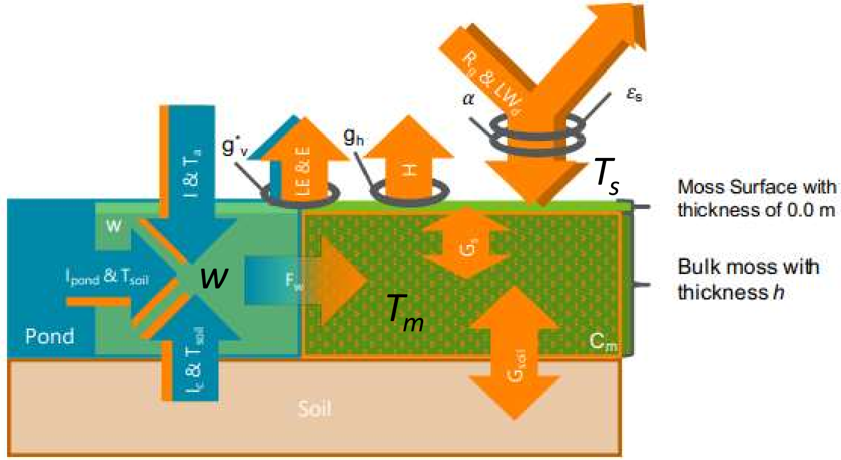
# Surface energy balance & modeling

Meeting with Erkka, Mika, Tiina & J-P at FMI 15.3.2023

# A process-based model

- **Mathematical representation of a system, its function and interactions with the surroundings**
- **Functions**: processes specific to respective ecosystem compartment
  - evaporation, heat exchange, absorption of light, photosynthesis…
- **State variables**: ds/dt = …
  - Tm, Ts, w, θ, GWL, LAI, carbon pools…
- **Properties:**
  - physical, structural, physiological. Can be static or vary with state variables.
- **Parameters, initial state** (inputs)
  - Set up the model for a specific system
- **Model forcing & boundary conditions**
  - Dynamic f(t), static, upper & lower BC
- **Fluxes** (internal, with surroundings)

Upper BC
Par, Nir (direct/diffuse)],
$LW_{dn}$, $e_a$, $T_a$,$C_a$,Prec,U, (u*)




Lower BC (Tsoil, wsoil)

**Model code**

Classes – generic model, class functions (processes) ← theory

Objects – class instances ← parameters, initial state

- Store state variables, properties

Functions not specific to any class

Input-output routines

A-J Kieloaho & S Launiainen

# Energy balance of moss-covered surface

The surface energy balance of the moss is described as:

$$(1-\alpha)R_g + \epsilon_s(LW_d - \sigma T_s^4) = H + LE + G_s$$

$$\frac{\partial C_m T_m}{\partial t} = G_s + G_{soil} + F_w$$

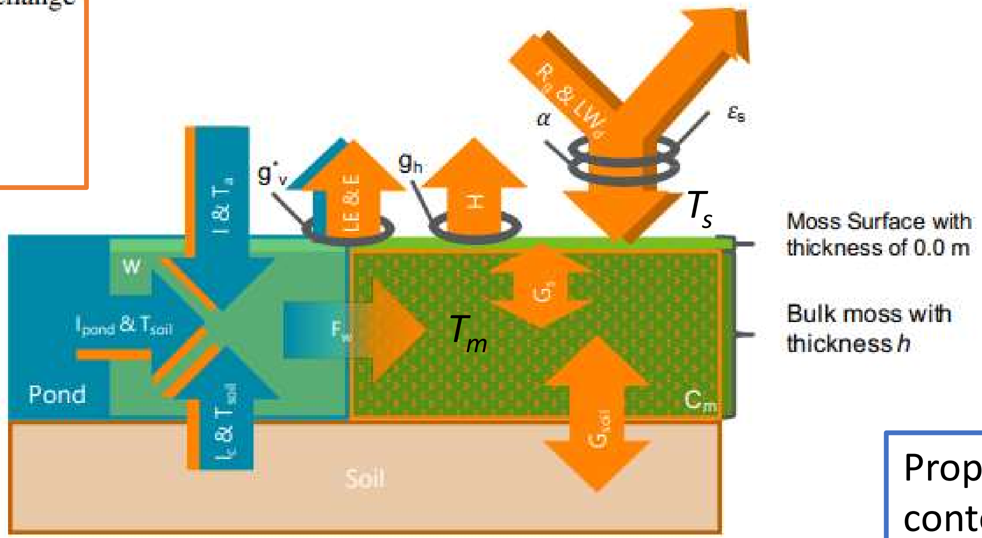
Moss temperature

where $C_m$ is the moss layer heat capacity (J K$^{-1}$ m$^{-2}$) and $T_m$ the temperature of bulk moss.

The sensible and latent heat exchange

$$H = c_p g_h (T_s - T_a)$$

$$LE = L g_v^* \frac{e_s(T_s) - e_a}{p_a}$$




Heat conduction defined by:

$$G_i = \lambda_i \frac{T_i - T_m}{\Delta z_i}$$

Heat is advected to the moss by interception of precipitation ($I$), capillary rise ($I_c$) and pond recharge ($I_{pond}$) (all in kg m$^{-2}$ s$^{-1}$):

$$F_w = c_w(I T_a + I_c T_{soil} + I_{pond} T_{soil}) \qquad (4)$$

Properties (depend on moss water content):
albedo $\alpha$
thermal conductivity $\lambda$
heat capacity $C_m$
conductance for water vapor $g_v$

# Water balance of moss-covered surface

The moss layer water balance (Fig. ??) is described as:

$$\frac{\partial w}{\partial t} = \frac{1}{m_{dry}}(-E + I + I_{pond} + I_c) \qquad (9)$$

where $t$ (s) is time, $m_{dry}$ dry mass of the moss (kg m$^{-2}$), $E$ evaporation/condensation rate, $I$ rainfall interception rate, $I_{pond}$ pond recharge rate and $I_c$ is the rate of capillary recharge from the underlying soil (all in kg m$^{-2}$ s$^{-1}$).

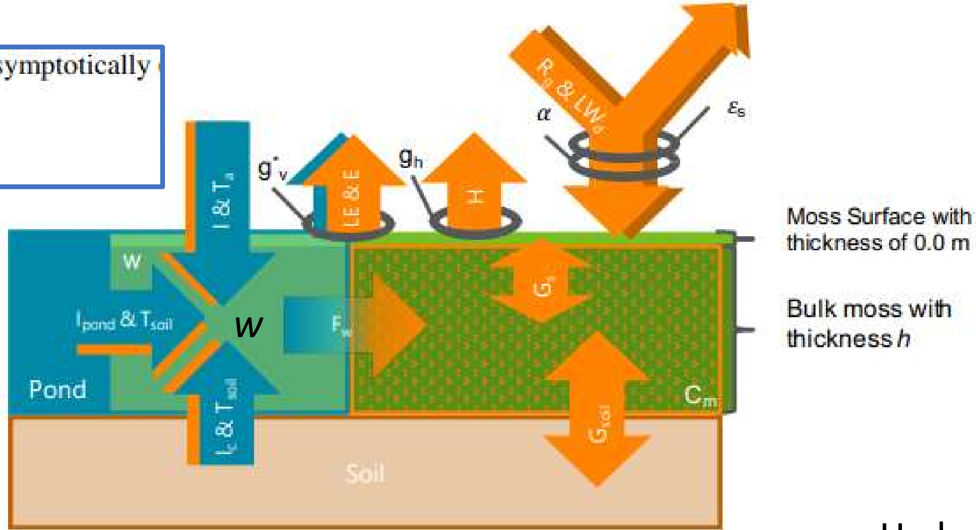
Interception rate is defined assuming $w_{max}$ is approached asymptotically

$$I = m_{dry}(w_{max} - w)\left[1 - \exp\left(\frac{P\Delta t}{m_{dry} w_{max}}\right)\right] / \Delta t$$

The $w$ is decreased by evaporation (from Eq. ??)

$$E = \frac{M_v}{L} LE$$

where $M_v$ is the molar mass of water (kg mol$^{-1}$).




