Supplement of Geosci. Model Dev., 15, 7573–7591, 2022
https://doi.org/10.5194/gmd-15-7573-2022-supplement

Geoscientific Model Development
Open Access

Supplement of

Low sensitivity of three terrestrial biosphere models to soil texture over the South American tropics

Félicien Meunier et al.

Correspondence to: Félicien Meunier (felicien.meunier@ugent.be)

Supplementary material

Supplementary section 1: Model belowground processes description

The Ecosystem Demography model, version 2

Part 1: Soil parameters and pedotransfer functions

The equations relating volumetric soil water content ($\theta\ [m^3 \cdot m^{-3}]$) with soil matric potential ($\Psi\ [m]$) and soil hydraulic conductivity ($k\ [m \cdot s^{-1}]$) are taken from Clapp and Hornberger (1978) and Brooks and Corey (1964), respectively. To account for the reduction of conductivity in case of partially/completely frozen soil, an additional correction term is applied to hydraulic conductivity:

$$\Psi(\theta) = \Psi_{sat} \left(\frac{\theta_{sat}}{\theta}\right)^b$$

$$k(\theta) = k_{sat} \left[10^{-7(1-l)}\right] \left(\frac{\theta}{\theta_{sat}}\right)^{2b+3}$$

where $l\ [-]$ is the fraction of liquid water of soil moisture. Shape parameters $\theta_{sat}\ [m^3 \cdot m^{-3}]$, $\Psi_{sat}\ [m]$, $b\ [-]$, and $k_{sat}\ [mcdots^{-1}]$ are derived from soil sand ($f_{sand}\ [-]$) and clay ($f_{clay}\ [-]$fractions, according to Cosby et al. (1984):

$$\theta_{sat} = 0.505 - 0.142 \cdot f_{sand} - 0.037 \cdot f_{clay}$$

$$\Psi_{sat} = -0.01 \cdot 10^{2.17-1.58 \cdot f_{sand} - 0.63 \cdot f_{clay}}$$

$$b = 3.1 - 0.3 \cdot f_{sand} + 15.7 \cdot f_{clay}$$

$$k_{sat} = 6.817 \times 10^{-6} \cdot 10^{-0.60+1.26 \cdot f_{sand} - 0.64 \cdot f_{clay}}$$

Following the definition of Romano and Santini (2002), the field capacity water content is reached when soil hydraulic conductivity is $0.1\, kg_w \cdot m^{-2} \cdot d^{-1}$:

$$\theta_{fc} = \theta_{sat} \cdot \left(\frac{1.16 \cdot 10^{-9}}{k_{sat}}\right)^{\frac{1}{2b+3}}$$

The permanent wilting point is defined as the soil water content when soil matric potential reaches -1.5 MPa:

$$\theta_{wp} = \theta_{sat} \left(-\frac{g\rho\Psi_{sat}}{1.5 \cdot 10^6}\right)^{\frac{1}{b}}$$

Part 2: Impact of drought stress on plant productivity

At any time, the plant instantaneous rate of evapotranspiration ($T\ [kg_w \cdot m^{-2} \cdot s^{-1}]$) is a linear combination of its rate under conditions of open ($T_o\ [kg_w \cdot m^{-2} \cdot s^{-1}]$) and closed ($T_c\ [kg_w \cdot m^{-2} \cdot s^{-1}]$) stomata:

$$T = f_o \cdot T_o + (1 - f_o) \cdot T_c$$

where $f_o\ [-]$ is the weighting factor which is determined by the plant's water availability relative to the overall water demand.

Several model versions coexist in the code to compute this weighting factor. In the default model version, f_o is expressed as a function of the ratio of the water demand (w_{demand} $\left[kg_w \cdot m^{-2} \cdot s^{-1}\right]$) and supply (w_{supply} $\left[kg_w \cdot m^{-2} \cdot s^{-1}\right]$):

$$f_0 = \frac{1}{1+\frac{w_{demand}}{w_{supply}}}$$

And the plant's water demand and supply are respectively computed as:

$$w_{demand} = T_o \cdot n_{plant} \cdot SLA \cdot B_{leaf}$$

$$w_{supply} = K_w \cdot W_{avail,tot} \cdot B_{root}$$

with $n_{plant}\left[m^{-2}\right]$ the cohort plant density, SLA $\left[m^2 \cdot kg_C^{-1}\right]$ the PFT specific leaf area, B_{leaf} $\left[kg_C\right]$ the cohort leaf biomass, K_w $\left[m^2 \cdot kg_C^{-1} \cdot s^{-1}\right]$ the root water conductance and B_{root} $\left[kg_C\right]$ the individual root biomass as determined by an allometric equation function of the plant DBH. The total amount of water accessible to the vegetation layer $W_{avail,tot}$ $[m]$ is calculated as the sum of over all soil layers integration in the root zone:

