrBE5 | 0.0135 | 1.0 | - | - | 0.020 | 10.0 | - | 3000 | 20 |
| TrBR | 0.0135 | 1.0 | - | - | 0.010 | 10.0 | - | 3000 | 20 |
| TeNE | 0.018 | 1.0 | - | - | 0.040 | -2.0 | 22.0 | 900 | 0 |
| TeBE | 0.008 | 1.0 | - | - | 0.040 | 3.0 | 18.8 | 1200 | 0 |
| TeBS | 0.010 | 1.0 | - | - | 0.013 | -17.0 | 15.5 | 1200 | 0 |
| CTeNE1 | 0.015 | 10.0 | - | - | 0.002 | -32.5 | - | 900 | 300 |
| CTeNE2 | 0.027 | 10.0 | - | - | 0.002 | -32.5 | - | 900 | 600 |
| CTeBS1 | 0.095 | 10.0 | - | - | 0.005 | -17.0 | - | 1200 | 900 |
| CTeBS2 | 0.095 | 10.0 | - | - | 0.007 | -17.0 | - | 1200 | 900 |
| CTeBS3 | 0.095 | 10.0 | - | - | 0.007 | -17.0 | - | 1200 | 300 |
| CTeBS4 | 0.095 | 10.0 | - | - | 0.001 | -17.0 | - | 900 | 300 |
| BoNE | 0.013 | 1.2 | - | - | 0.005 | -32.5 | -2.0 | 600 | 0 |
| \*1 | 0.018 | 1.0 | - | - | 0.010 | -40.0 | -2.0 | 320 | 0 |
| \*2 | 0.008 | 1.0 | - | - | 0.010 | -40.0 | -2.0 | 450 | 0 |
| BoNS | 0.001 | 1.5 | - | - | 0.013 | -45.0 | -2.0 | 250 | 350 |
| BoBS | 0.045 | 1.0 | - | - | 0.010 | -40.0 | -2.0 | 340 | 700 |
| TeH | - | - | - | - | - | -45.0 | 15.5 | - | - |
| TrH | - | - | - | - | - | 15,5 | - | - | - |