The rate of capillary rise from underlying soil is

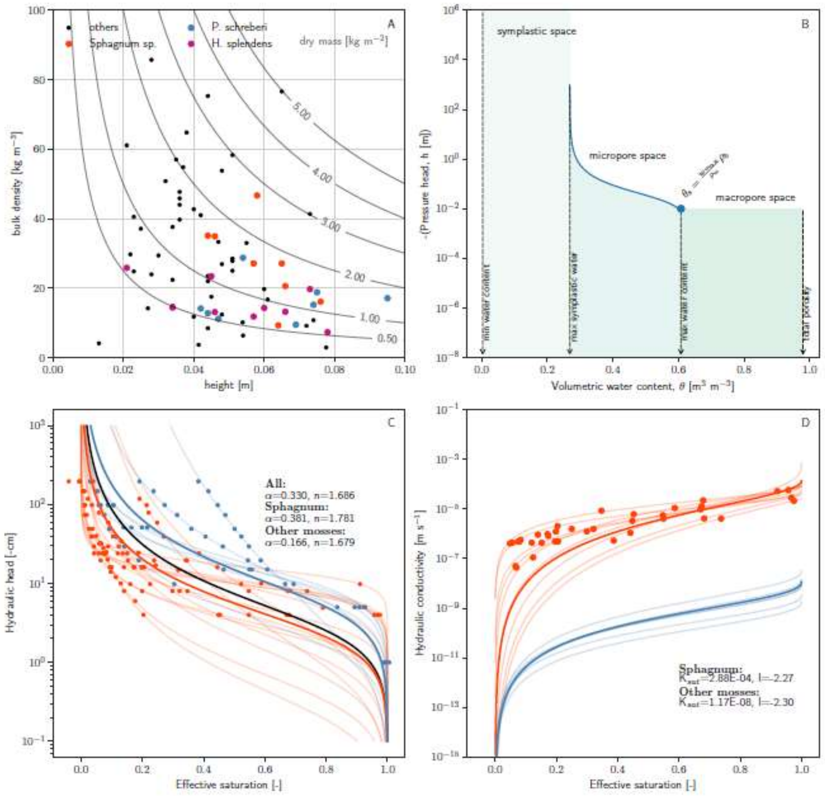
$$I_c = \max\left[0.0, -\rho_w K_{soil}\left(\frac{\psi - \psi_{soil}}{\Delta z_{soil}} + 1.0\right)\right]$$

where $\rho_w$ is water density (kg m$^{-3}$), $\psi$ and $\psi_{soil}$ are the water potential (m) of the moss layer and the topmost soil layer, $\Delta z_{soil}$ is the distance (m) between the midpoints of the moss and the topmost soil layer, $K_{soil}$ is the hydraulic conductivity (ms$^{-1}$)

Hydraulic conductivity K depends on moss & peat water content

# Parameters: from empirical studies, guestimates, from model calibration against measurements

```python
# this is general Sphagnum parametrisation based on literature review
Sphagnum = {
    'name': 'Sphagnum sp.',
    'layer_type': 'bryophyte',
    'coverage': 1.0,
    'height': 0.06, # [0.044, 0.076]
    'roughness_height': 0.02,
    'bulk_density': 35.1,  # [9.28, 46.7]
    'max_water_content': 17.8,  # [15.6, 24.4]
    'water_content_ratio': 0.43,  # max_symplast_water_content:max_water_content -ratio
    'min_water_content': 0.1,
    'porosity': 0.98,

    'photosynthesis': { # farquhar-parameters
        'Vcmax': 45.0, 'Jmax': 85.5, 'Rd': 1.35, # umolm-2s-1
        'alpha': 0.3, 'theta': 0.8, 'beta': 0.9, # quantum yield, curvature, co-limitation
        'gmax': 0.04, 'wopt': 7.0, 'a0': 0.7, 'a1': -0.263, 'CAP_desic': [0.58, 10.0],
        'tresp': {
            'Vcmax': [69.83, 200.0, 649.],
            'Jmax': [100.28, 147.92,646.],
            'Rd': [33.0]
        }
    },
    'optical_properties': { # moisture responses are hard-coded
        'emissivity': 0.98,
        'albedo': {'PAR': 0.10, 'NIR': 0.27} # albedos when fully hydrated [-]
    },
    'water_retention': {
        'alpha': 0.381,  # based on fitted value
        'n': 1.781,  # based on fitted value
        'saturated_conductivity': 1e-5, #2.88e-4,  # [m s-1], based on fitted value
        'pore_connectivity': -2.27  # based on fitted value
    },
    'initial_conditions': {
        'temperature': 10.0,
        'water_content': 10.0
    }
}
```



# Moss albedo

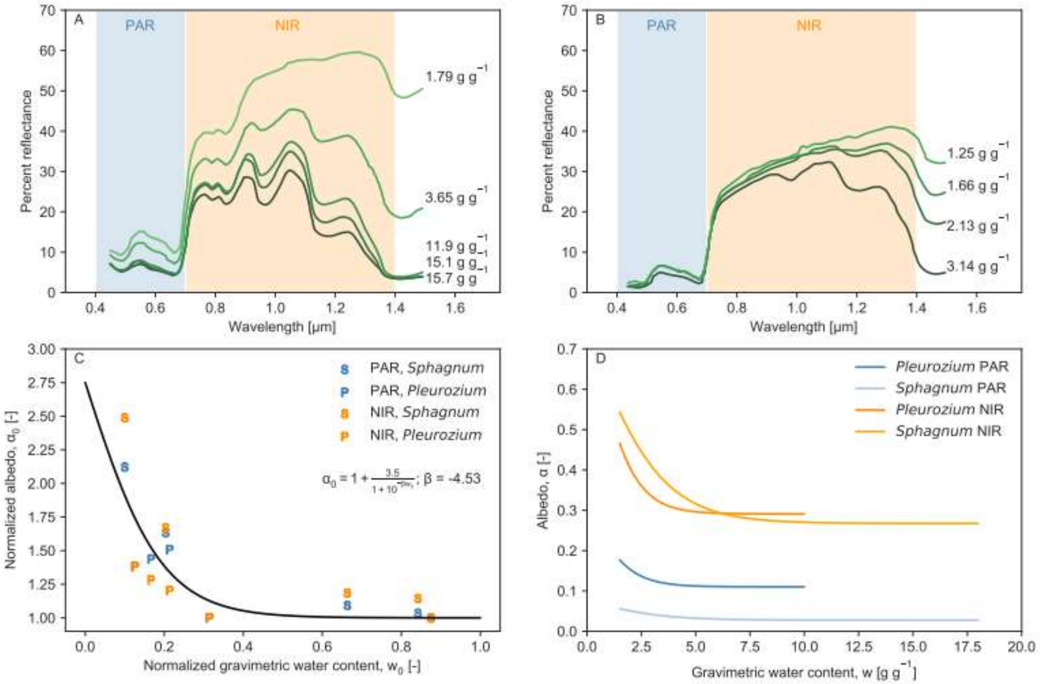
The surface energy balance of the moss is described as:

$$(1-\alpha)R_g + \epsilon_s(LW_d - \sigma T_s^4) = H + LE + G_s$$

- Non-linear function of water content
- Varies across moss type
- Emissivity ε 0.94-0.98

```python
def reflectance(water_content, max_water_content, albedo):
        """

        Water-content depended bryophyte reflectivity for PAR (400-700 nm) and
        NIR (750-1400) wavebands.

        The effect of water content of spectral properties are based on studies by
        Vogelmann and Moss (1993, Sphagnum cuspidatum) and Fernandes (1999, Pleurozium schreberi).
        Relative moisture dependency is assumed same for both wavebands.

        References:
            Vogelmann and Moss (1993). Remote Sensing of Environment 45:273-279.
            Fernandes (1999). PhD thesis entitled: 'Scale influences of surface
                parametrization on modelled boreal carbon and water budgets'
        Args:
            - 'water_content' (float): gravimetric water content [g g\ :sup:`-1`\]
            - 'max_water_content' (float): maximum gravimetric water content [g g\ :sup:`-1`\]
            - albedo (dict):
                - 'PAR' (float): PAR albedo at max_water_content [-]
                - 'NIR' (float): NIR albedo at max_water_content [-]
        Returns
            - res (dict):
                - 'PAR' (float): PAR albedo at water_content [-]
                - 'NIR' (float): NIR albedo at water_content [-]
        """

        x = water_content / max_water_content

        scaling_coefficient = 1.0 + (4.5 - 1.0) / (1.00 + np.power(10, 4.53 * x))

        albedo_nir = albedo['NIR'] * scaling_coefficient
        albedo_par = albedo['PAR'] * scaling_coefficient

        return {'PAR': albedo_par, 'NIR': albedo_nir}
```

Sphagnum sp. Pleurozium sp.