$$W_{avail,tot} = \sum_{i=1}^{N_{max}} W_{avail,i}$$

with $N_{max}\left[-\right]$ is the total soil layer corresponding to the maximum rooting depth $z_{max}\left[m\right]$. The water available in each soil layer i, $W_{avail,i}$ $[m]$, is given either (i) by the total soil water above wilting point:

$$W_{avail,i} = D_i \cdot (\theta_i - \theta_{wp,i})$$

where D_i $[m]$ is the soil layer thickness or (ii) by the soil water content at field capacity minus wilting point, scaled by the so-called wilting factor:

$$W_{avail,i} = D_i \cdot (\theta_{fc,i} - \theta_{wp,i}) \cdot \left[\frac{\Psi_i - (H - z_i - \Psi_{wp,i})}{\Psi_{fc,i} - \Psi_{wp,i}}\right]$$

and H $[m]$ the crown height.

In ED2, the normalized soil drought index (SDI) is given by f_0.

The ORCHIDEE model, version 2.2

A full description of the ORCHIDEE v2.2 model and the hydrology module can be found on the ORCHIDEE wiki[1] and in Peylin et al. (In prep) and Tafasca et al. (2020).

Part 1: Soil parameters and pedotransfer functions

Soil water flow in ORCHIDEE follows the description of De Rosnay et al. (2002). It relies on a one-dimensional Fokker-Planck equation which combines the mass and momentum conservation equations using volumetric water content (θ) as the tracked state variable instead of the pressure head.

ORCHIDEE is designed to compute processes at a large spatial resolution. In this context, lateral fluxes between grid cells are ignored and all variables are horizontally homogeneous so that the mass conservation equation relates the vertical distribution of θ to its flux field $q\ [m \cdot s^{-1}]$:

$$\frac{\delta\theta(z,t)}{\delta t} = -\frac{\delta q(z,t)}{\delta z} - S(z,t)$$

where $z\ [m]$ is the depth below the soil surface, and $t\ [s]$ is the time. The sink term $S\ [m^3 \cdot m^{-3} \cdot s^{-1}]$ represents the plant water uptake and depends on the root's density profile. Flux field *q* is defined based on Darcy's equations (Darcy, 1856) for the saturated zone, extended by Buckingham's equations (Buckingham 1907) for unsaturated conditions.

Hydraulic conductivity $k\ [m \cdot s^{-1}]$ and diffusivity $D\ [m^2 \cdot s^{-1}]$ are defined by the link between the volumetric soil water content θ and the soil matric potential $\Psi\ [m]$:

$$D(\theta(z,t)) = k(\theta(z,t))\frac{\delta\Psi}{\delta\theta}(\theta(z,t))$$

k, D, and Ψ are defined by the equations of Mualem (1976) and van Genuchten (1980):

$$k(\theta) = k_{sat}\sqrt{\theta_f}(1 - (1 - \theta_f^{\frac{1}{m}})^m)^2$$

$$D(\theta) = \frac{(1-m)K(\theta)}{\alpha m}\frac{1}{\theta-\theta_r}\theta_f^{-1/m}(\theta_f^{-1/m} - 1)^{-m}$$

where $k_{sat}\ [m \cdot s^{-1}]$ is the saturated hydraulic conductivity, $\alpha\ [m \cdot s^{-1}]$ is the inverse of the air entry suction, $m\ [-]$is a dimensionless parameter related to the Van Genuchten parameter $n\ [-]$with $m = 1 - 1/n$, and θ_f is the relative water content varying between the residual water content $\theta_r\ [m^3 \cdot m^{-3}]$ and the saturated water content $\theta_s\ [m^3 \cdot m^{-3}]$:

$$\theta_f = \frac{\theta-\theta_r}{\theta_s-\theta_r}$$

The matric potential Ψ is related to the volumetric water content through:

$$\Psi(\theta) = -\frac{1}{\alpha}(\theta_f^{-1/m} - 1)^{1/n}$$

All the parameters involved in Van Genuchten relationships depend on soil texture. In ORCHIDEE, corresponding parameters (i.e. k_{sat}, a, θ_s, θ_r, n) are taken from Carsel and Parrish (1988) as a function of the dominant USDA soil texture class, so that each parameter is constant for each soil class. Only k_{sat}

