Process-oriented models of autumn leaf phenology: ways to sound calibration and implications of uncertain projections

Michael Meier, Christof Bigler
https://doi.org/10.5194/gmd-16-1-2023-supplement

Correspondence to: Michael Meier (michael.meier@cefe.cnrs.fr)

S1 Process-oriented models for autumn phenology

In this study, we compared 21 process-oriented models for autumn phenology (Meier, 2022). In all models, the projected date for autumn phenology corresponds to the first day of year [doy] a daily accumulated senescence rate (Eq. S1) exceeds a corresponding threshold (Eq. S2):

$$S_{d_n} = \sum_{i=d_1}^{d_n} R_{S_i}$$

Eq. S1

$$S_{d_n} \geq Y_{crit}$$

Eq. S2

Here, R_{Si} is the senescence rate of the i^{th} day of the accumulation period for R_{Si} that consists of n consecutive days and starts with d_1. S_{dn} is the senescence status at day d_n, and Y_{crit} is the corresponding threshold value.

Depending on the model, the daily senescence rate is formulated in one of three different ways and, with colder temperatures, follows either a monotonically increasing (Eqs. S3 and S4) or a sigmoidal ($R_{S,Sig}$; Eq. S5) response curve, with the monotonous increase weakened ($R_{S,Mon-}$; Eq. S3) or amplified ($R_{S,Mon+}$; Eq. S4) with shorter days (Delpierre et al., 2009; Lang et al., 2019; Dufrêne et al., 2005).

$$R_{S,Mon-_i} = \begin{cases} (T_{base} - T_i)^x \times \left({L_i}/{L_{base}} \right)^y & , \quad T_i < T_{base} \wedge L_i < L_{base} \\ 0 & , \quad T_i \geq T_{base} \vee L_i \geq L_{base} \end{cases}$$

Eq. S3

$$R_{S,Mon+_i} = \begin{cases} (T_{base} - T_i)^x \times \left(1 - {L_i}/{L_{base}} \right)^y & , \quad T_i < T_{base} \wedge L_i < L_{base} \\ 0 & , \quad T_i \geq T_{base} \vee L_i \geq L_{base} \end{cases}$$

Eq. S4

$$R_{S,Sig_i} = {1}/{1 + e^{a \times (T_i \times L_i - b)}}$$

Eq. S5

Here, T_i and L_i are the minimum temperature and day length of day i, T_{base} and L_{base} are the corresponding threshold values fitted during model calibration. The parameters x, y, a, and b are free parameters, which are also fitted during model calibration. For the DM1 and DM2 models, x and y are restrained to integers [$\in$ (0, 1, 2)] (Delpierre et al., 2009), whereas for the SIAM model, x and y are fixed to 1 (Keenan and Richardson, 2015). Moreover, in the CDD model, R_S depends linearly on daily minimum temperature and the response is neither decreasing nor increasing with shorter day lengths (i.e. x = 1 and y = 0; Dufrêne et al., 2005). We used the daily minimum temperature in all models for the reasons discussed in Sect. 4.5.2, rather than the daily mean temperature in the models CDD, DM1, DM2, SIAM, TDM1, TDM2, PDM1, PDM2, TPDM1, and TPDM2, which would have been in accordance to the corresponding original publications (Delpierre et al., 2009; Dufrêne et al., 2005; Keenan and Richardson, 2015; Liu et al., 2019).

The first day of the accumulation period (d_1) depends on the day of year, on daily minimum temperature, and/or on day length. Depending on the model, the earliest possible day for d_1 is either the 173th or 200th day of year, with the former day corresponding to summer solstice. Thereafter, d_1 is the first day with a lower temperature than T_{base} (CDD and TPMt) or a shorter day length than L_{base} (TPMp, $SIAM_{Za20}$, TDM_{Za20}, PDM_{Za20}, $TPDM_{Za20}$, PIA_{GSI}, PIA^+, and PIA^-) or both (other models). Furthermore, in all models R_S approaches or becomes 0 with high temperatures (Eqs. S3–S5). Therefore, even if d_1 is theoretically independent of temperature in certain models, the accumulation of R_S generally only starts after temperatures are sufficiently low.