*Albedo*

Moss albedo is modeled as a decreasing non-linear function of water content

$$\alpha(w_o) = \alpha_i \times \left(1.0 + \frac{\beta_1}{1.0 + 10^{-\beta_2 w_o}}\right),$$

where $w_o = w/w_{max}$ is relative water content and fitting parameters $\beta_1 = 3.5$ and $\beta_2 = -4.53$

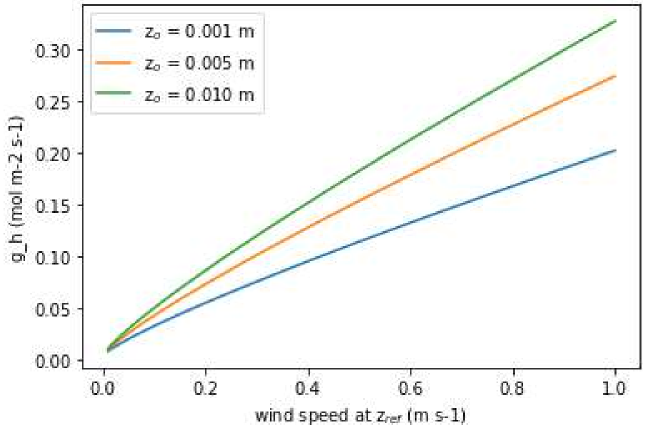
# H, LE, G & conductances

$$g_h = \rho_a \frac{k u_*}{Pr - \ln(\delta_0 / z_{ref})}$$

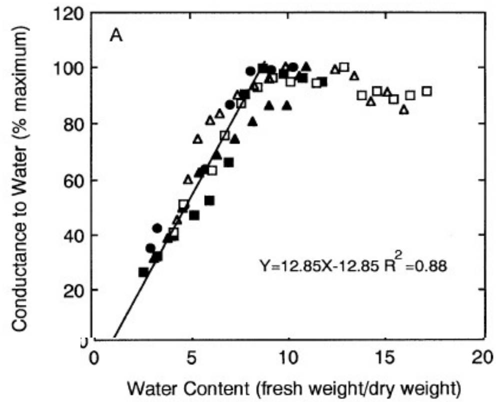
with

$$u_* = \frac{uk}{\ln(z_{ref}/z_0)} \text{ and } \delta_0 = \nu/(k u_*)$$

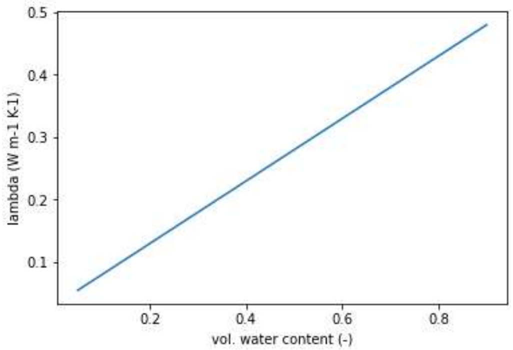
$$g_v^* = g_v \times \begin{cases} 1, & w \geq w_{sym} \\ w/(w_{sym} - w_{min}), & w_{min} < w < w_{sym} \\ 0, & w \leq w_{min} \end{cases}$$




heat




evaporation




The sensible and latent heat exchange

$$H = c_p g_h (T_s - T_a)$$

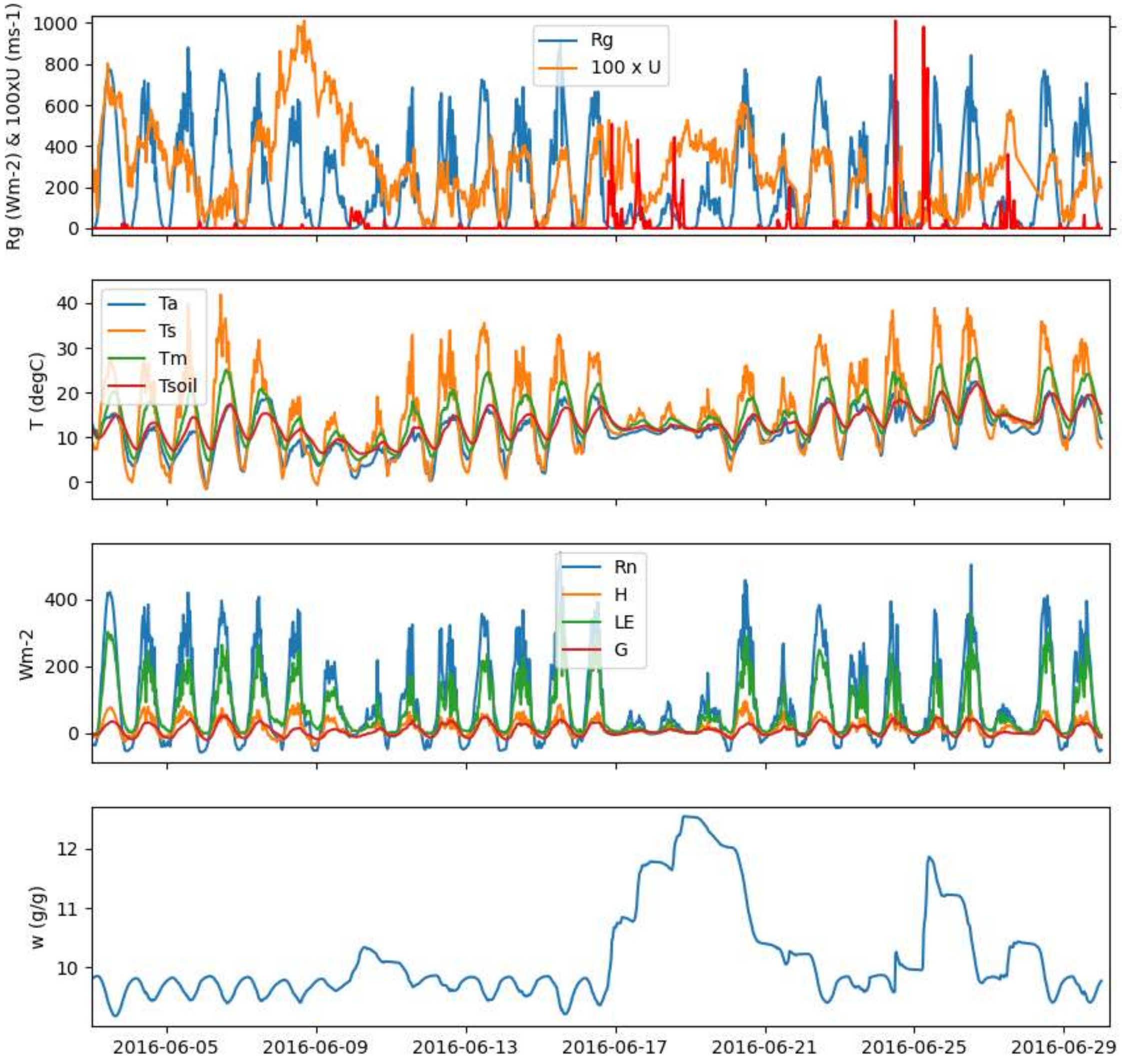
$$LE = L g_v^* \frac{e_s(T_s) - e_a}{p_a}$$

Heat conduction defined by:

$$G_i = \lambda_i \frac{T_i - T_m}{\Delta z_i}$$

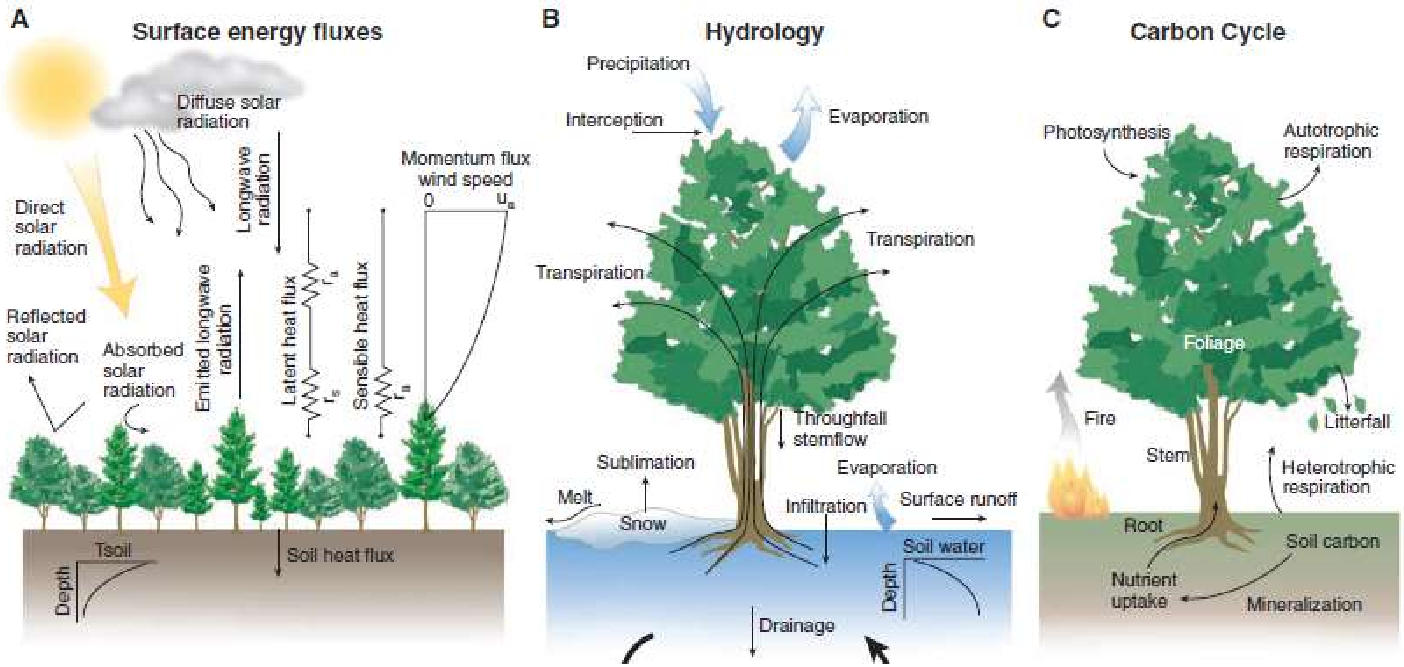
# Typical modeling steps

- Define research question / simulation goals
- Define system and its boundaries:
  - Parameterize for a given site or problem
  - Collect forcing data. E.g. Par, Nir, LWdn, Tair, U, $H_2O$, $CO_2$ timeseries (upper BC)
  - Define lower BC's
- Initialize the model
  - Parameters
  - Initial conditions
- Run the model for N timesteps
  - System behavior & state depends on: forcing(t) & systems state at (t-1)
- Interpret the results (against data?)
- Iterate to improve
  - parameterization, simulation setup, model code