[1]http://forge.ipsl.jussieu.fr/orchidee/attachment/wiki/Documentation/eqs_hydrol_25April2018_Ducharne.pdf

decreases exponentially with soil depth ($k(z)$) to account for soil compaction and bioturbation (d'Orgeval, Polcher, and de Rosnay 2008):

$$k_{sat}(z) = k_{sat}^{ref} \cdot F_K(z)$$

with:

$$F_K(z) = min(max(exp(-f(z - z_{lim}), 1/F_K^{max}), 1)$$

with k_{sat}^{ref} the reference value of k_{sat} based on the soil texture. Other parameters are PFT or soil dependent: z_{lim} is the depth at which the decrease of k_{sat} starts, $f\ [m^{-1}]$ is a decay factor. Soil depth is constant and set to 2m in the model, but is extended to 10 m to compute heat capacity and conductivity.

Part 2: Impact of drought stress on plant productivity

In addition to the Van Genuchten relationships, ORCHIDEE introduces a specific constraint on transpiration noted $\theta_{\%}$, corresponding to the soil moisture above which transpiration is maximum (i.e. not limited by water supply):

$$\theta_{\%} = \theta_{wp} + p \cdot (\theta_{fc} - \theta_{wp})$$

with θ_{wp} the water content at wilting point, θ_{fc} the water content at field capacity and $p\ [-]$ is a constant fixed to 0.8 for all soil classes.

The soil sink $S(z,t)$ describes the interplay between the transpiration flux, the soil moisture profile, and the root density profile which is assumed to decrease exponentially according to PFT-specific parameters (de Rosnay and Polcher 1998).

In each soil layer i, expected the top one which does not contribute to transpiration, the local sink S_i is linked to the drought stress factor U_s controlling the transpiration Et:

$$Et = \sum_{i>1} S_i$$

$$S_i = u_i \frac{Et}{U_s}$$

$$U_s = \sum_{i>1} u_i$$

with u_i the local drought stress factor varying linearly from 0 (full stress) at the wilting point θ_{wp} to 1 (no stress) at $\theta_{\%}$, which is smaller or equal to the water content at field capacity θ_{fc}. The stress factor u_i in each soil layer also depends on the mean relative root density in the layer i, called $n_{root}(i)$, with:

$$\sum_i n_{root}(i) = 1$$

$$u_1 = 0$$

$$u_i = n_{root}(i) max(0, min(1, (\theta_i - \theta_{wp})/(\theta_{\%} - \theta_{wp})))$$

The PFT aggregation at the grid-cell scale is additive, for both the transpiration flux and the total sink term.

Finally, the drought stress factor U_s will directly affect leaf stomatal g_s and mesophyll g_m conductances:

$$g_m = g_{m25} fT_{gm} U_s$$

$$g_s = g_0 \cdot U_s + \frac{A_n}{C_s - \Gamma} f_{VPD}$$

$$f_{VPD} = \frac{1}{1/min(1, a - bVPD)} U_s$$

with g_{m25} the reference g_m at 25°C, fT_{gm} the leaf temperature response, g_0 the residual stomatal conductance, A_n the net assimilation, C_s and Γ the leaf surface CO2 concentration and the CO_2 compensation point, respectively, and f_{VPD} a factor describing the effect of the vapor pressure deficit VPD on g_s, with a and b PFT-dependent constants.

In ORCHIDEE v2.2, the normalized soil drought index (SDI) is given by U_s.

The LPJ-GUESS model, version 4

Part 1: Soil parameters and pedotransfer functions

Based on soil texture input, the model will calculate soil hydraulic properties, based on the pedotransfer functions of Cosby et al. (1984) and Haxeltine and Prentice (1996). Soil matric potential Ψ is related to the volumetric water content θ:

$$\Psi = \Psi_{sat} \left(\frac{\theta}{\theta_{sat}} \right)^b$$

where θ_{sat} is the volumetric water content at saturation. The other two parameters are usually derived from fitting this function to moisture retention data: Ψ_{sat} is the soil matric potential at saturation, and b is a shape parameter. Just like in ED2, LPJ-GUESS derives these three parameters from the provided soil texture data following Cosby et al. (1984):

$$\theta_{sat} = 0.505 - 0.142 \cdot f_{sand} - 0.037 \cdot f_{clay}$$

$$\Psi_{sat} = -0.01 \cdot 10^{2.17 - 1.58 \cdot f_{sand} - 0.63 \cdot f_{clay}}$$

$$b = 3.1 - 0.3 \cdot f_{sand} + 15.7 \cdot f_{clay}$$

Soil matric potentials at wilting point and field capacity are defined as soil matric potential of $10^{-4.2}$ cm and 0.01 cm, respectively. Volumetric water contents at these potentials are derived from inverting the power function:

$$\theta_{wp} = \theta_{sat} \left(\frac{\Psi_{wp}}{\Psi_{sat}} \right)^{1/b}$$

$$\theta_{fc} = \theta_{sat} \left(\frac{\Psi_{fc}}{\Psi_{sat}} \right)^{1/b}$$

Available water capacity θ_{awc} is calculated as the difference between these two quantities: $\theta_{awc} = \theta_{fc} - \theta_{wp}$.

