

pyAPES: Atmosphere – Plant Ecosystem Simulator

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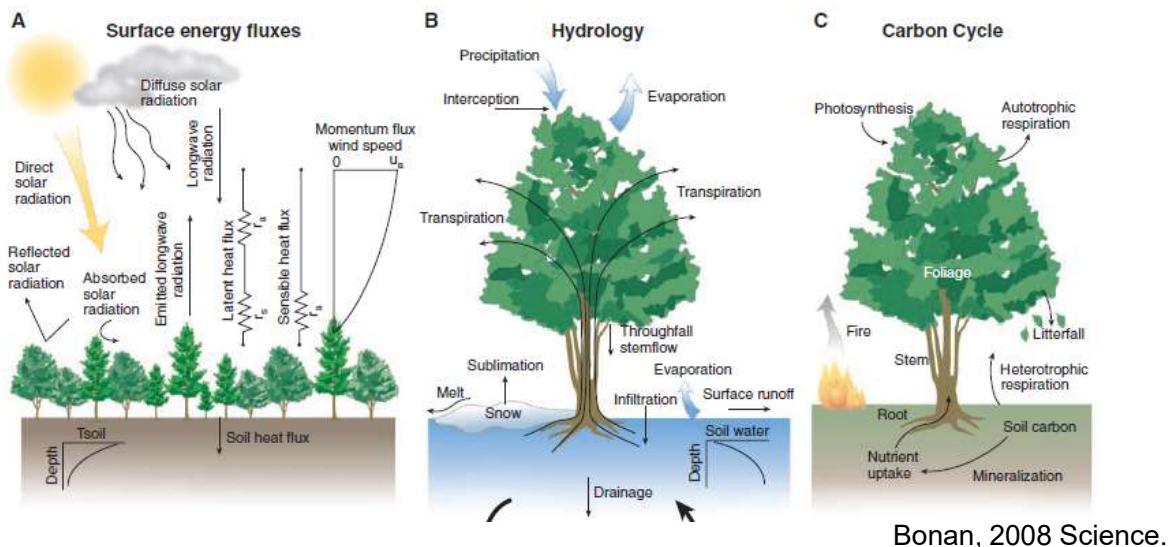


Outline

- What is pyAPES?
- Principles and modeling strategy
- Case studies
- Current development & research
- Summary

Soil - plant – atmosphere interactions

- Energy – water – carbon cycles coupled
 - Processes non-linear to environmental drivers
 - Numerous feedbacks; instantaneous or delayed
- Individuals – species – plant functional types
 - Plant traits, canopy structure
 - Ecosystem components
- Macroclimate vs. microclimate
- Spatial and temporal scale
- **Model boundaries and goal!**



Light environment Turbulence Photosynthesis Heat fluxes Leaf temperature	Water flows Snow dynamics Soil T & moisture Respiration	Phenology NEP, GPP, NPP iWUE C stocks	Growth Management
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1s