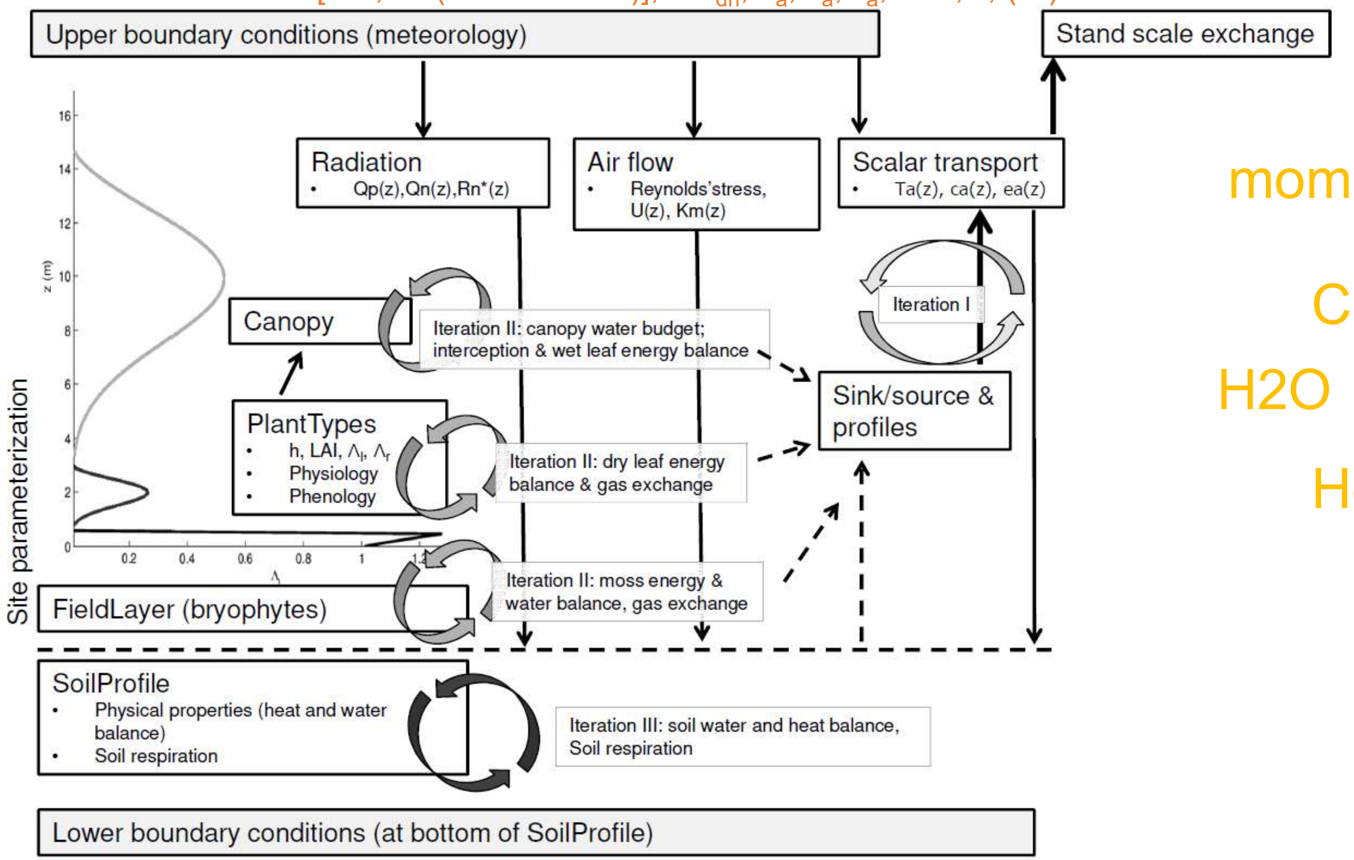

Demo!

- WTD set to 0.15cm below soil surface
- No vascular plants




Bonan, 2008 Science.

Timescale ½ h: SW [Par,Nir (direct/diffuse)], $LW_{dn}$, $e_a$, $T_a$,$C_a$,Prec,U, (u*)




momentum

$CO_2$

$H_2O$

Heat



APES (Launiainen et al. 2015 Ecol. Mod.; Leppä et al. 2020 AFM)

# Leaf temperature

radiation balance · Heat flux · Latent heat flux

$$\frac{C_l T_l}{dt} = (1-\alpha)\,SW + \epsilon(LW_{in} - \sigma T_l^4) - c_p\, g_b\,(T_l - T_a) - \lambda\, g_v\, D$$

$$D = \frac{e_{sat}(T_l) - e_a}{p_a}$$

**boundary-layer conductance**

$$g_b \propto a_1 \sqrt{\frac{U}{d}} + a_2 \left(\frac{T_l - T_a}{d}\right)^{1/4}$$

$$g_v = \frac{g_b\, g_s}{g_b + g_s}$$

**stomatal conductance**

$$g_s = 1.6\left(1 + \frac{a_3}{\sqrt{D}}\right)\frac{A_n}{c_s}$$

photosynthesis

$$A_n = \frac{g_b}{1.6}(c_a - c_s) = \frac{g_s}{1.6}(c_s - c_i) = min(A_1, A_2) - r_d$$

$$A_1 = V_{cmax}\frac{c_i - \Gamma_*}{c_i + K_c(1 + O_a/K_o)}$$

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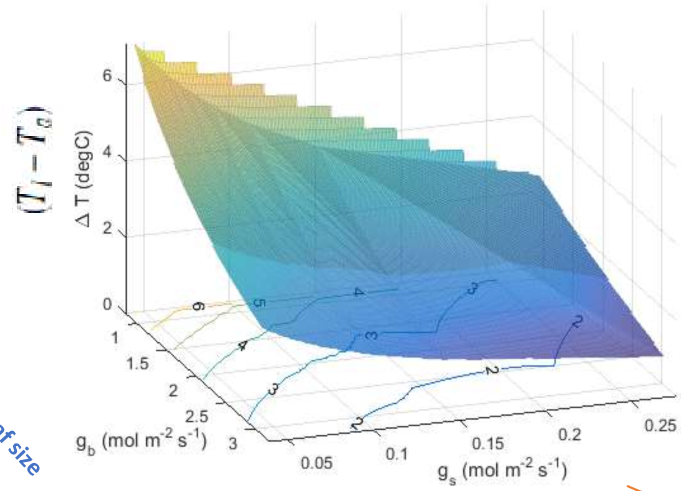
$$A_2 = \frac{J}{4}\frac{c_i - \Gamma_*}{c_i + 2\Gamma_*},$$

$$J = \frac{(\gamma(1-\alpha)\,SW - J_{max}) - \sqrt{((1-\alpha)\,SW - J_{max})^2 - 4\theta(1-\alpha)\,SW\, J_{max}}}{2\theta}$$

$$V_{cmax},\, J_{max}, r_d = non-linear\ f(T_l,\, N_l,\, \psi_l, ...history)$$

$$\Gamma_*, K_c, K_o = non-linear\ f(T_l)$$




Leaf size

Thirsty & productive

leaf properties (traits)

$\alpha, \epsilon, d, a_3$

External conditions

$U, SW, LW, T_a, e_a, c_a, ...$

# Soil water
# 1D Richards eq.

$$\frac{\partial \theta(\psi_s)}{\partial t} = \frac{\partial}{\partial z_s}\left[K_L(\psi_s)\frac{\partial \psi_s}{\partial z_s} + (K_L + K_{L,m})\right] - R(z) - D(z),$$

- R(z) root uptake
- D(z) horizontal flow (e.g. ditch drainage)

**Hydraulic properties = f(soil type, $z_s$)**

- Water retention curves
- Saturated hydraulic conductivity
- Simple adjustment for macropore infiltration
- Upper BC: flux based (potential infiltration – soil E – capillary rise to mosses)
- Lower BC: impermeable, free drainage or fixed potential
- Ditch drainage via Hooghoud equation.