The threshold value (Y_{crit}; Eq. S6) is either a constant (c) which is optimized during model calibration (for the CDD, DM1, DM2, $DM1_{Za20}$, $DM2_{Za20}$, TPMt, and TPMp models) or depends linearly on one or two seasonal drivers. If Y_{crit} depends linearly on seasonal drivers (D_1 and D_2), the coefficients for the intercept (b_0) and respective drivers (b_1 and b_2) are optimized during model calibration.

$$Y_{crit} = b_0 + b_1 D_1 + b_2 D_2$$

Eq. S6

Generally, the seasonal drivers correspond to a typical growing period which was defined before the calibration (e.g. observed spring phenology to averaged autumn phenology). But the seasonal drivers for the models by Liu et al. (2019; i.e. TDM1, TDM2, PDM1, PDM2, TPDM1, and TPDM2 models) correspond to the “leafy season”, defined as the period from the observed spring phenology to the first day of the accumulation period (d_1). This day is the first day after summer solstice for which $L_i < L_{base}$. and it may change for each year at a given site and for a given species.

Table S1. The 21 process-oriented phenology models compared in this study with their functions, free parameters and corresponding boundaries for parameter optimization.

Model	Daily senescence rate (R_S), starting day (d_1), and threshold (Y_{crit})	Free parameters and boundaries
CDD (Du05)	$R_S = R_{S,Mon-}$ with $x = 1$ and $y = 0$	$15 \leq T_{base} \leq 30$
	$d_1 = min(i)$ for which $i > 200 \wedge T_i < T_{base}$	
	$Y_{crit} = c$	$0 \leq c \leq 15000$
DM1 (De09)	$R_S = R_{S,Mon-}$	$15 \leq T_{base} \leq 30$ $11 \leq L_{base} \leq 20$ $x \in (0,1,2)$ $y \in (0,1,2)$
	$d_1 = min(i)$ for which $i > 173 \wedge T_i < T_{base} \wedge L_i < L_{base}$	
	$Y_{crit} = c$	$0 \leq c \leq 15000$
DM1$_{Za20}$ (Za20)	$R_S = R_{S,Mon-}$ with $x = 1$ and $y = 1$	$15 \leq T_{base} \leq 35$ $11 \leq L_{base} \leq 20$
	$d_1 = min(i)$ for which $i > 173 \wedge T_i < T_{base} \wedge L_i < L_{base}$	
	$Y_{crit} = c$	$0 \leq c \leq 15000$
DM2 (De09)	$R_S = R_{S,Mon+}$	$15 \leq T_{base} \leq 30$ $11 \leq L_{base} \leq 20$ $x \in (0,1,2)$ $y \in (0,1,2)$
	$d_1 = min(i)$ for which $i > 173 \wedge T_i < T_{base} \wedge L_i < L_{base}$	
	$Y_{crit} = c$	$0 \leq c \leq 15000$
DM2$_{Za20}$ (Za20)	$R_S = R_{S,Mon+}$ with $x = 1$ and $y = 1$	$15 \leq T_{base} \leq 35$ $11 \leq L_{base} \leq 20$
	$d_1 = min(i)$ for which $i > 173 \wedge T_i < T_{base} \wedge L_i < L_{base}$	
	$Y_{crit} = c$	$0 \leq c \leq 15000$
SIAM (Ke15)	$R_S = R_{S,Mon-}$ with $x = 1$ and $y = 1$	$15 \leq T_{base} \leq 35$ $11 \leq L_{base} \leq 20$
	$d_1 = min(i)$ for which $i > 173 \wedge T_i < T_{base} \wedge L_i < L_{base}$	
	$Y_{crit} = b_0 + b_1 \times a.d_{SP}$	$0 \leq b_0 \leq 15000$ $0 \leq b_1 \leq 5$
SIAM$_{Za20}$ (Za20)	$R_S = R_{S,Sig}$	$0 \leq a \leq 0.1$ $0 \leq b \leq 250$
	$d_1 = min(i)$ for which $i > 173 \wedge L_i < L_{base}$	$10 \leq L_{base} \leq 20$
	$Y_{crit} = b_0 + b_1 \times a.d_{SP}$	$0 \leq b_0 \leq 150$ $0 \leq b_1 \leq 5$
TPMt (La19)	$R_S = R_{S,Sig}$	$0 \leq a \leq 0.1$ $0 \leq b \leq 250$
	$d_1 = min(i)$ for which $i > 200 \wedge T_i < T_{base}$	$0 \leq T_{base} \leq 35$
	$Y_{crit} = c$	$0 \leq c \leq 150$
TPMp (La19)	$R_S = R_{S,Sig}$	$0 \leq a \leq 0.1$ $0 \leq b \leq 250$
	$d_1 = min(i)$ for which $i > 173 \wedge L_i < L_{base}$	$10 \leq L_{base} \leq 20$
	$Y_{crit} = c$	$0 \leq c \leq 150$

