

# Terrestrial Ecosystem Model in R (TEMIR) version 1.0: simulating ecophysiological responses of vegetation to atmospheric chemical and meteorological changes

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**Abstract.** The newly developed offline land ecosystem model Terrestrial Ecosystem Model in R (TEMIR) version 1.0 is described here. This version of the model simulates plant ecophysiological (e.g., photosynthetic and stomatal) responses to varying meteorological conditions and concentrations of CO<sub>2</sub> and ground-level ozone (O<sub>3</sub>) based on prescribed meteorological and atmospheric chemical inputs from various sources. Driven by the same meteorological data used in the GEOS-Chem chemical transport model, this allows asynchronously coupled experiments with GEOS-Chem simulations with unique coherency for investigating biosphere–atmosphere chemical interactions. TEMIR agrees well with FLUXNET site-level gross primary productivity (GPP) in terms of both the diurnal and monthly cycles (correlation coefficients  $R^2 > 0.85$  and  $R^2 > 0.8$ , respectively) for most plant functional types (PFTs). Grass and shrub PFTs have larger biases due to generic model representations. The model performs best when driven by local site-level meteorology rather than reanalyzed gridded meteorology. Simulation using gridded meteorology agrees well for annual GPP in seasonality and spatial distribution with a global average of 134 Pg C yr<sup>−1</sup>. Application of Monin–Obukhov similarity theory to infer canopy conditions from gridded meteorology does not improve model performance, predicting a uniform increase of +21 % C<sub>ET</sub> for global GPP. Present-day O<sub>3</sub> concentrations simulated by GEOS-Chem and an O<sub>3</sub> damage scheme at high sensitivity show a 2 %

reduction in global GPP with prominent reductions of up to 15 % in eastern China and the eastern USA. Regional correlations are generally unchanged when O<sub>3</sub> is present and biases are reduced, especially for regions with high O<sub>3</sub> damage. An increase in atmospheric CO<sub>2</sub> concentration of 20 ppmv from the level in 2000 to the level in 2010 modestly decreases O<sub>3</sub> damage due to reduced stomatal uptake, consistent with ecophysiological understanding. Our work showcases the utility of this version of TEMIR for evaluating biogeophysical responses of vegetation to changes in atmospheric composition and meteorological conditions.

## 1 Introduction

Terrestrial vegetation, as an integral part of the global biosphere, plays many vital roles in regulating the earth system. It facilitates a substantial portion of the global land–atmosphere exchange of energy, momentum, and chemical species relevant for climate and atmospheric chemistry. It is a major sink for atmospheric carbon, sequestering an estimated 123 ± 8 Pg C of carbon dioxide (CO<sub>2</sub>) from the atmosphere annually through plant photosynthesis (Beer et al., 2010; Le Quéré et al., 2015), albeit with a relatively large observation-constrained range of 119–175 Pg C yr<sup>−1</sup>.

This vegetation-mediated process of CO<sub>2</sub> sequestration, also known as gross primary productivity (GPP), is a key

The model considers co-limitation (Collatz et al., 1991; Collatz et al., 1992), and the leaf-level gross photosynthesis rate ( $A$ , in  $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ ) is given by the smaller root of the following equations:

$$\begin{aligned} \Theta_{c_j} A_i^2 - (A_c + A_j) A_i + A_c A_j &= 0, \\ \Theta_{ip} A^2 - (A_i + A_p) A + A_i A_p &= 0. \end{aligned} \quad (17)$$

**C32** The net photosynthesis rate ( $A_n$ , in  $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ ) is then

$$\begin{aligned} A_n &= A - R_d \\ R_d &= \begin{cases} 0.015 V_{\text{cmax}} \frac{f_{R_d}(T_v)}{f_{V_{\text{cmax}}}(T_v)} & \text{for } C_3 \text{ plants} \\ 0.025 V_{\text{cmax}} \left( \frac{(1+\exp[s_1(T_v-s_2)])(1+\exp[s_3(T_v-s_4)])}{1+\exp[s_5(T_v-s_6)]} \right) & \text{for } C_4 \text{ plants,} \end{cases} \end{aligned} \quad (18)$$

where  $R_d$  (in  $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ ) is the dark respiration rate;  $s_1$ ,  $s_3$ , and  $s_5$  are 0.3, 0.2, and 1.3 K, respectively;  $s_2$ ,  $s_4$ , and  $s_6$  are 313.15, 288.15, and 328.15  $\text{K}^{-1}$ , respectively;  $T_v$  is leaf temperature (in degrees K); and  $f_{R_d}(T_v)$  and  $f_{V_{\text{cmax}}}(T_v)$  are functions to adjust for variations due to temperature (Bonan et al., 2011). All of the parameters ( $V_{\text{cmax}}$ ,  $J_{\text{max}}$ ,  $T_p$ ,  $R_d$ ,  $K_c$ ,  $K_o$ ,  $\Gamma_*$ , and  $k_p$ ) are temperature-dependent and scale with their respective PFT-specific standard values at 25 °C by different formulations. Temperature acclimation of  $V_{\text{cmax}}$  and  $J_{\text{max}}$  from the previous 10 d, as well as day-length dependence of  $V_{\text{cmax}}$ , is implemented as the default option. These are all detailed in Sects. 8.2 and 8.3 of Oleson et al. (2013).