# heat balance
# 1D Fourier eq.

$$\frac{\partial C_P T_s}{\partial t} = \frac{\partial}{\partial z}\left[\lambda_h(\theta)\frac{\partial T_s}{\partial z}\right] + C_w\frac{\partial q_l T_s}{\partial z},$$

**Thermal properties = f(soil type, θ)**

- Heat capacity $C_p$
- Thermal conductivity $\lambda_h$
  - deVries (196x); mineral soils
  - O'Donnell et al. (2009); organic layers
- Soil freezing –melting (phase changes)
- Upper BC: surface heat flux (conduction) or surface temperature Ts(t)
- Lower BC: heat conduction through bottom or T(t)

# Test for Degerö, Northern Sweden

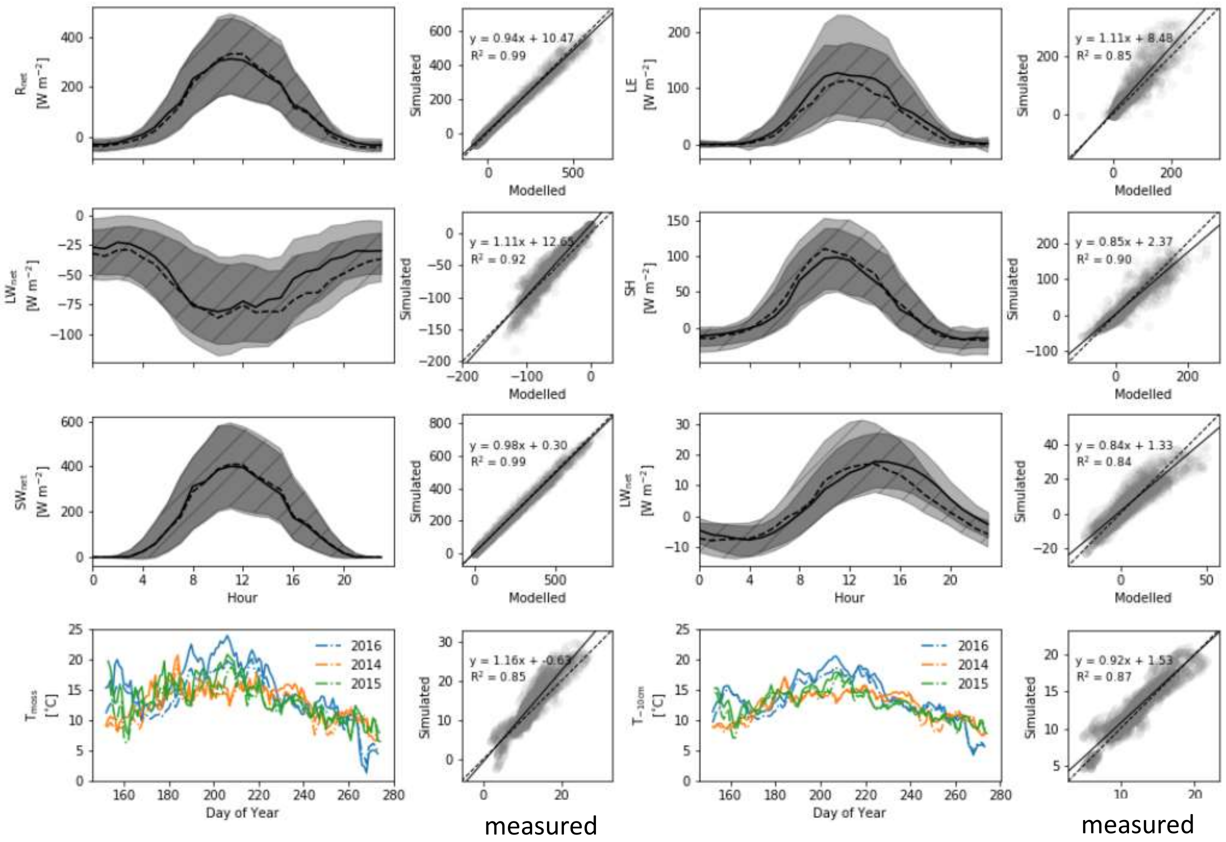



**Figure 4.** Simulated (solid lines and shaded area) and measured (dashed line and hatched area) mean diurnal cycle and its standard deviation together with comparisons of measured and simulated energy balance components in dry canopy conditions in Degerö Stromyr during snow free period (from June to September) in 2014–2016. Simulated (solid lines) and measured (dashed lines) daily mean temperatures of moss and underlying peat layer together with comparisons of measured and simulated temperatures.

- Sphagnum –moss cover
- Sedges, LAImax 0.7 m2m-2
- Simulate three growing seasons, compare to measured EC-fluxes, WTD, soil temperature profile

- No data on moss fluxes & state ☹
- No extreme conditions; shallow WTD all the time
- Modeling peatland water balance with a column model difficult (lateral water flows)
- More sites needed!

# Sensitivity analysis of moss energy fluxes

**Table 2.** Influentiality ($\mu^{\star}$) of moss parameters on energy balance components ($R_{net}$, $T_{surf}$, H, LE, G) and overall influentiality on energy balance by using normalized $\mu^{\star}$ over all the components; mean or mean of daily amplitudes are calculated from output variables from June to September in 2016 in Degerö Stormyr. The most influential (highest) values are bolded.

| Parameter | H ($\mu^{\star}$) mean / ampl. | LE ($\mu^{\star}$) mean / ampl. | G ($\mu^{\star}$) mean / ampl | $R_{net}$ ($\mu^{\star}$) mean / ampl. | $T_{surf}$ ($\mu^{\star}$) mean / ampl | All (norm. $\mu^{\star}$) mean / ampl. |
|---|---|---|---|---|---|---|
| $h$ | 0.09 (-) / 4.01 (+) | 0.14 (+) / 4.81 (+) | 0.12[1] (+) / **23.5** (-) | 0.14 (+) / 5.98 (-) | 0.04 (-) / 0.79 (+) | 0.97 / 1.73 |
| $r_h$ | **1.98** (-) / 8.47 (+) | **8.28** (+) / 26.0 (+) | 0.01 (-) / 5.40[1] (-) | **6.08** (+) / 14.2[1] (+) | **1.12** (-) / 2.25[1] (-) | **4.71** / 2.43 |
| $\rho_b$ | 0.69 (+) / **17.0** (-) | 2.34 (-) / **31.8** (-) | **0.14** (-) / 12.0 (+) | 2.03 (-) / **27.5** (+) | 0.55 (+) / **6.12** (-) | 2.45 / **4.51** |
| $w_{max}$ | 0.24 (+) / 6.32 (-) | 0.92 (-) / 12.6 (-) | 0.06[1] (-) / 4.66 (+) | 0.78 (-) / 11.9 (+) | 0.21 (+) / 2.41 (-) | 0.96 / 1.79 |
| $\alpha_{PAR}$ | 0.95 (-) / 2.40 (-) | 2.03 (-) / 7.24 (-) | 0.03 (-) / 0.40 (-) | 2.94 (-) / 11.0 (-) | 0.21 (-) / 0.51 (-) | 1.63 / 0.87 |
| $\alpha_{NIR}$ | 0.63 (-) / 1.46 (-) | 1.36 (-) / 4.74 (-) | 0.02 (-) / 0.15 (-) | 1.97 (-) / 7.34 (-) | 0.14 (-) / 0.34 (-) | 1.08 / 0.56 |

[1] coefficient of variation ($\frac{\sigma}{\mu^{\star}}$) > 0.5; (-/+) is direction of effect (sign of $\mu$)

Morris method to identify most influential parameters:
Roughness height → surface – atm conductance
Moss bulk density → moss layer water storage & heat capacity