Percolation from a given layer is calculated following Haxeltine and Prentice (1996) and Sitch et al. (2003), which use the empirical relationship of Neilson (1995), namely:

$$Perc = k_{perc} W^2$$

where $k_{perc} = 5.87 - 0.29 \cdot b$ is the soil texture dependent percolation rate $[mm \cdot d^{-1}]$ at field capacity (Haxeltine and Prentice 1996) and *W* is the relative volumetric water content of the layer, expressed as a fraction of its available water holding capacity.

Part 2: Impact of drought stress on plant productivity

Drought stress is expressed as a balance between root water supply and leaf water demand:

$$SDI = \frac{w_{supply}}{w_{demand}}$$

When the water supply is lower than the demand, the plant is considered drought-stressed and stomatal conductance is reduced, which will in turn reduce productivity (Sitch et al. 2003)

The root distribution β_{root} of a given PFT will determine the fraction of total root biomass (*rootdist*) present in each soil layer (Jackson et al. 1996). In the LPJ standard parameterization of water uptake, this distribution will then determine the maximum water uptake (wu), summed over all soil layers (*i*):

$$wu = \sum_i rootdist(i) \times wcont(i) * r_{FPC}$$

where $wcont(i)$ is the relative soil moisture, expressed as a fraction of available water capacity, and $r_{FPC} = 1/FPC_{tot}$ is a patch-level rescaling factor to account for spatial overlap between cohorts, where FPC_{tot} is the total foliar projective cover of the current patch $[m^2 m^{-2}]$. The actual water supply for this PFT is computed as:

$$w_{supply} = e_{max} \cdot wu \cdot phen$$

where $phen$ indicates the leaf phenological status as a fraction of the potential leaf cover and e_{max} is a PFT-parameter indicating the maximum daily transpiration rate $[mmd^{-1}]$.

Leaf water demand is initially driven by the atmospheric evaporative demand (equilibrium evapotranspiration, EET; $[mmd^{-1}]$) which is calculated from input air temperature and incoming radiation and integrated over each simulated day (Prentice et al. 1992). The net EET for the vegetated parts (EET_{veg}) is then calculated by deducting patch-level interception losses.

Water demand is calculated using the hyperbolic representation from Huntingford and Monteith (1998), using EET_{veg} and the patch canopy conductance under no stress conditions (g_p,$[mms^{-1}]$):

$$w_{demand} = EET_{veg} \cdot \alpha_m \cdot \frac{g_p}{g_p + G_m}$$

where $\alpha_m = 1.391$, $G_m = 3.26 \;\; mm/s$. Canopy conductance under no drought stress (g_p) is calculated using the coupled photosynthesis and stomatal conductance equations, assuming that the stomata are fully opened, i.e. the ratio of intercellular to ambient CO_2 partial pressure (λ) is set to its maximum (λ_{max}, a PFT-specific parameter).

When $w_{supply} < w_{demand}$, the PFT is drought-stressed. Canopy conductance for a PFT under drought stressed conditions is then calculated using:

$$g_{c,base} = \frac{G_m \cdot w_{supply}}{\alpha_m \cdot EET_{veg} - w_{supply}} - g_{min} \cdot \frac{w_{supply}}{w_{demand}}$$

where g_{min} is the component of canopy conductance not associated with photosynthesis (PFT-specific parameter).

Using the canopy conductance under drought stress, the model will try to iteratively find a value for λ which simultaneously satisfies a canopy conductance- and light-based formulation of photosynthesis (Haxeltine and Prentice 1996).