### \*1: *Pice obovata* (East Siberia): This tree species is not used in the simulation

### \*2: *Pinus sylvestris* (East Siberia): This tree species is not used in the simulation

### B6. PFT-specific respiration and turnover parameters

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| PFT | RM | *PNf* | *RGf* | *RGs* | *RGr* | *RGstockin* | *RGstockout* | *TOf* | *TOs* | *TOr* |
|  | (gC gN–1 day–1) | (gN gDM–1) | (gDM gDM–1) | (gDM gDM–1) | (gDM gDM–1) | (gDM gDM–1) | (gDM gDM–1) | (year–1) | (year–1) | (year–1) |
| TrBE1 | 0.1 | 0.016 | 1.56 | 1.68 | 1.34 | 1.07 | 1.00 | 0.59 | - | 0.76 |
| TrBE2 | 0.1 | 0.016 | 1.56 | 1.68 | 1.34 | 1.07 | 1.00 | 0.59 | - | 0.76 |
| TrBE3 | 0.1 | 0.016 | 1.56 | 1.68 | 1.34 | 1.07 | 1.00 | 0.59 | - | 0.76 |
| TrBE4 | 0.1 | 0.016 | 1.56 | 1.68 | 1.34 | 1.07 | 1.00 | 0.59 | - | 0.76 |
| TrBE5 | 0.1 | 0.016 | 1.56 | 1.68 | 1.34 | 1.07 | 1.00 | 0.59 | - | 0.59 |
| TrBR | 0.1 | 0.022 | 1.56 | 1.68 | 1.34 | 1.07 | 1.00 | 1.59 | - | 1.59 |
| TeNE | 0.1 | 0.012 | 1.56 | 1.68 | 1.34 | 1.07 | 1.00 | 0.22 | 0.05 | 0.64 |
| TeBE | 0.1 | 0.012 | 1.56 | 1.68 | 1.34 | 1.07 | 1.00 | 0.38 | 0.05 | 0.64 |
| TeBS | 0.1 | 0.022 | 1.56 | 1.68 | 1.34 | 1.07 | 1.00 | 2.17 | 0.05 | 0.64 |
| CTeNE1 | 0.1 | 0.0084 | 1.56 | 1.68 | 1.34 | 1.07 | 1.00 | 0.213 | 0.05 | 0.64 |
| CTeNE2 | 0.1 | 0.013 | 1.56 | 1.68 | 1.34 | 1.07 | 1.00 | 0.123 | 0.05 | 0.64 |
| CTeBS1 | 0.1 | 0.025 | 1.56 | 1.68 | 1.34 | 1.07 | 1.00 | 6.7 | 0.05 | 0.64 |
| CTeBS2 | 0.1 | 0.025 | 1.56 | 1.68 | 1.34 | 1.07 | 1.00 | 6.7 | 0.05 | 0.64 |
| CTeBS3 | 0.1 | 0.025 | 1.56 | 1.68 | 1.34 | 1.07 | 1.00 | 2.9 | 0.05 | 0.64 |
| CTeBS4 | 0.1 | 0.025 | 1.56 | 1.68 | 1.34 | 1.07 | 1.00 | 2.9 | 0.05 | 0.64 |
| BoNE | 0.1 | 0.012 | 1.56 | 1.68 | 1.34 | 1.07 | 1.00 | 0.22 | 0.05 | 0.42 |
| \*1 | 0.1 | 0.017 | 1.56 | 1.68 | 1.34 | 1.07 | 1.00 | 0.12 | - | 0.20 |
| \*2 | 0.1 | 0.013 | 1.56 | 1.68 | 1.34 | 1.07 | 1.00 | 0.44 | - | 0.20 |
| BoNS | 0.1 | 0.016 | 1.56 | 1.68 | 1.34 | 1.07 | 1.00 | 3.19 | - | 0.20 |
| BoBS | 0.1 | 0.042 | 1.56 | 1.68 | 1.34 | 1.07 | 1.00 | 2.00 | - | 0.47 |
| TeH | 0.1 | 0.027 | 1.50 | - | 1.34 | 1.07 | 1.00 | 0.5 | ●†1 | 0.40 |
| TrH | 0.1 | 0.018 | 1.50 | - | 1.34 | 1.07 | 1.00 | 0.5 | - | 0.77 |