Table S1. Continued.

TDM1 (Li19)	$R_S = R_{S,Mon-}$	$10 \leq T_{base} \leq 35$ $11 \leq L_{base} \leq 20$ $0 \leq x \leq 2$ $0 \leq y \leq 2$
	$d_1 =$ $min(i)$ for which $i > 173 \wedge T_i < T_{base} \wedge L_i < L_{base}$	
	$Y_{crit} = b_0 + b_1 \times \overline{\sum_{i=d_{SP}}^{d_1} T_i}$	$0 \leq b_0 \leq 15000$ $-50 \leq b_1 \leq 15$
PDM1 (Li19)	$R_S = R_{S,Mon-}$	$10 \leq T_{base} \leq 35$ $11 \leq L_{base} \leq 20$ $0 \leq x \leq 2$ $0 \leq y \leq 2$
	$d_1 =$ $min(i)$ for which $i > 173 \wedge T_i < T_{base} \wedge L_i < L_{base}$	
	$Y_{crit} = b_0 + b_1 \times \overline{\sum_{i=d_{SP}}^{d_1} LPI_i}$	$0 \leq b_0 \leq 15000$ $-40 \leq b_1 \leq 15$
TPDM1 (Li19)	$R_S = R_{S,Mon-}$	$10 \leq T_{base} \leq 35$ $11 \leq L_{base} \leq 20$ $0 \leq x \leq 2$ $0 \leq y \leq 2$
	$d_1 =$ $min(i)$ for which $i > 173 \wedge T_i < T_{base} \wedge L_i < L_{base}$	
	$Y_{crit} = b_0 + b_1 \times \overline{\sum_{i=d_{SP}}^{d_1} T_i} + b_2 \times \overline{\sum_{i=d_{SP}}^{d_1} LPI_i}$	$0 \leq b_0 \leq 15000$ $-50 \leq b_1 \leq 15$ $-40 \leq b_2 \leq 15$
TDM2 (Li19)	$R_S = R_{S,Mon+}$	$10 \leq T_{base} \leq 35$ $11 \leq L_{base} \leq 20$ $0 \leq x \leq 2$ $0 \leq y \leq 2$
	$d_1 =$ $min(i)$ for which $i > 173 \wedge T_i < T_{base} \wedge L_i < L_{base}$	
	$Y_{crit} = b_0 + b_1 \times \overline{\sum_{i=d_{SP}}^{d_1} T_i}$	$0 \leq b_0 \leq 15000$ $-50 \leq b_1 \leq 15$
PDM2 (Li19)	$R_S = R_{S,Mon+}$	$10 \leq T_{base} \leq 35$ $11 \leq L_{base} \leq 20$ $0 \leq x \leq 2$ $0 \leq y \leq 2$
	$d_1 =$ $min(i)$ for which $i > 173 \wedge T_i < T_{base} \wedge L_i < L_{base}$	
	$Y_{crit} = b_0 + b_1 \times \overline{\sum_{i=d_{SP}}^{d_1} LPI_i}$	$0 \leq b_0 \leq 15000$ $-40 \leq b_1 \leq 15$