Supplementary section 2: supplementary Figures

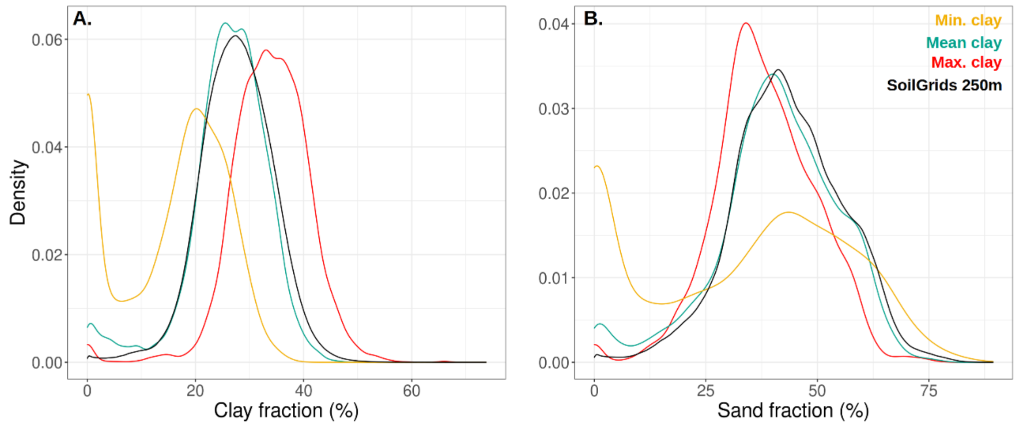
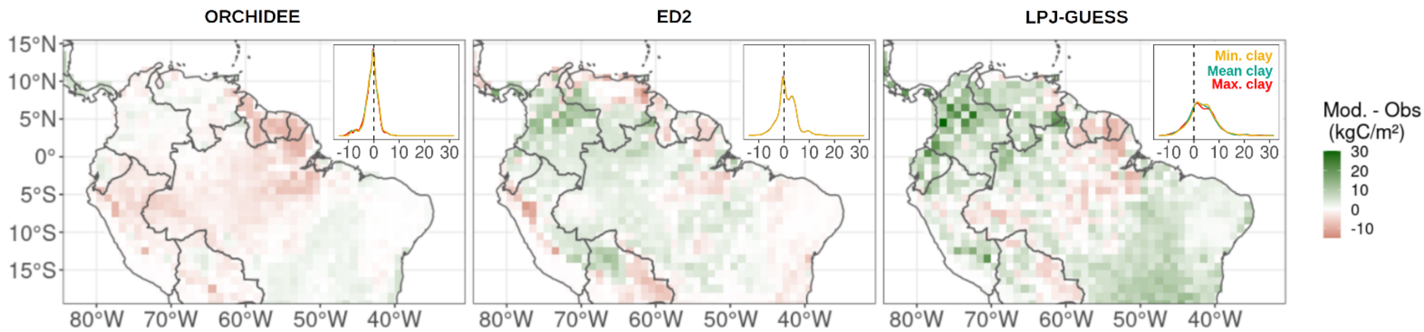


Figure S1: Soil clay (subplot A) and sand (subplot B) fraction distribution according to all three scenarios (coloured lines) and the SoilGrids 250m (black line).



Difference between the above-ground biomass spatial distribution predicted at the end of the historical period (average over the 2006-2016 period) by the three terrestrial biosphere models used in this study for the Mean clay scenario (Mod) and that generated by Avitabile et al. (2016) (Obs). The upper-right corners in each plot show the above-ground biomass density distributions of those differences over the simulated region for all three scenarios.