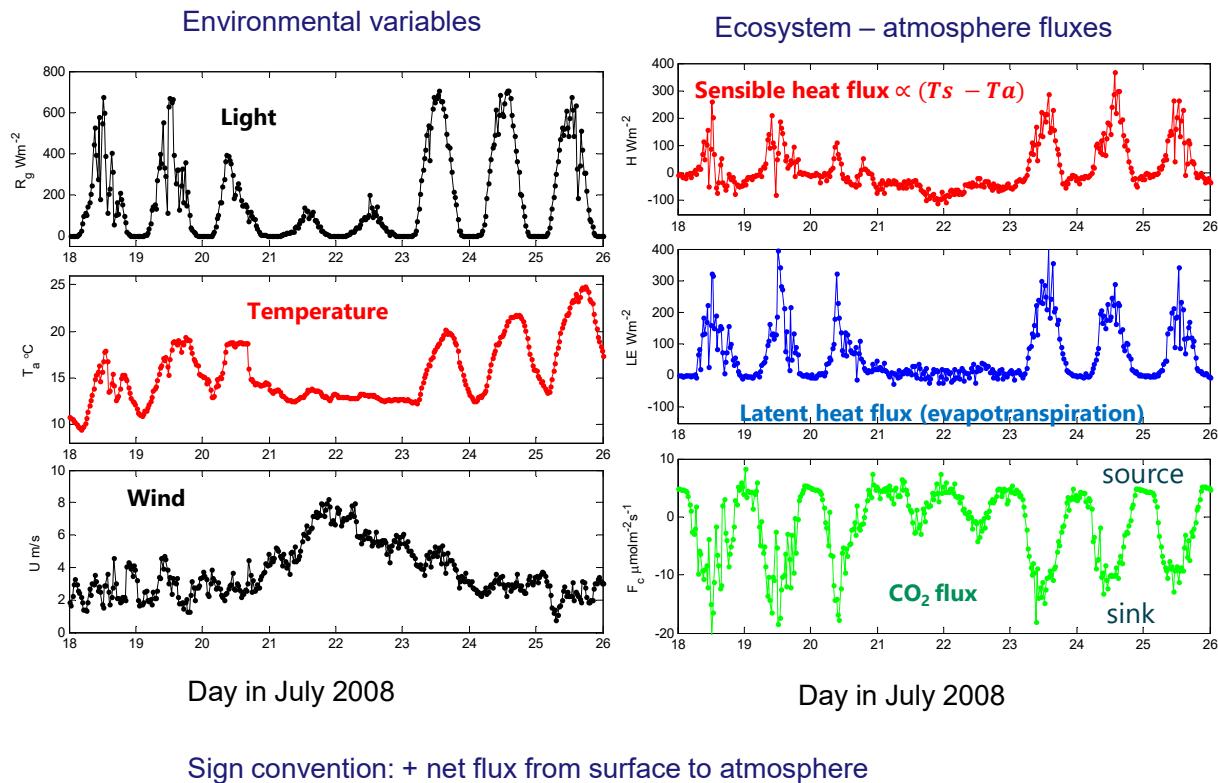
30 min

1d

seasonal

annual

decadal



How ecosystem C, water and energy fluxes respond to: i) climatic drivers, ii) weather extremes, iii) ecosystem structure, iv) management?

How to better interpret observations (EC, chambers, stable isotopes...)?

To which degree management can mitigate climate-related risks?

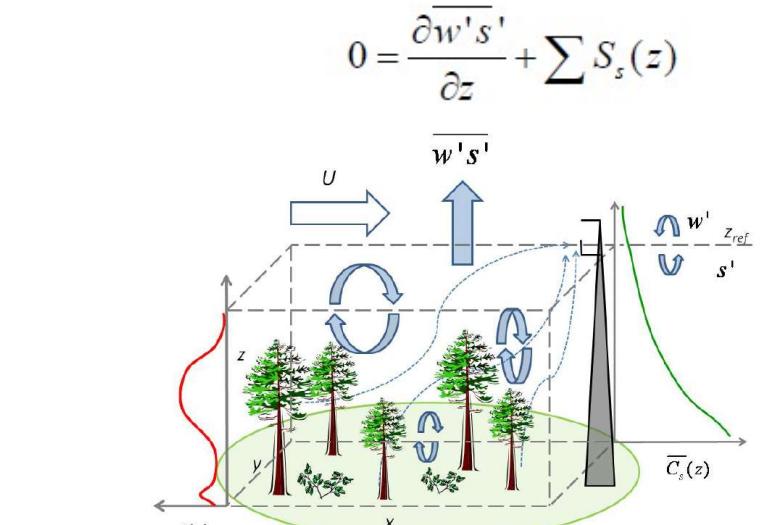
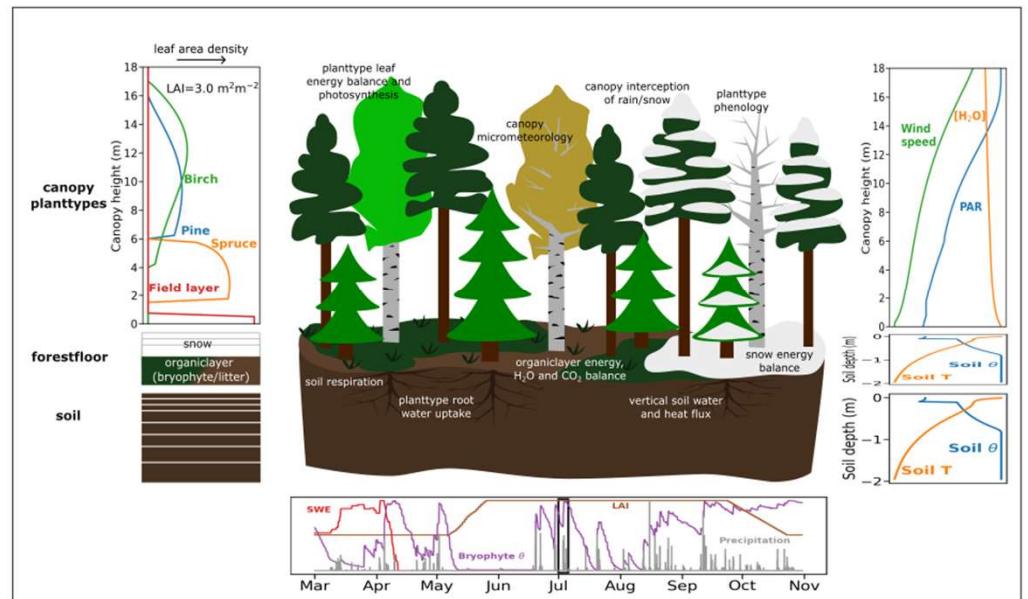


