PreLES – an empirical model for daily GPP, evapotranspiration and soil water in a forest stand

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Basic features

"Name etymology": Prediction of LUE, Evapotranspiration, and Soil water

Consists of three stand-alone component models (GPP, ET, SW) that can be used in a chain

Two versions for the ET model:
(i) "simple" (ET-S)
(ii) Penman-Monteith (ET-PM)

Works with a daily time step at a stand level

Work in progress: the aim is to develop a simple practical tool for predicting GPP and evapotranspiration in Finland (in a changing climate) with input variables that are easy to obtain

Basic features (2)

Driving variables (daily totals / daily means)

- GPP: PAR, T, VPD, SWC
- ET-S: PAR, VPD, SWC, GPP
- ET-PM: R_n, T, VPD, SWC, GPP, U
- SW: T, Precip, ET

State / driving variables for which initial values are required

- GPP: X_{start}
- SW: Snow, SWC

PAR: photosynthetically active radiation
T: air temperature
VPD: water vapour pressure deficit
SWC: soil water content
R_n: net radiation

U: wind speed
Precip: precipitation
X_{start}: starting value for delay transformation of T
Snow: amount of snow on ground

GPP model

Ecosystem GPP in day t is modelled with the light-use efficiency (LUE) approach:

$$GPP(t) = \beta \cdot \underbrace{fAPAR(t) \cdot PAR(t)}_{\text{PAR absorbed by canopy}} \cdot f_{PAR}(t) \cdot f_T(t) \cdot \min\{f_{VPD}(t),\ f_{SWC}(t)\},$$

where β is LUE at optimal conditions, *potential LUE*

fAPAR (t) is fraction of PAR absorbed by canopy during day t (here assumed constant 0.75)

$f_i(t)$ are modifying factors accounting for suboptimal conditions in day t, $f_i(t) \in [0, 1]$

Mäkelä A *et al.* (2008) Developing an empirical model of stand GPP with the LUE approach: analysis of eddy covariance data at five contrasting conifer sites in Europe. *Global Change Biology* 14(1):92–108.

GPP model: modifiers

Light:

$$f_{PAR}(t) = \frac{1}{\gamma\, PAR(t) + 1}$$

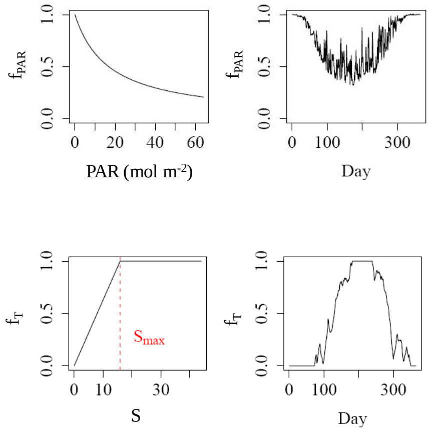
Temperature (state of acclimation):

$$X(t) = X(t-1) + \frac{1}{\tau}\left[T(t-1) - X(t-1)\right],$$

$$X(1) = X_{start}$$

$$S(t) = \max\left\{X(t) - X_0,\, 0\right\}$$

$$f_T(t) = \min\left\{\frac{S(t)}{S_{max}},\, 1\right\}$$



GPP model: modifiers (2)

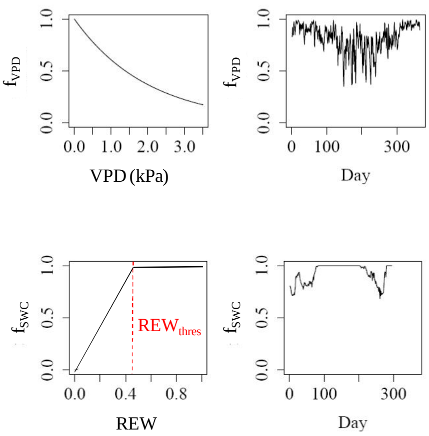
VPD:

$$f_{VPD}(t) = e^{-\kappa\, VPD(t)} \quad (\kappa > 0)$$

Soil water content (relative extractable water):

$$REW(t) = \min\left\{\frac{SWC(t) - \theta_{PWP}}{\theta_{FC} - \theta_{PWP}},\, 1\right\}$$

$$f_{SWC}(t) = \min\left\{\frac{REW(t)}{REW_{thres}},\, 1\right\}$$



θ_{PWP}: SWC at permanent wilting point, here θ_{PWP}= 0.225
θ_{FC}: SWC at field capacity, here θ_{PWP}= 0.075

ET-S model

Ecosystem evapotranspiration in day t is modelled as the sum of transpiration (from vegetation) and evaporation (from ground):

$$ET(t) = \left(\beta_{ET} \frac{GPP(t)}{e^{\kappa_{ET} VPD(t)}} \right) VPD(t)$$

Estimate of canopy conductance, $\kappa_{ET} > 0$

$$+ \ \alpha \ \underbrace{[1 - fAPAR(t)]\, PAR(t)}_{\text{Amount of radiation reaching ground}} \ \min\left\{ \frac{SWC(t)}{\theta_{sat}}, 1 \right\}$$

Amount of radiation reaching ground

θ_{sat}: SWC at saturation ("relative pore volume"), here $\theta_{sat} = 0.5$

ET-PM model

Penman-Monteith model for ecosystem evapotranspiration in day t:

$$ET(t) = \frac{s(t)R_n(t) + c\rho(t)g_a(t)\,VPD(t)}{\lambda(t)\left[s(t) + \chi(t)\left(1 + \frac{g_a(t)}{g_s(t)} \right) \right]},$$

where c is heat capacity of dry air, constant

s(t) is slope of water vapour pressure at saturation w.r.t to air temperature, function of T(t)