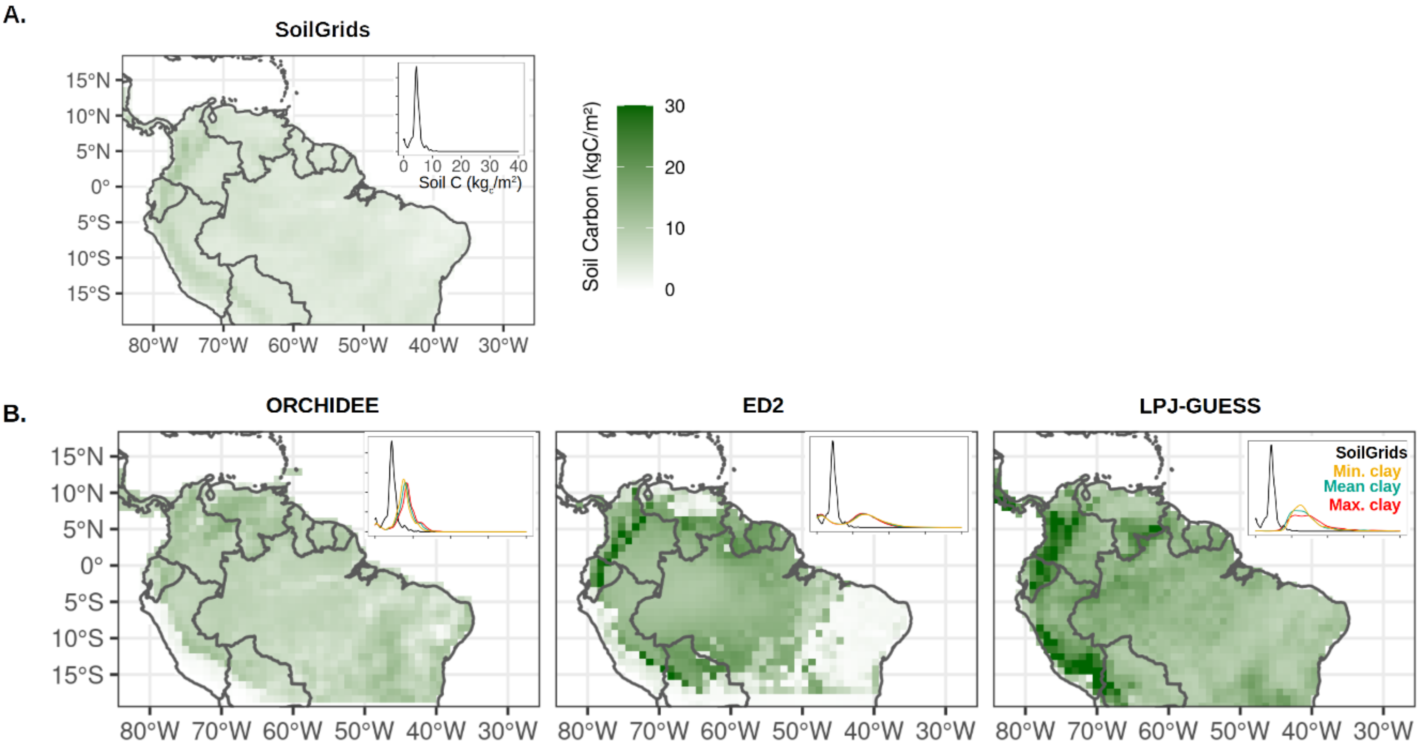


Figure S3: Soil carbon spatial distribution, as compiled by SoilGrids (A) or as simulated by the three terrestrial biosphere models used in this study for the *Mean clay* scenario (B). The upper-right corners in each subplot represent the soil carbon density distributions over the simulated region for all three scenarios (coloured lines) and the SoilGrids database (black).

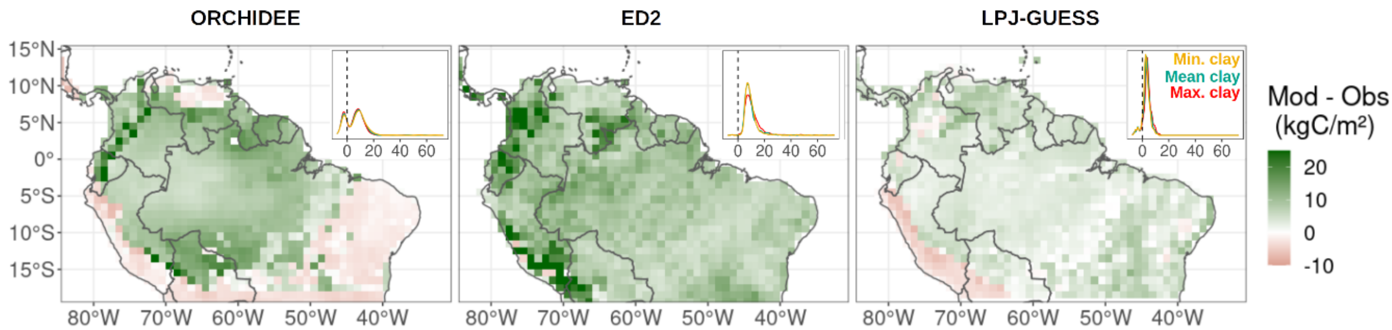


Figure S4: Difference between the soil carbon spatial distribution predicted at the end of the historical period (average over the 2006-2016 period) by the three terrestrial biosphere models used in this study for the Mean clay scenario (Mod) and that from SoilGrids (Obs). The upper-right corners in each plot show the soil carbon density distributions of those differences over the simulated region for all three scenarios.