# Energy partitioning & its controls in forests

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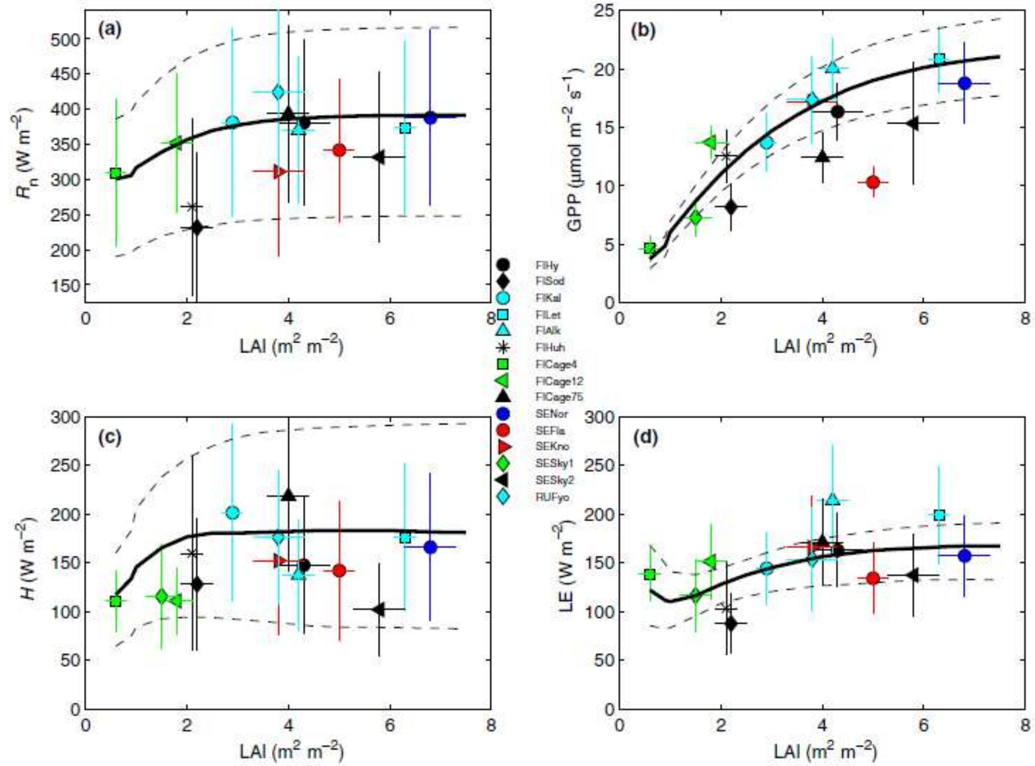



**Fig. 1** Measured and model-predicted ecosystem-scale (a) net radiation ($R_n$), (b) gross primary productivity (GPP), (c) sensible heat flux ($H$) and (d) latent heat flux (LE) as a function of total (overstory + understory) leaf area index (LAI). Symbols and vertical lines give measured daytime (10–17) medians and 25th/75th percentiles, respectively. For model, these are given by thick and dashed lines, respectively. The sites on mineral soils are classified as follows: black – Scots pine; red – Norway spruce; green – regenerating sites; dark blue – mixed coniferous. The light blue sites are peatland forests.

- EC-data from 15 Nordic sites
- APES simulations for generic coniferous forest
    - Same forcing for all sites
    - Vary LAI
    - Analyze EC-data & model results analogously
    - Interpret measurements with model → why fluxes vary / do not vary with LAI


Global Change Biology

Global Change Biology (2016), doi: 10.1111/gcb.13497


**Do the energy fluxes and surface conductance of boreal coniferous forests in Europe scale with leaf area?**


SAMULI LAUNIAINEN[1], GABRIEL G. KATUL[2], PASI KOLARI[3], ANDERS LINDROTH[4], ANNALEA LOHILA[5], MIKA AURELA[5], ANDREJ VARLAGIN[6], ACHIM GRELLE[7] and TIMO VESALA[3,8]

[1]*Nature Resources Institute Finland, Environmental Impacts of Production, Jokiniemenkuja 1, Vantaa, Finland,* [2]*Nicholas School*

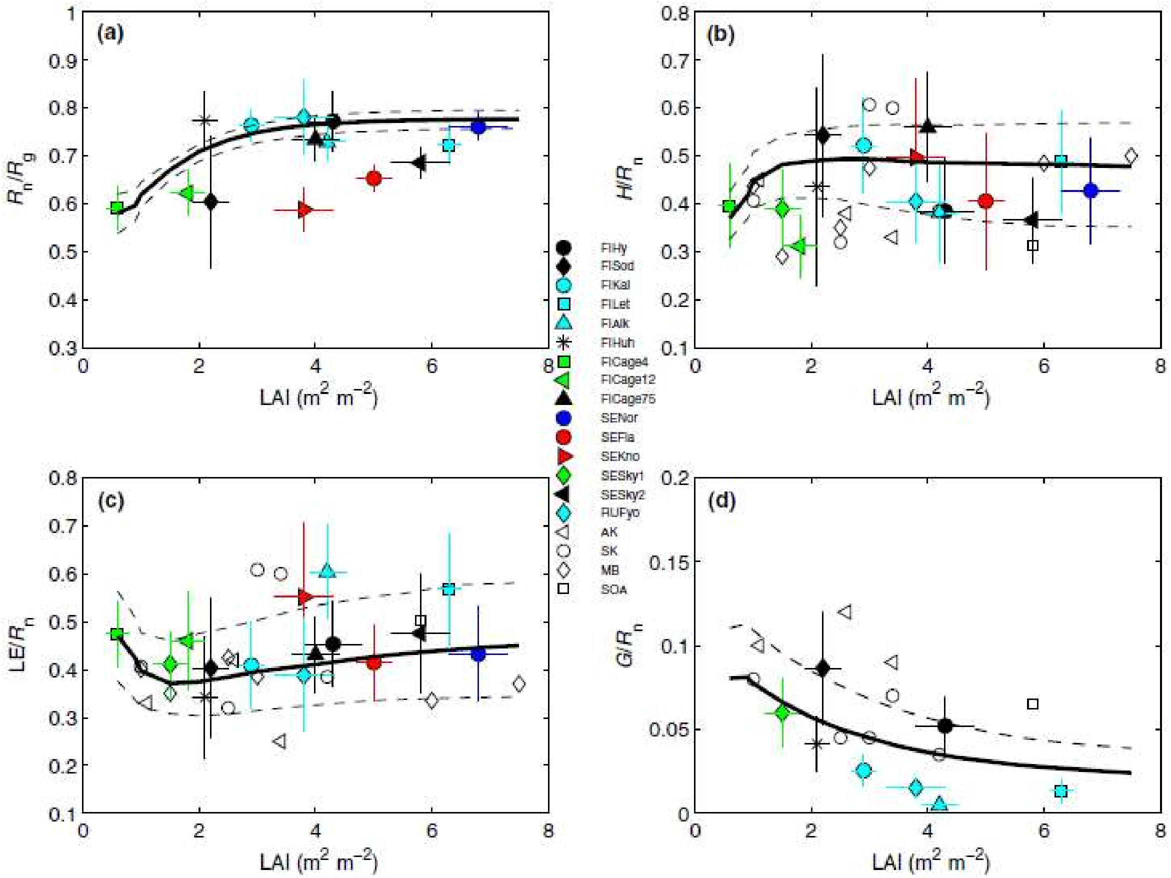



**Fig. 2** Daytime dry-canopy energy partitioning as a function of leaf area index (LAI). The net radiation $R_n$ is normalized by incoming global radiation $R_g$ while the other fluxes are shown relative to $R_n$. The dashed and solid lines in (d) give model-predicted soil heat flux $G$ at soil surface and 10 cm depth, respectively. The open symbols show data from Canadian boreal forests (Amiro *et al.*, 2006b) and conditions are as in Fig. 1.

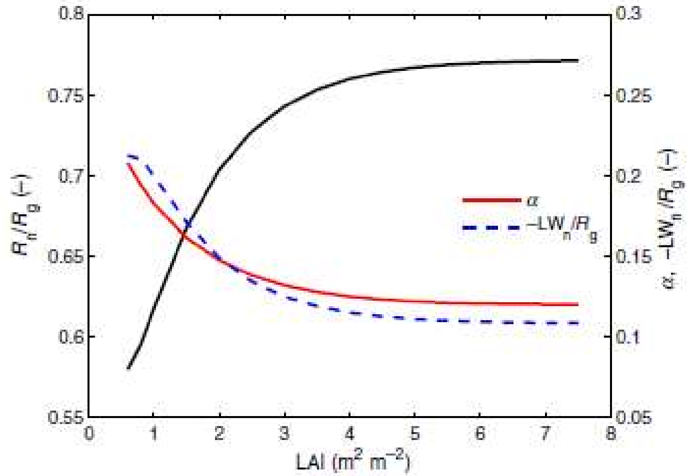



**Fig. 10** Model-predicted response of ecosystem-scale net radiation ($R_n$), short-wave albedo ($\alpha$) and net long-wave radiation ($LW_n$) to ecosystem leaf area index LAI. The $R_n$ and $LW_n$ are normalized by incoming global radiation $R_g$.