Figure 9: The principle of eddy-covariance is based on mass balance approach. In horizontally homogenous and stationary conditions the turbulent vertical flux at upper edge of the box (z_{ref}) should equal the integral over all sources and sinks, $S(z)$, within the studied volume (eq. 10). Eddies create correlated variations in vertical wind speed (w') and scalar concentration (s') and thus efficiently transport mass and energy in vertical direction. Schematic concentration profile $\overline{C}_s(z)$ is shown in right.

What is pyAPES?

pyAPES (Atmosphere - Plant Ecosystem Simulator)

- Process-based ecosystem model in pure Python
- Designed to interpret ecosystem functions and fluxes from sub-daily to annual (decadal) timescales
 - Vegetation structure imposed – plants do not grow but have seasonal cycle
- Three domains:
 - Canopy: vascular plant processes and canopy microclimate (light, T, H₂O, CO₂)
 - Forest floor: bottom layer and snowpack
 - Soil: heat and water budget
- Can simulate e.g. multi-species forests, alternative harvests, water management, climate responses and drought & heat stress



State-of-the-art land-surface model with 1D canopy and soil profile, but with static vegetation



Launiainen et al., 2015 (Ecol. Mod.)
 Launiainen et al., 2016 (Global Change Biol.)
 Leppä et al. 2020 (Agric. For. Met.)
 Tikkasalo et al. 2026 (in prep.)

Process-based ecosystem model?

define process-based ecosystem model

Copilot ⓘ

A **process-based ecosystem model** is a type of ecological model that represents ecosystems by explicitly simulating the underlying **biophysical, chemical, and biological processes** that govern energy, water, carbon, and nutrient flows. Instead of relying on empirical correlations, these models use mechanistic descriptions of processes to predict ecosystem dynamics under varying conditions.

Key Characteristics

- **Mechanistic Approach:** Models processes such as photosynthesis, respiration, decomposition, nutrient cycling, and hydrology based on physical and biological principles.
- **Dynamic Simulation:** Tracks changes over time in state variables like biomass, soil carbon, water content, and nutrient pools.
- **Environmental Drivers:** Incorporates climate variables (temperature, precipitation, radiation), soil properties, and sometimes management practices.
- **Scalability:** Can be applied at different spatial scales—from plot to global—depending on data availability and complexity.

define difference between explanatory and predictive model

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The difference between **explanatory models** and **predictive models** lies in their **primary goal** and **evaluation criteria**:

Explanatory Model

- **Purpose:** To understand and explain the underlying relationships between variables (cause-effect or mechanism).
- **Focus:** Interpretation and inference.
- **Evaluation:** How well the model captures the true structure of the system (e.g., significance of parameters, goodness-of-fit).
- **Example:** A regression model used to test whether temperature significantly affects plant growth.
- **Key Question:** *Why does this happen?*

Predictive Model

- **Purpose:** To accurately predict future or unseen outcomes.
- **Focus:** Accuracy and generalization.
- **Evaluation:** Predictive performance on new data (e.g., RMSE, accuracy, cross-validation).
- **Example:** A machine learning model predicting next year's crop yield based on climate data.
- **Key Question:** *What will happen?*

Summary in one sentence:

Explanatory models aim for **understanding**, while predictive models aim for **forecasting accuracy**, even if the underlying mechanism is not fully interpretable.