### \*1: *Pice obovata* (East Siberia): This tree species is not used in the simulation

### \*2: *Pinus sylvestris* (East Siberia): This tree species is not used in the simulation

†1: 稈の回転率。なお、粗根は次の一斉枯死まで回転しないと仮定している。

### B7. PFT-specific photosynthesis parameters

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| PFT | *PMAX* | EK0 | *LUE0* | *Topt0* | *Tmin* | *Tmax* | *Statwater\_opt* | *Statwater\_min* | *Statwater\_max* | *GSb1* | *GSb2* | *GSb3* | *KM* | *CO2cmp* | *RootDepth* |
|  | (μmol CO2 m–2 s–1) | - | (mol CO2 mol photon–1) | (C °) | (C °) | (C °) | fraction | fraction | fraction | (mol H2O m–2 s–1) | - | (hPa) | (μmol mol–1) | (μmol CO2 mol–1 air) | (×10cm) |
| TrBE1 | 9.4 | 0.5 | 0.10 | 27.5 | 2.0 | 47.5 | 0.90 | 0.10 | 0.99 | 0.01 | 9.0 | 10.0 | 33.0 | 35.0 | 5 |
| TrBE2 | 9.9 | 0.5 | 0.06 | 27.5 | 2.0 | 47.5 | 0.90 | 0.10 | 0.99 | 0.01 | 9.0 | 10.0 | 33.0 | 35.0 | 5 |
| TrBE3 | 26.0 | 0.5 | 0.06 | 27.5 | 2.0 | 47.5 | 0.90 | 0.10 | 0.99 | 0.01 | 9.0 | 10.0 | 33.0 | 35.0 | 5 |
| TrBE4 | 16.3 | 0.5 | 0.09 | 27.5 | 2.0 | 47.5 | 0.90 | 0.10 | 0.99 | 0.01 | 9.0 | 10.0 | 33.0 | 35.0 | 5 |
| TrBE5 | 8.1 | 0.5 | 0.05 | 27.5 | 2.0 | 47.5 | 0.90 | 0.10 | 0.99 | 0.01 | 9.0 | 10.0 | 33.0 | 35.0 | 5 |
| TrBR | 11.9 | 0.5 | 0.05 | 27.5 | 2.0 | 47.5 | 0.90 | 0.10 | 0.99 | 0.01 | 9.0 | 10.0 | 30.0 | 35.0 | 5 |
| TeNE | 9.0 | 0.5 | 0.05 | 25.0 | 0.0 | 45.0 | 0.90 | 0.10 | 0.99 | 0.01 | 9.0 | 10.0 | 30.0 | 35.0 | 5 |
| TeBE | 9.0 | 0.5 | 0.05 | 25.5 | 0.0 | 45.0 | 0.90 | 0.10 | 0.99 | 0.01 | 9.0 | 10.0 | 30.0 | 35.0 | 5 |
| TeBS | 12.0 | 0.5 | 0.05 | 22.5 | -2.0 | 42.5 | 0.90 | 0.10 | 0.99 | 0.01 | 9.0 | 10.0 | 30.0 | 35.0 | 5 |
| CTeNE1 | 3.0 | 0.5 | 0.05 | 17.0 | -3.1 | 40.0 | 0.65 | 0.10 | 0.80 | 0.01 | 9.0 | 10.0 | 30.0 | 35.0 | 5 |
| CTeNE2 | 3.98 | 0.5 | 0.05 | 25.0 | -5.5 | 40.0 | 0.75 | 0.20 | 0.90 | 0.01 | 9.0 | 10.0 | 30.0 | 35.0 | 5 |
| CTeBS1 | 11.48 | 0.5 | 0.05 | 25.0 | 0.0 | 45.0 | 0.85 | 0.30 | 1.00 | 0.01 | 9.0 | 10.0 | 30.0 | 35.0 | 5 |
| CTeBS2 | 8.13 | 0.5 | 0.05 | 25.0 | 0.0 | 45.0 | 0.75 | 0.20 | 0.90 | 0.01 | 9.0 | 10.0 | 30.0 | 35.0 | 5 |
| CTeBS3 | 6.46 | 0.5 | 0.05 | 25.0 | 0.0 | 45.0 | 0.85 | 0.30 | 1.00 | 0.01 | 9.0 | 10.0 | 30.0 | 35.0 | 5 |
| CTeBS4 | 8.50 | 0.5 | 0.05 | 25.0 | 0.0 | 45.0 | 0.65 | 0.10 | 0.80 | 0.01 | 9.0 | 10.0 | 30.0 | 35.0 | 5 |
| BoNE | 9.3 | 0.5 | 0.05 | 18.0 | -4.0 | 38.5 | 0.90 | 0.10 | 0.99 | 0.01 | 9.0 | 10.0 | 30.0 | 35.0 | 5 |
| \*1 | 10.0 | 0.5 | 0.05 | 13.0 | -3.0 | 40.0 | 0.90 | 0.10 | 0.99 | 0.01 | 9.0 | 10.0 | 30.0 | 35.0 | 5 |
| \*2 | - | 0.5 | 0.043 | 20.0 | -2.0 | 43.0 | 0.90 | 0.10 | 0.99 | 0.01 | 9.0 | 10.0 | 35.0 | 35.0 | 5 |
| BoNS | 26.0 | 0.5 | 0.041 | 21.0 | -2.0 | 38.0 | 0.90 | 0.10 | 0.99 | 0.01 | 9.0 | 10.0 | 30.0 | 35.0 | 5 |
| BoBS | 21.7 | 0.5 | 0.039 | 18.0 | -4.0 | 38.5 | 0.90 | 0.10 | 0.99 | 0.01 | 9.0 | 10.0 | 35.0 | 35.0 | 5 |
| TeH | 8.0 | 0.5 | 0.05 | † | -1.0 | 45.0 | 0.90 | 0.10 | 0.99 | 0.01 | 9.0 | 10.0 | 37.0 | 35.0 | 1 |
| TrH | 12.0 | 0.5 | 0.05 | † | 2.5 | 55.0 | 0.90 | 0.10 | 0.99 | 0.01 | 9.0 | 10.0 | 10.0 | 5.0 | 1 |

### \*1: *Pice obovata* (East Siberia): This tree species is not used in the simulation

### \*2: *Pinus sylvestris* (East Siberia): This tree species is not used in the simulation

### †: Automatically adjusted to the environment (see main text for detail)B8. Classification scheme of vegetation type, taken from Haxeltine and Prentice (1996) with some simplifications and modifications.