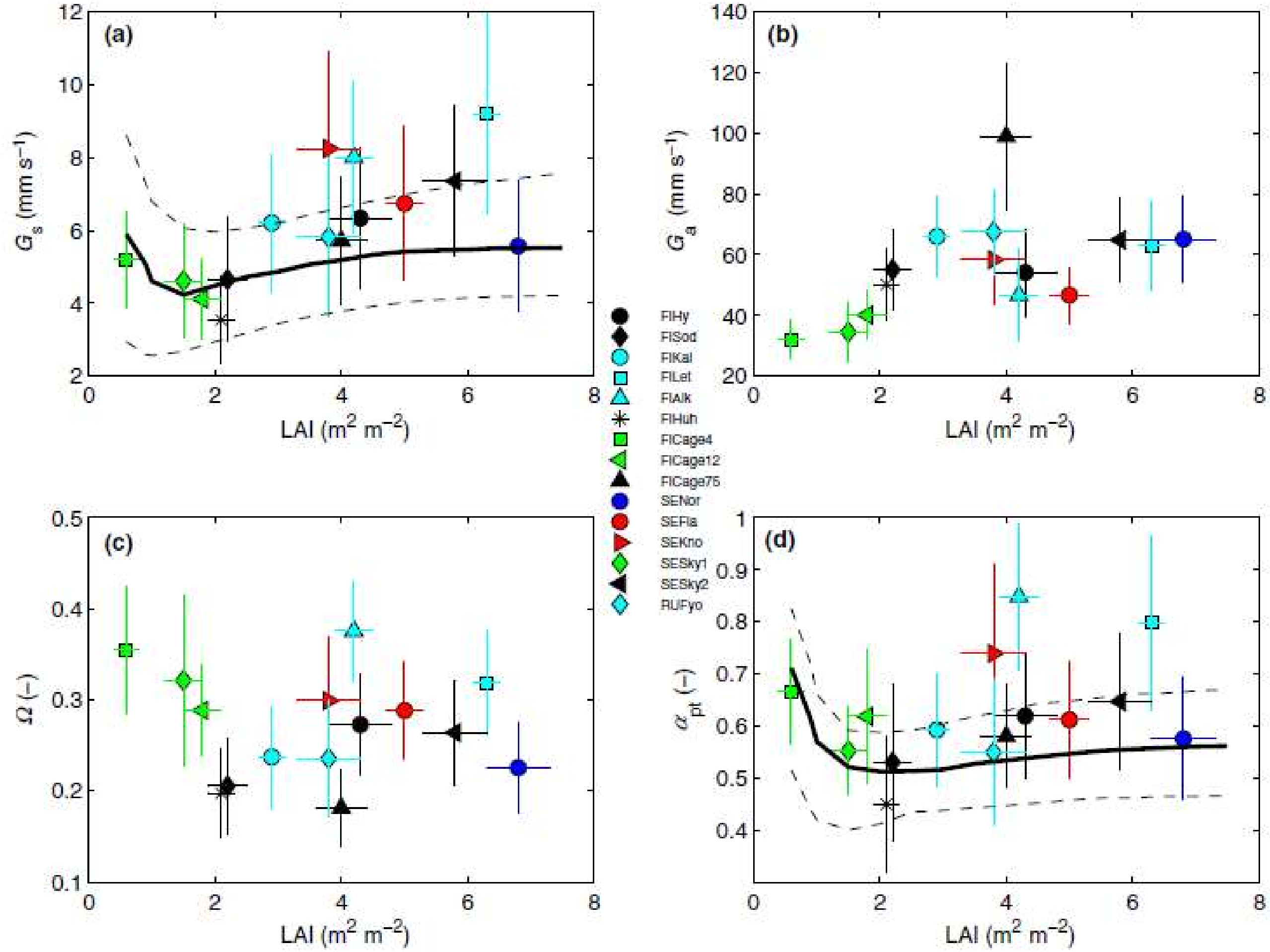



**Fig. 4** (a) Surface conductance ($G_s$), (b) aerodynamic conductance ($G_a$), (c) coupling coefficient ($\Omega$) and (d) ratio of actual to equilibrium evaporation ($\alpha_{pt}$) as a function of leaf area index (LAI). The symbols and conditions are as in Fig. 1

The $G_s$ was estimated from the EC data by inverting Eqn (2) as

$$G_s = \left[\frac{1}{G_a}\left(\frac{\frac{\gamma}{\Delta}R_n + \rho_a c_p G_a\, D/\gamma}{LE} - \frac{\gamma}{\Delta} - 1\right)\right]^{-1}, \qquad (5)$$

where $R_n$ is used instead of ($R_n$ - $G$) as $G$ was not measured at all sites. Based on analysis of the multilayer model predictions, this assumption yields an underestimation of ensemble-averaged daytime $G_s$ by <0.3 mm s$^{-1}$ (or <6%) at the site with lowest LAI; in denser stands, the error is even smaller.

The $G_a$ was estimated as in Verma (1989)

$$G_a = \left[\frac{U}{u_*^2} + \frac{\mathrm{kB}^{-1}}{ku_*}\right]^{-1}, \qquad (6)$$

where $k = 0.41$ is the von Kárman constant, and the mean wind speed ($U$) and $u_*$ refer to values at the EC measurement height. The first term in Eqn (6) describes the aerodynamic resistance due to eddy motion and the second is approxima-

(m s$^{-1}$). Using the decoupling theory (McNaughton & Jarvis, 1983), Eqn (2) can be decomposed into

$$LE = \underbrace{\Omega\,\frac{\Delta(R_n - G)}{\Delta + \gamma}}_{LEeq} + \underbrace{(1-\Omega)\,\frac{\rho_a c_p G_s\, D}{\gamma}}_{LEimp}, \qquad (3)$$

where the equilibrium evaporation rate (in energy units) $LE_{eq}$ is driven by available energy ($R_n$ - $G$) and temperature (through $\Delta$) while the 'imposed' rate ($LE_{imp}$) is related to surface control of evaporation. The coupling coefficient $\Omega$ varies between 0 and 1 and is defined as