The calculation of photosynthesis rates described above is coupled with that of stomatal conductance of water ( $g_s$ , in  $\text{m s}^{-1}$ ) following the formulation of Ball et al. (1987) with  $m$  and  $b$  being the slope and intercept parameters derived from empirical data:

$$g_s = \alpha \left( m A_n \frac{\frac{e_s}{e_{\text{sat}}}}{\frac{c_s}{P_{\text{atm}}}} + b \right), \quad (19)$$

where  $g_s$  is controlled by the leaf surface  $\text{CO}_2$  partial pressure  $c_s$  (in Pa), leaf surface water vapor pressure  $e_s$  (in Pa), and temperature-dependent saturation vapor pressure  $e_{\text{sat}}$  (in Pa);  $m = 9$  and  $b = 10\,000 \mu\text{mol m}^{-2} \text{ s}^{-1}$  for  $C_3$  plants, and  $m = 4$  and  $b = 40\,000 \mu\text{mol m}^{-2} \text{ s}^{-1}$  for  $C_4$  plants; and the factor  $\alpha$  converts the unit of conductances from  $\mu\text{mol H}_2\text{O m}^{-2} \text{ s}^{-1}$ , which is more common in eco-physiology literature, to  $\text{m s}^{-1}$ , which is common in atmospheric science literature:

$$\alpha = \frac{10^{-6} R_{\text{uni}} \theta_{\text{atm}}}{P_{\text{atm}}}, \quad (20)$$

where  $R_{\text{uni}} = 8.314468 \text{ J K}^{-1} \text{ mol}^{-1}$  is the universal gas constant and  $\theta_{\text{atm}}$  (in degrees K) is the ambient atmospheric potential temperature. An alternative stomatal conductance

scheme (Medlyn et al., 2011; Franks et al., 2017) is also implemented:

$$g_s = \alpha \left[ 1.6 \left( 1 + \frac{m}{\sqrt{\text{VPD}}} \right) \frac{A_n}{\frac{c_s}{P_{\text{atm}}}} + b \right], \quad (21)$$

where  $\text{VPD} = 0.001(e_{\text{sat}} - e_s)$  (in kPa) is the vapor pressure deficit,  $m$  has PFT-specific values consistent with CLM5.0 (Sect. 9.3 of Lawrence et al., 2020), and  $b = 100 \mu\text{mol m}^{-2} \text{ s}^{-1}$ . Photosynthesis and stomatal conductance are further related by the diffusive flux equations for  $\text{CO}_2$  and water vapor:

$$\begin{aligned} A_n &= \frac{1}{\alpha} \left( \frac{1.4}{g_b} + \frac{1.6}{g_s} \right)^{-1} \frac{c_a - c_i}{P_{\text{atm}}} = \frac{g_b}{1.4\alpha} \frac{c_a - c_s}{P_{\text{atm}}} \\ &= \frac{g_s}{1.6\alpha} \frac{c_s - c_i}{P_{\text{atm}}}, \end{aligned} \quad (22)$$

$$\begin{aligned} E' &= \frac{1}{\alpha} \left( \frac{1}{g_b} + \frac{1}{g_s} \right)^{-1} \frac{e_a - e_i}{P_{\text{atm}}} = \frac{g_b}{\alpha} \frac{e_a - e_s}{P_{\text{atm}}} \\ &= \frac{g_s}{\alpha} \frac{e_s - e_i}{P_{\text{atm}}}, \end{aligned} \quad (23)$$

where  $c_a$  (in Pa) and  $e_a$  (in Pa) are the canopy air  $\text{CO}_2$  partial and water vapor pressure,  $e_i$  (in Pa) is the saturation vapor pressure at the leaf temperature,  $E'$  (in  $\mu\text{mol H}_2\text{O m}^{-2} \text{ s}^{-1}$ ) is the transpiration flux, and  $g_b$  (in  $\text{m s}^{-1}$ ) is the leaf boundary layer conductance:

$$g_b = C_v \sqrt{\frac{u_*}{d_l}}. \quad (24)$$

The photosynthesis–stomatal conductance model considers limitation arising from soil water stress. A soil water stress factor ( $\beta_t$ ) scales the photosynthesis rate and stomatal conductance, being multiplied directly to  $A$ ,  $R_d$  in Eq. (18) and  $b$  in Eq. (19) or Eq. (21) to account for soil water stress (Porporato et al., 2001; Verhoef and Egea, 2014). To compute  $\beta_t$ , we consider a two-layer soil model consisting of a top-soil layer (0–5 cm) and a root zone beneath the top soil (5–100 cm), consistent with and constrained by the input soil moisture and model structure of MERRA-2. First, the soil matric potential in each layer  $i$ ,  $\psi_i$  (in mm), that represents water availability in ecophysiological terms is evaluated as a function of soil wetness ( $s_i$ ) and soil type:

$$\psi_i = \psi_{\text{sat},i} s_i^{-B_i}, \quad (25)$$

where  $\psi_{\text{sat},i}$  and  $B_i$  refer to the saturated soil matric potential and soil water characteristic parameter, respectively, both depending on soil texture. A wilting factor,  $w_i$ , is formulated as a function of  $\psi_i$  as well as  $\psi_c$  and  $\psi_o$  (Table S2), which refer to the matric potential at which stomatal closure and stomatal opening occur to the full extent, respectively:

$$w_i = \begin{cases} 1 & \text{for } \psi_i > \psi_o \\ \frac{\psi_c - \psi_i}{\psi_c - \psi_o} & \text{for } \psi_c \leq \psi_i \leq \psi_o \\ 0 & \text{for } \psi_i < \psi_c. \end{cases} \quad (26)$$