|  |
| --- |
| Vegetation type conditions Dominant PFT Other |
| Group 1 |
| Desert (polar) any *GDD0* < 150 |
| Group 2 |
| Arctic / Alpine-tundra any *GDD5* < 370 |
| Group 3 |
| Tropical forest TrBE 2.5 ≤ *LAImax* |
| Tropical deciduous forest TrBR 2.5 ≤ *LAImax* |
| Temperate evergreen forest TeNE 1.5 ≤ *LAImax* |
| Temperate evergreen forest TeBE 3.0 ≤ *LAImax* |
| Temperate deciduous forest TeBS 2.5 ≤ *LAImax* |
| Boreal evergreen forest BoNE |
| Boreal deciduous forest BoNS or BoBS |
| Group 4 |
| Xeric wood-land / scrub Tropical woody or TeBE 1.0 ≤ *LAImax* |
| Boreal woody or TeNE or TeBS 1.5 ≤ *LAImax* |
| Group 5 |
| Grass land / Savannas / Steppe any 0.2 ≤ *LAImax* |
| Desert (arid) any *LAImax* < 0.2 |

Note: Priority of classification: Group 1 > Group 2 > Group 3 > Group 4 > Group 5, *GDD0* : growing-degree-day at 0 ºC base

, *GDD5*: growing-degree-day at 5 ºC base, *LAImax* : maximum leaf area index of the previous year (m2 m–2)

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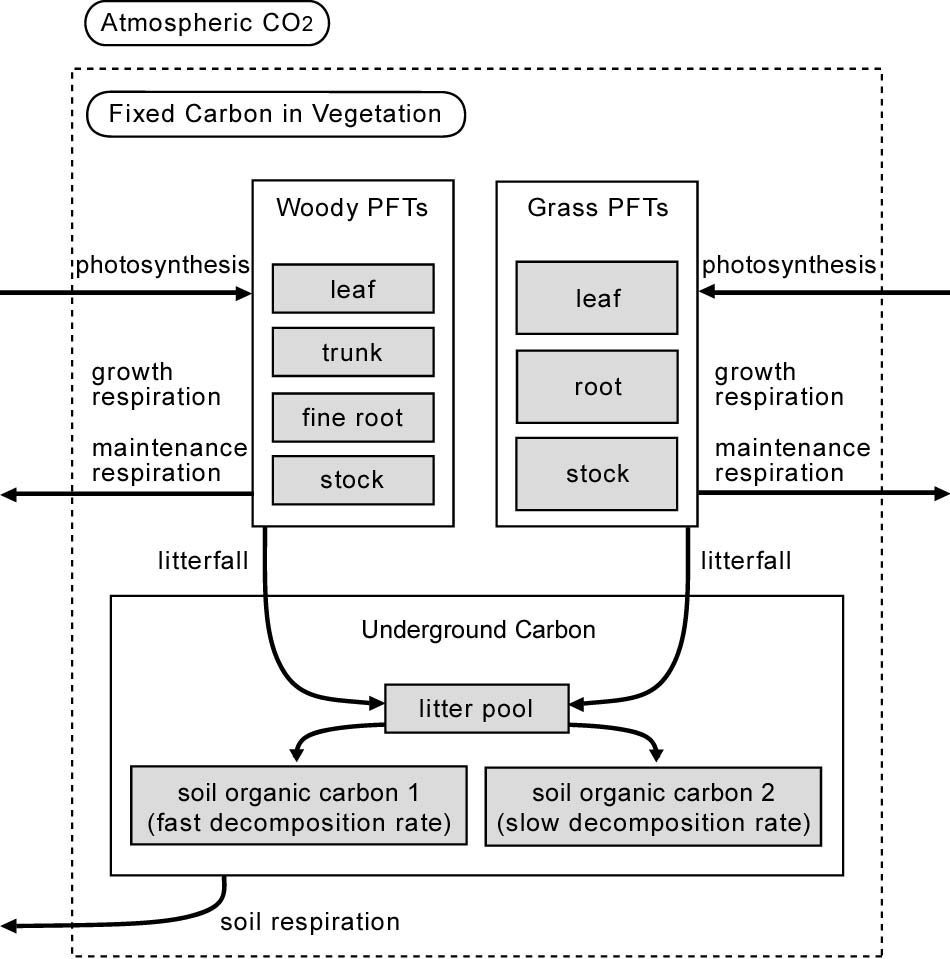
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# Figures

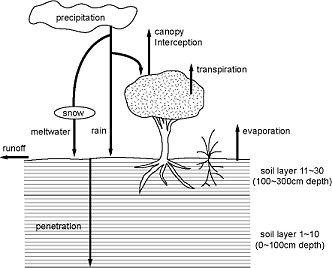
### fig01Figure 1

Representation of individual trees in the SEIB–DGVM. Each tree is composed of a crown, trunk, and fine roots. The trunk is composed of heartwood and sapwood. Trunk biomass includes branches and coarse/tap roots. The crown consists of 10 cm-deep ‘disks’. The trunk and crown have cylindrical shapes, while the fine roots are formless (i.e., represented only by biomass).