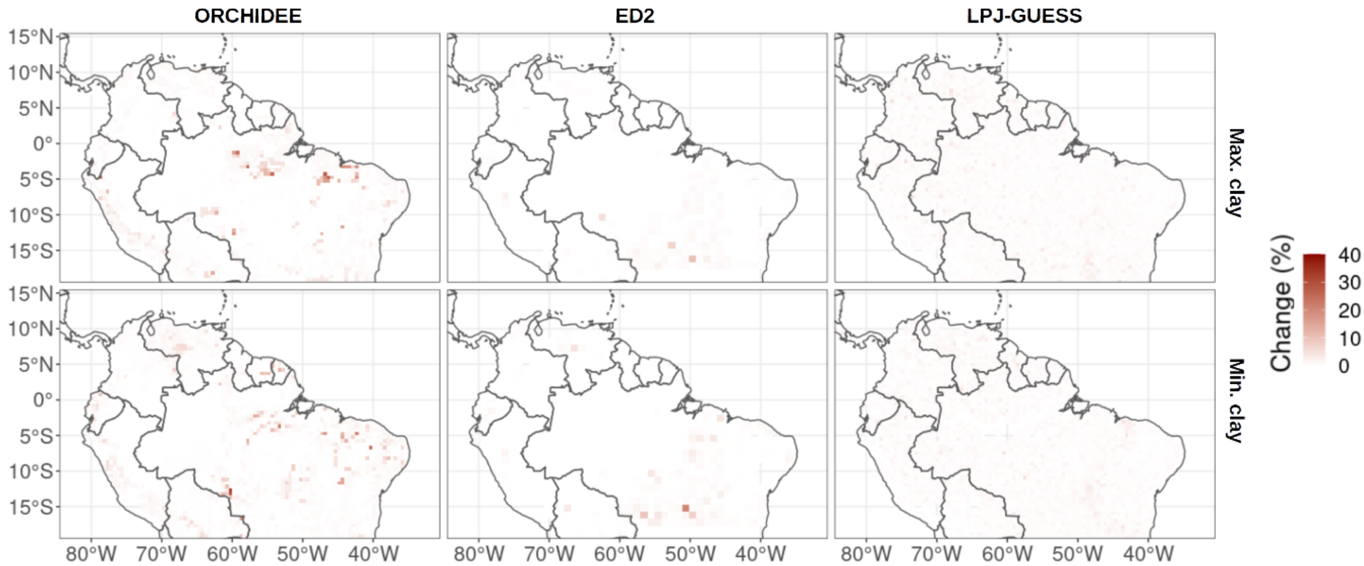


Figure S5: Location of the gridcells with important changes in the PFT-level GPP for all three TBMs (columns) and scenarios (rows). Here, change refers to the maximum PFT-level absolute relative change in average GPP over the ten last years of the simulation (2006-2016)

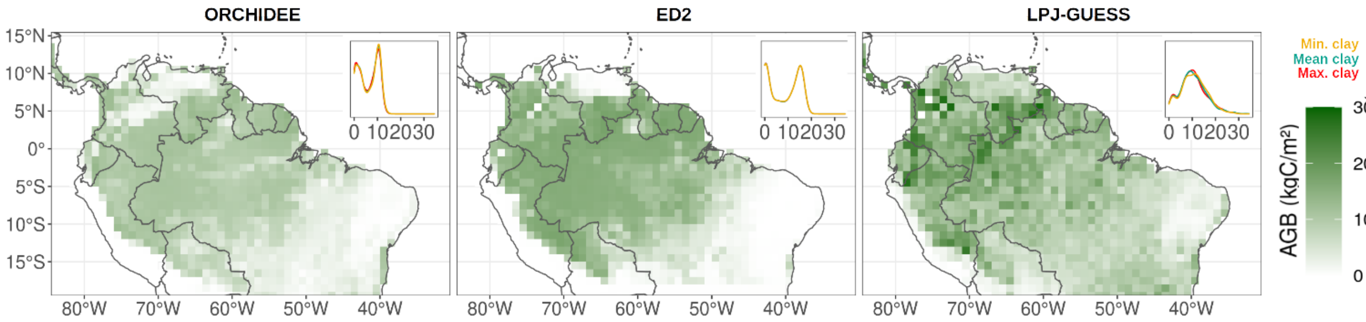


Figure S6: Aboveground biomass spatial distribution as simulated by the three terrestrial biosphere models used in this study at the end of the spin-up phase for the average clay scenario. The upper-right corners in each subplot represent the spin-up aboveground biomass density distributions over the simulated region for all three scenarios (coloured lines).