$\rho(t)$ is molar density of dry air, function of T(t) and air pressure, air pressure computed as a function of altitude

$\lambda(t)$ is heat of condensation, function of T(t)

$\chi(t)$ is "psychrometric constant", function of T(t) and atmospheric pressure

ET-PM model (2)

$g_a(t)$ is atmospheric conductance, function of
wind speed U(t) (here assumed constant 3 m/s),
zero displacement height (function of stand height),
and measurement and roughness heights for
momentum and heat / vapour fluxes (functions of
stand height)
$g_s(t)$ is surface conductance

ET-PM model (3)

Surface conductance is modelled as the sum of canopy conductance $g_c(t)$, soil conductance $g_{sw}(t)$ and conductance of surfacial water in ecosystem $g_{cw}(t)$:

$g_s(t) = g_c(t) + g_{sw}(t) + g_{cw}(t)$

$$g_c(t) = \frac{\gamma_{ET}\,\mathrm{GPP}(t)}{c_a \mathrm{VPD}(t)^{\kappa_{ET}}}, \quad \kappa_{ET} > 0$$

$$g_{sw}(t) = \alpha\,[1 - \mathrm{fAPAR}(t)]\min\left\{\frac{\mathrm{SWC}(t)}{\theta_{sat}}, 1\right\}$$

$$g_{cw}(t) = \beta_{ET}\, W_C(t)$$

c_a: CO_2 concentration in atmosphere, c_a = 380 ppm
θ_{sat}: SWC at saturation ("relative pore volume"), θ_{sat} = 0.5
$W_C(t)$: size of surfacial water "storage" in day t, computed in SW model

SW model

Soil water balance is computed with the "open bucket" principle:

- water comes into soil through precipitation Precip(t), part of precipitation is intercepted by canopy
- water gets out of soil through evapotranspiration ET(t)
- water exceeding field capacity runs off in number of days given by τ_D
- snow dynamics induce a delay in the water input to soil

If ET-PM model is used, precipitation intercepted by canopy goes to storage of surfacial water ($W_C(t)$ in the equation of $g_{cw}(t)$)

- storage has maximum size W_{cmax}, interception exceeding this runs to soil
- this storage is emptied with ET(t) before soil water is influenced

SW model (2)

Computation is performed by updating state variables recursively in a daily time step

Starting values: amount of soil water SoilWater(t_0) = SWC(t_0) · soildepth
amount of snow on ground Snow(t_0) (here soildepth = 529 mm)

SW model (3)

$$\text{SnowThrough}(t) = \begin{cases} \text{Precip}(t), & T(t) < T_{snow} \\ 0, & T(t) \geq T_{snow} \end{cases}$$

$$\text{SnowMelt}(t) = \begin{cases} 0, & T(t) < T_{melt} \\ \min\{c_{melt}[T(t) - T_{melt}], \text{Snow}(t-1) + \text{SnowThrough}(t)\}, & T(t) \geq T_{melt} \end{cases}$$

Snow(t) = Snow(t−1) + SnowThrough(t) − SnowMelt(t)

$$\text{RainThrough}(t) = \begin{cases} 0, & T(t) < T_{snow} \\ (1 - I_0)\,\text{Precip}(t), & T(t) \geq T_{snow} \end{cases}$$

T_{snow}: temperature under which precipitation comes as snow, here T_{snow} = 0°C
T_{melt}: temperature above which snow melts, here T_{melt} = 0°C
c_{melt}: snow melting coefficient, here c_{melt} = 1.5 mm/°C
I_0: fraction of precipitation (not in snow) intercepted by canopy, here I_0 = 0.33

SW model (4)

If ET-S is employed for computing ET(t):

SoilWaterBeforeDrainage(t) = SoilWater(t−1) + RainThrough(t) + SnowMelt(t) − ET(t)

$$\text{Drainage}(t) = \max\{0, [\text{SoilWaterBeforeDrainage}(t) - \underbrace{\theta_{FC} \cdot \text{soiltdepth}}_{\text{Maximum amount of water soil can retain}}] / \tau_D\}$$

SoilWater(t) = SoilWaterBeforeDrainage(t) − Drainage(t)

SWC(t) = SoilWater(t)/soildepth

SW model (5)

If ET-PM is employed for computing ET(t):

Interception(t) = I_0 Precip(t)

SurfacialWaterBeforeET(t) =
min { SurfacialWater(t−1) + Interception(t), W_{Cmax} },

where W_{Cmax} is the maximum size of surfacial water storage

Surfacial water exceeding W_{cmax} runs to soil

SurfacialWaterThrough(t) =
max { SurfacialWater(t−1) + Interception(t) − W_{Cmax}, 0 }

Evapo-transpiration is first used to empty surfacial storage

SoilWaterBeforeDrainage(t) = SoilWater(t−1)
+ RainThrough(t) + SnowMelt(t)
+ SurfacialWaterThrough(t)
− max { 0, [ET(t) − SurfacialWaterBeforeET(t)] }

SW model (6)

SurfacialWater(t) = max { SurfacialWaterBeforeET(t) − ET(t), 0 }

Drainage(t), SoilWater(t) and SWC(t) as before

Bayesian estimation of model parameters

Parameters of each model estimated separately, with measured daily data as input

Likelihood function constructed assuming GPP / ET / SW values in each day (random variables)

(i) independent of each other (no temporal autocorrelation)

(ii) normally distributed with mean given by the GPP / ET-PM / SW model and variance proportional to squared mean

Prior distributions of parameters uniform (uninformative)

Estimation with Markov chain Monte Carlo, parameter estimates from means of marginal posterior distributions

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