Table S1. Continued.

TPDM2 (Li19)	$R_S = R_{S,Mon+}$	$10 \leq T_{base} \leq 35$ $11 \leq L_{base} \leq 20$ $0 \leq x \leq 2$ $0 \leq y \leq 2$
	$d_1 = min(i)$ for which $i > 173 \wedge T_i < T_{base} \wedge L_i < L_{base}$	
	$Y_{crit} = b_0 + b_1 \times \overline{\sum_{i=d_{SP}}^{d_1} T_i} + b_2 \times \overline{\sum_{i=d_{SP}}^{d_1} LPI_i}$	$0 \leq b_0 \leq 15000$ $-50 \leq b_1 \leq 15$ $-40 \leq b_2 \leq 15$
TDM$_{Za20}$ (Za20)	$R_S = R_{S,Sig}$	$0 \leq a \leq 0.1$ $0 \leq b \leq 250$
	$d_1 = min(i)$ for which $i > 173 \wedge L_i < L_{base}$	$10 \leq L_{base} \leq 20$
	$Y_{crit} = b_0 + b_1 \times \sum_{i=d_{SP}}^{d_{\overline{AP}}} T_i$	$0 \leq b_0 \leq 150$ $-50 \leq b_1 \leq 15$
PDM$_{Za20}$ (Za20)	$R_S = R_{S,Sig}$	$0 \leq a \leq 0.1$ $0 \leq b \leq 250$
	$d_1 = min(i)$ for which $i > 173 \wedge L_i < L_{base}$	$10 \leq L_{base} \leq 20$
	$Y_{crit} = b_0 + b_1 \times LPI_{Za20}$	$0 \leq b_0 \leq 150$ $-15 \leq b_1 \leq 40$
TPDM$_{Za20}$ (Za20)	$R_S = R_{S,Sig}$	$0 \leq a \leq 0.1$ $0 \leq b \leq 250$
	$d_1 = min(i)$ for which $i > 173 \wedge L_i < L_{base}$	$10 \leq L_{base} \leq 20$
	$Y_{crit} = b_0 + b_1 \times \overline{\sum_{i=d_{SP}}^{d_{\overline{AP}}} T_i} + b_2 \times LPI_{Za20}$	$0 \leq b_0 \leq 150$ $-15 \leq b_1 \leq 40$ $-40 \leq b_2 \leq 15$
PIA$_{GSI}$ (Za20)	$R_S = R_{S,Sig}$	$0 \leq a \leq 0.1$ $0 \leq b \leq 250$
	$d_1 = min(i)$ for which $i > 173 \wedge L_i < L_{base}$	$10 \leq L_{base} \leq 20$
	$Y_{crit} = b_0 + b_1 \times a.GSI_{Za20}$	$0 \leq b_0 \leq 300$ $0 \leq b_1 \leq 5$
PIA$^+$ (Za20)	$R_S = R_{S,Sig}$	$0 \leq a \leq 0.1$ $0 \leq b \leq 250$
	$d_1 = min(i)$ for which $i > 173 \wedge L_i < L_{base}$	$10 \leq L_{base} \leq 20$
	$Y_{crit} = b_0 + b_1 \times a.A_{net}$	$0 \leq b_0 \leq 300$ $0 \leq b_1 \leq 5$
PIA$^-$ (Za20)	$R_S = R_{S,Sig}$	$0 \leq a \leq 0.1$ $0 \leq b \leq 250$
	$d_1 = min(i)$ for which $i > 173 \wedge L_i < L_{base}$	$10 \leq L_{base} \leq 20$
	$Y_{crit} = b_0 + b_1 \times a.A_{net-w}$	$0 \leq b_0 \leq 300$ $0 \leq b_1 \leq 5$