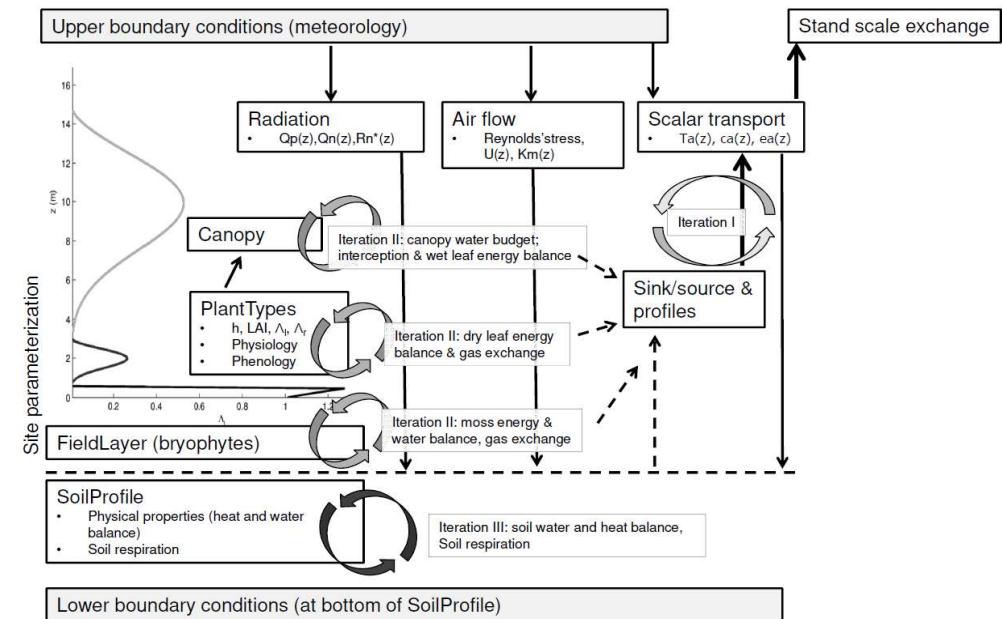


pyAPES

- Process-model, based on **biogeophysical & ecophysiological theory**
 - Mass & energy conservation
 - Established model components: A-gs, radiative transfer, soil water and heat flow, snowpack
 - Parameters can be measured or independently estimated
 - Leaf/shoot gas-exchange, leaf-area density profiles, soil texture, hydrological properties, drainage architecture,
 - Easy (?) to apply for different ecosystems; theory is 'generic'
- Resolves fluxes at canopy and soil layers and upscales to plant group and ecosystem level (timestep = $\frac{1}{2}$ or 1h)
- Accounts for **interactions and feedbacks** between processes, e.g.
 - soil water status impacts leaf functioning
 - Canopy water use affects soil water
 - microclimate affects leaf processes