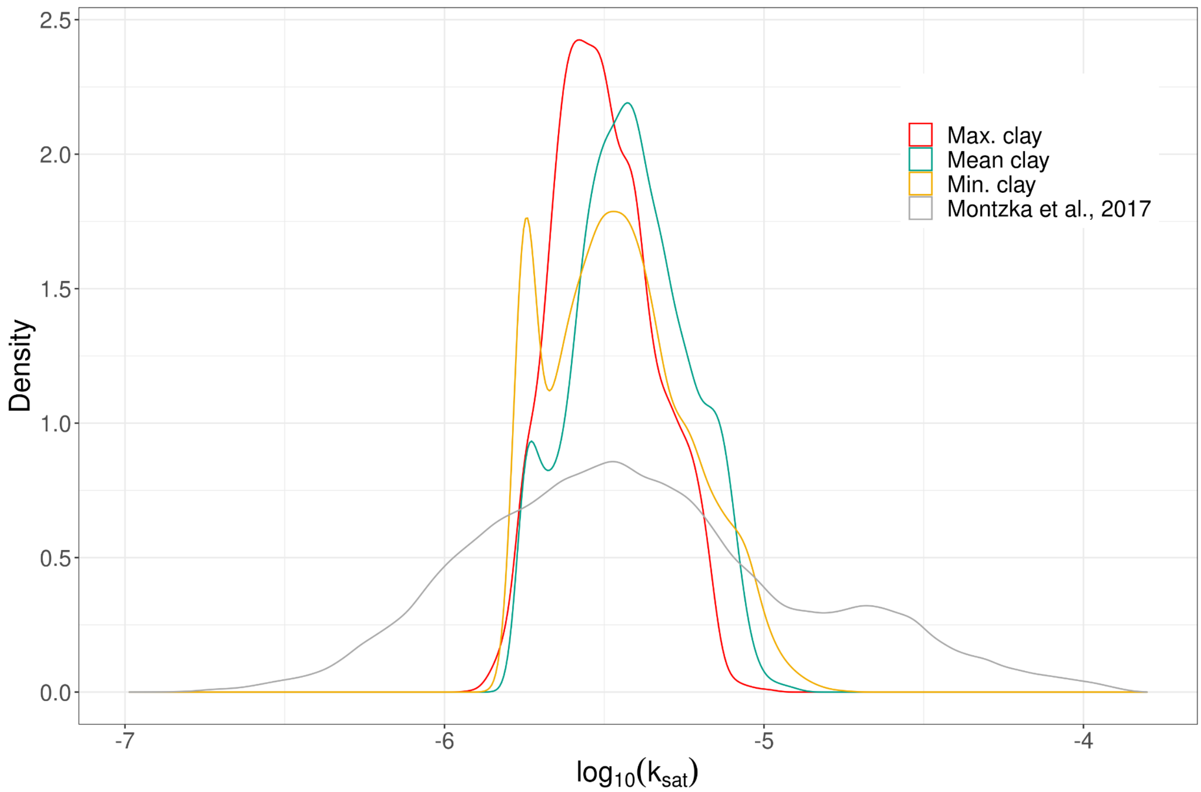


Figure S7: Soil saturated hydraulic conductivity (k_{sat}) as derived from the soil textural data of SoilGrids 250m, the three soil scenarios and the pedotransfer functions used in ED2 (colored distributions), or as generated by Montzka et al. (2017) for the South-American tropics (grey distribution) using different soil pedotransfer functions.

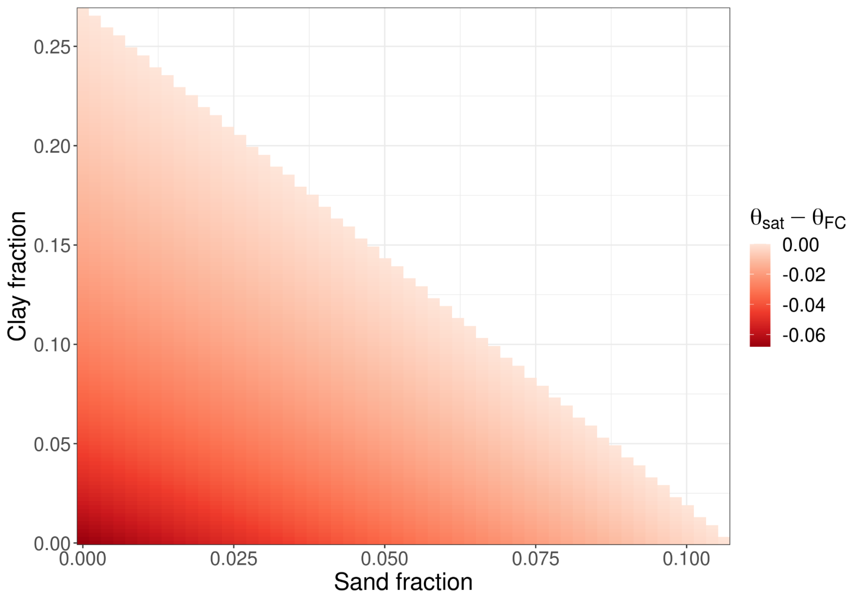


Figure S8: Sand and clay fractions leading to larger water content at field capacity than at saturation in LPJ-GUESS, and hence model crash after initialization.