$$\Omega = \frac{\Delta/\gamma + 1}{\Delta/\gamma + 1 + G_a/G_s}. \qquad (4)$$

Microclimate responds to forest structure changes

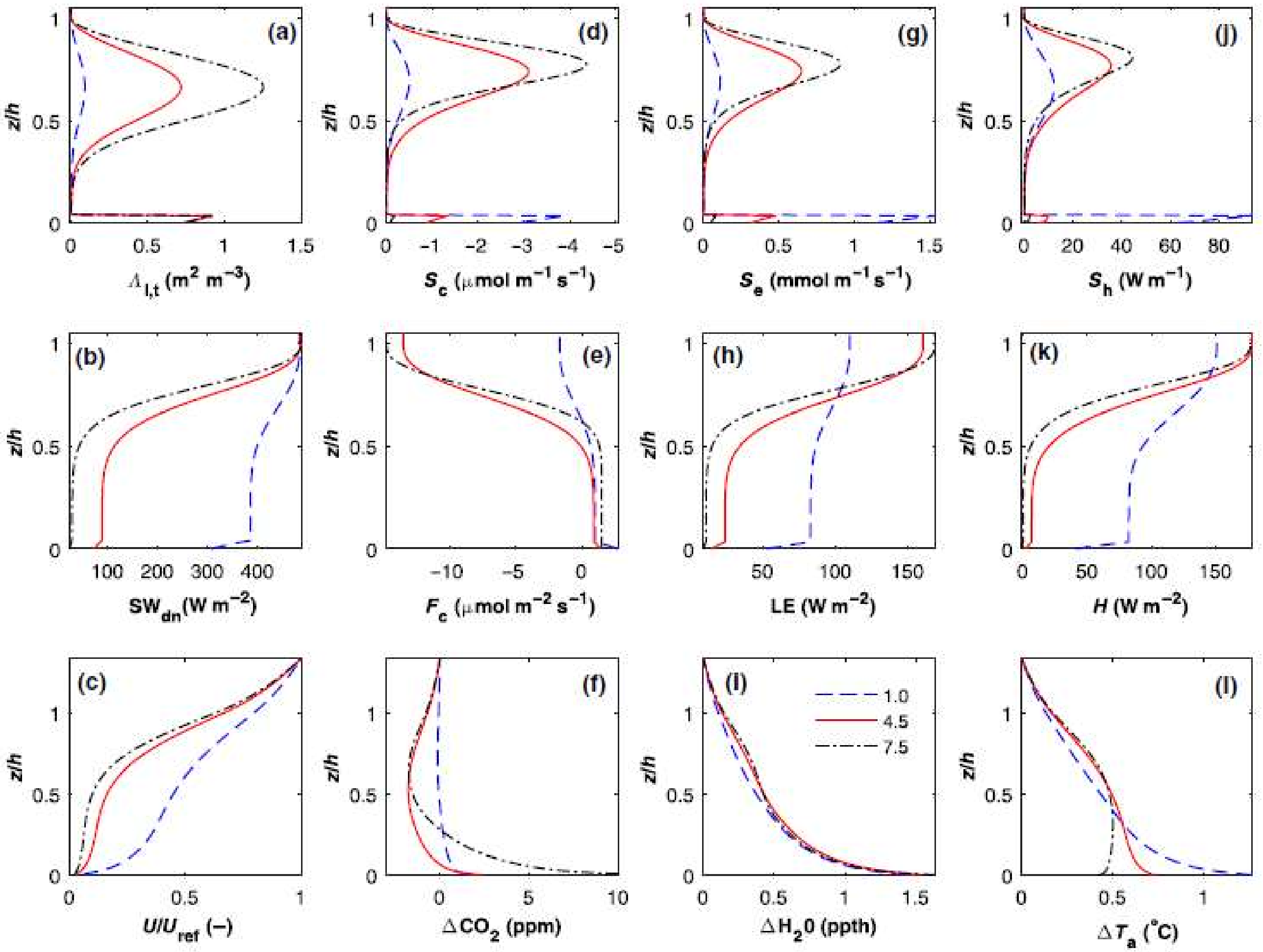
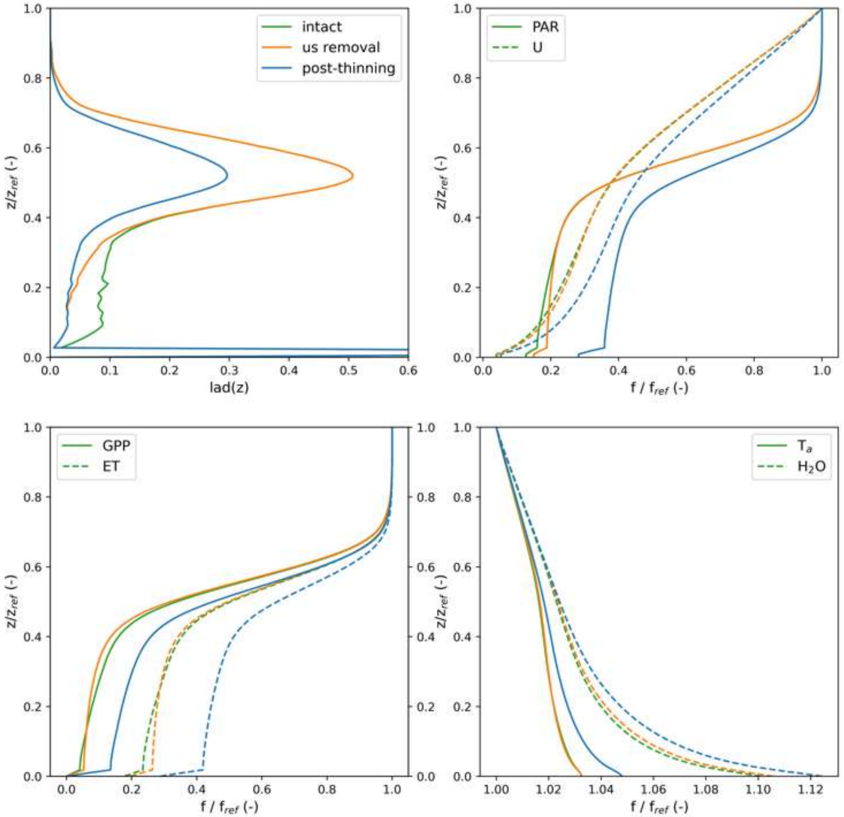
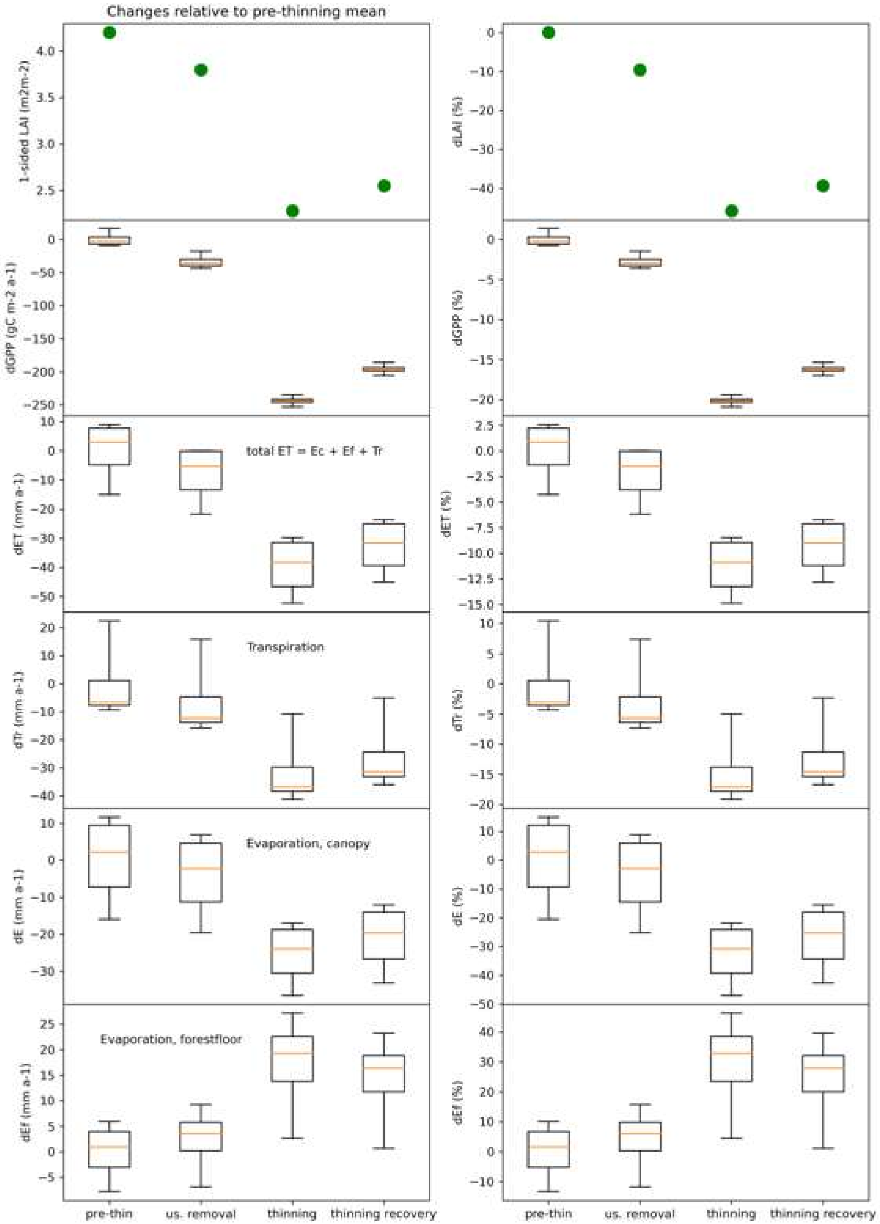



**Fig. 6** Model-predicted impacts of (a) leaf area density $\Lambda_{L,t}$ on profiles of (b) short-wave (SW) radiation and (c) wind speed (normalized by the value at uppermost gridpoint). The resulting sink/source ($S_i$), flux ($F_i$) and scalar profiles are shown for $CO_2$ (d–f), $H_2O$ (g–i) and heat (j–l). Negative values indicate uptake or net flux from the atmosphere. The profiles show daytime (10–17) averages in dry-canopy conditions, and scalar profiles indicate deviations from the uppermost gridpoint at $z = h = 1.23$. The vertical axis shows height $z$ relative to canopy height $h$ and colors represent different LAI (1.0, 4.5 and 7.5 m$^2$ m$^{-2}$).

# Hyytiälä thinning




Toprak Aslan et co.



# Next steps & collaboration?

- pyAPES Python-code description + documentation to GMD
  - Notebooks; teaching & demonstration
- pyAPES-Peatland: testing for Erkka's sites? → agreed on Halssiaapa; Erkka provides data.
  - drought periods, testing moss & peat hydrology
  - Flux data, meteorological data, water table, peat moisture
- Interpreting drivers of EC-based surface temperature
  - Better understanding?
  - Deeper discussion & generalizationsng?
- How change in peatland structure & management affects microclimate (beyond Ts)?
- How peatland & forest structure (management) affects energy budget and convective boundary-layer dynamics?
  - Ecosystem – boundary-layer feedbacks through H & LE the most direct climate impact
- ForClimate; management effects? Synergies with GreenFeedBack, ForClimateStress & BiBiFe –synthesis?

# GreenFeedBack WP3

- *”to enhance knowledge of the effects from a changing climate and increasing frequency of extreme events at high northern latitudes on terrestrial GHG exchanges and C cycle”*
- T3.1 Arctic and boreal vegetation dynamics under a changing climate
- T3.3 $CO_2$ sink/source functioning at high northern latitudes
  - Improve our understanding of off-season fluxes.
  - Effects of extreme weather events on C cycling.
  - Synthesis of the arctic and boreal $CO_2$ sink and source functioning.
- T3.4 $CH_4$ and $N_2O$ fluxes in the arctic and boreal regions
  - Modelling wetlands and associated $CH_4$ fluxes
- T3.5 Human induced disturbances to arctic and boreal ecosystems:
  - Impact of human pressure on arctic and boreal GHG fluxes. Primarily forest management.
  - Uncover how ecosystem resilience varies between natural ecosystems and those directly influenced by humans

Statistical flux data analysis (peatlands, forests, tundra), modeling by Orchidee & LPJ-Guess.