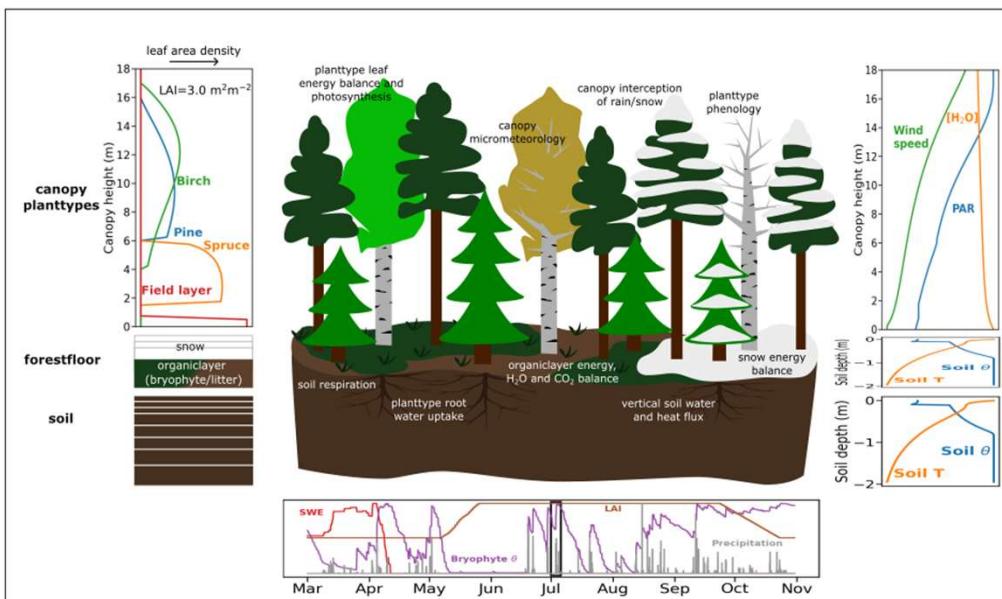
leaf fluxes affect microclimate...

 - Allows exploring interplay between species traits, canopy structure, soil texture and weather conditions



Forcing and outputs

site or scenario parameterization



Soil boundary conditions (optional): Soil moisture, soil temperature at depth z_{sref}

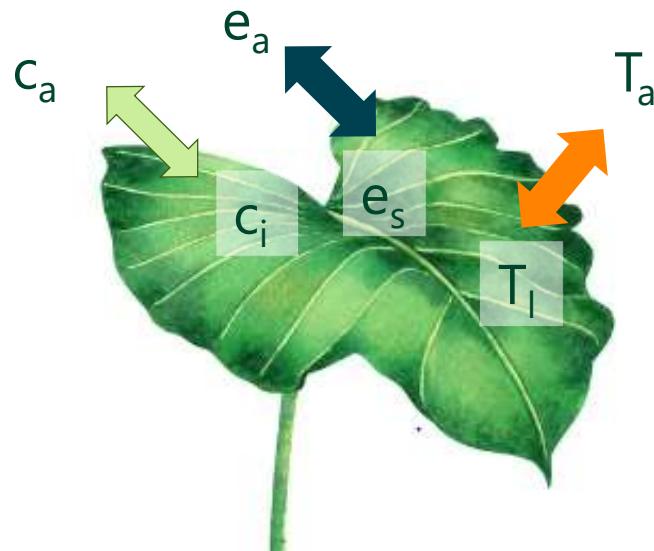


Weather data (1/2h): PAR, NIR, wind speed, air temperature, humidity, CO₂, precipitation rate

- **Carbon fluxes:** NEP, GPP, Reco (ecosystem, canopy layer, PlantType, OrganicLayer)
- **Water fluxes:** e.g. ET, transpiration, evaporation, drainage, ditch drainage
- **Energy fluxes:** e.g. net radiation, sensible heat, latent heat, ground heat flux, snowpack heat flux
- **State variables:** snowpack, organic layer & soil temperature, water content, water table depth, dynamic soil properties...
- **Microclimate:** light regime, ecosystem albedo, wind speed, temperature, humidity and CO₂ profiles
- **Can be configured by user:** virtually all variables at each possible level of code can be output

Example: leaf-level net photosynthesis, transpiration and energy balance

© Luke



$$SW_{abs} + (LW_{abs} - 2\epsilon\sigma T_l^4) - c_p g_h (T_l - T_a) - \lambda_v (e_s(T_l) - e_a)/p_a = 0$$

Radiation balance

heat flux

transpiration

For know:

- 1) Ambient environment around the leaf (light, Ta, VPD, CO₂, wind)
- 2) Plant state (from previous ½ h): photosynthetic & stomatal traits, albedo, leaf size, leaf water potential

Solve for:

- leaf layer temperature
- photosynthesis & dark respiration rate, transpiration rate, stomatal conductance, WUE, iWUE
- ... at each canopy layer, for all PlantTypes