Note: The functions for the daily senescence rate (R_S), starting day of the accumulation of the rate (d_1), and respective threshold value (Y_{crit}) to determine the date of autumn phenology are listed together with the corresponding free parameters and their boundaries. Daily drivers of the senescence rate are minimum temperature (T_i) and/or day length (L_i) of day i [doy]. Seasonal drivers of the threshold value for the senescence rate are averaged daily low precipitation indices (LPI_i), minimum temperatures (T_i), and actual adapted low precipitation indices by Za20 (LPI_{Za20}), as well as site-specific anomalies of spring phenology ($a.d_{SP}$), of the growing season index by Za20 ($a.GSI_{Za20}$), and of accumulated net daytime net photosynthesis without or with water limitation ($a.A_{net}$ or $a.A_{net-w}$). The averaged drivers either correspond to the period from spring phenology (d_{SP}) to the starting day of the accumulation of the rate (d_1) or to the site-specific average of autumn phenology ($d_{\overline{AP}}$). Free parameters may be a threshold value for daily temperature and day length (T_{base} and L_{base}), shaping parameters of the monotonic decreasing or increasing or the sigmoid response function of the senescence rate (x, y, a, and b), a constant or coefficients of the linear function determining the threshold value for the senescence rate (c, b_0, b_1, and b_2), depending on the model. References for the models are De09: Delpierre et al. (2009); Du05: Dufrêne et al. (2005); Ke15: Keenan and Richardson (2015); La19: Lang et al. (2019); Li19: Liu et al. (2019); Za20: Zani et al. (2020).

References

Delpierre, N., Dufrene, E., Soudani, K., Ulrich, E., Cecchini, S., Boe, J., and Francois, C.: Modelling interannual and spatial variability of leaf senescence for three deciduous tree species in France, Agricultural and Forest Meteorology, 149, 938-948, 10.1016/j.agrformet.2008.11.014, 2009.

Dufrêne, E., Davi, H., Francois, C., le Maire, G., Le Dantec, V., and Granier, A.: Modelling carbon and water cycles in a beech forest Part I: Model description and uncertainty analysis on modelled NEE, Ecol. Model., 185, 407-436, 10.1016/j.ecolmodel.2005.01.004, 2005.

Keenan, T. F. and Richardson, A. D.: The timing of autumn senescence is affected by the timing of spring phenology: implications for predictive models, Glob Chang Biol, 21, 2634-2641, 10.1111/gcb.12890, 2015.

Lang, W., Chen, X., Qian, S., Liu, G., and Piao, S.: A new process-based model for predicting autumn phenology: How is leaf senescence controlled by photoperiod and temperature coupling?, Agricultural and Forest Meteorology, 268, 124-135, 10.1016/j.agrformet.2019.01.006, 2019.

Liu, G., Chen, X. Q., Fu, Y. S., and Delpierre, N.: Modelling leaf coloration dates over temperate China by considering effects of leafy season climate, Ecol. Model., 394, 34-43, 10.1016/j.ecolmodel.2018.12.020, 2019.

Meier, M.: Process-oriented models of autumn leaf phenology (1.0) [Code]. https://doi.org/10.5281/zenodo.7188160, 2022.

Zani, D., Crowther, T. W., Mo, L., Renner, S. S., and Zohner, C. M.: Increased growing-season productivity drives earlier autumn leaf senescence in temperate trees, Science, 370, 1066-1071, 10.1126/science.abd8911, 2020.