### Figure 2

The carbon flow through a terrestrial ecosystem as simulated by the SEIB–DGVM.

Figure 3

The water flows through the terrestrial ecosystem as simulated by the SEIB–DGVM.

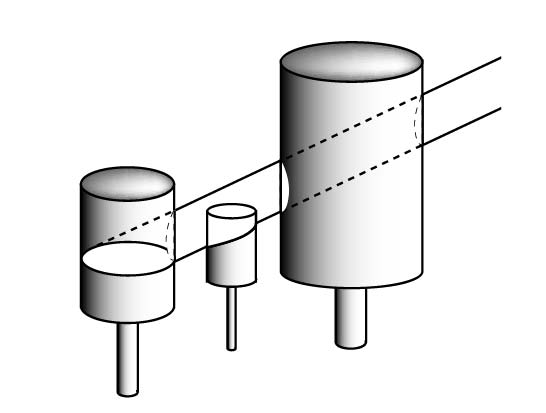
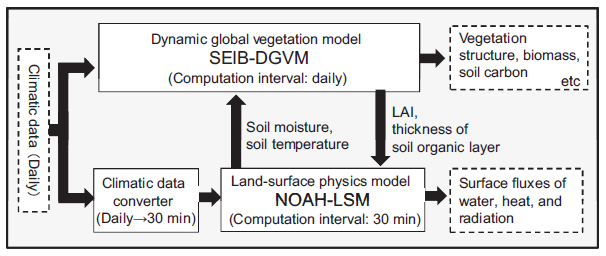


Figure 4

Schematic diagram of how to allocate direct radiation among trees in the SEIB-DGVM. See the main text for an explanation.

Figure 5

A schematic diagram of the integrated model developed for this study. Solid boxes show sub-models, and dashed boxes and labeled arrows represent climate variables and ecosystem functions. This figure is taken from Sato et al. (2016).

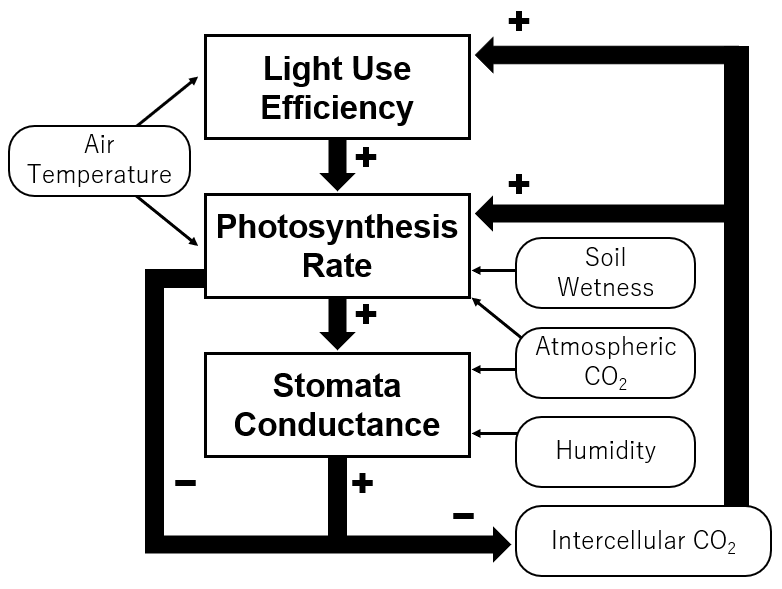


Figure 6

A schematic diagram of interactions among light use efficiency, photosynthesis rate, and stomata conductance. Thick arrows show feedback loops among these three processes. Plus and minus signs indicate positive and negative influences on the following process. Variables in round boxes are environmental factors, and thin allows show processes under these environmental factors' control.