Flux = conductance x (concentration difference)

planttype.leaf_gas_exchange()

$$\frac{C_l T_l}{dt} = (1 - \alpha) S W + \epsilon (L W_{in} - \sigma T_l^4) - c_p g_b (T_l - T_a) - \lambda g_v D$$

$$D = \frac{e_{sat}(T_l) - e_a}{p_a} \quad \leftarrow \text{Tleaf, air humidity}$$

$$g_b \propto a_1 \sqrt{\frac{U}{d}} + a_2 \left(\frac{T_l - T_a}{d} \right)^{1/4} \quad \leftarrow \text{Leaf size, wind, } T_{\text{leaf}}$$

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

Stomatal conductance (Medlyn et al., 2011)

$$g_s = 1.6 \left(1 + \frac{a_3}{\sqrt{D}} \right) \frac{A_n}{c_s} \quad \begin{matrix} \leftarrow & \text{air humidity, } A, \\ \leftarrow & \text{stomatal traits} \end{matrix}$$

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

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

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

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

Photosynthesis
(Farquhar et al.)

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

leaf.photosynthesis()

$\Gamma_*, K_c, K_\theta = \text{non-linear } f(T)$

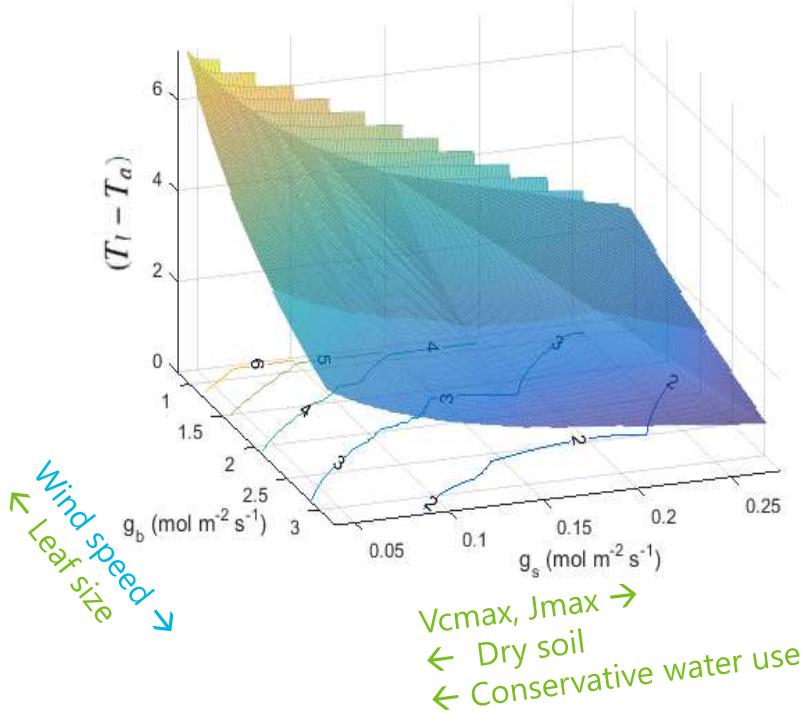
← Leaf nitrogen,
water potential

```
photo.py ● planttype.py ● rootzone.py ● micromet.py
pyAPES > planttype > planttype.py > PlantType > leaf_gas_exchange
65 class PlantType(object):
373
374     def leaf_gas_exchange(self, forcing: Dict, controls: Dict, leaftype: str) -> dict:
375         """
376             Solves leaf gas-exchange and energy balance (optionally).
377             Energy balance is solved using Taylor's expansion (i.e isothermal net radiation -approximation),
378             which eliminates need for iterations with the LW radiation scheme.
379
380         Args:
381             forcing (dict):
382                 'h2o': water vapor mixing ratio (mol/mol)
383                 'co2': carbon dioxide mixing ratio (ppm)
384                 'air_temperature': ambient air temperature (degC)
385                 'par_incident': incident PAR at leaves (umol/m2s-1)
386                 'sw_absorbed': absorbed SW (PAR + NIR) at leaves (W/m2)
387                 'lw_net': net isothermal long-wave radiation (W/m2)
388                 'wind_speed': mean wind speed (m/s)
389                 'air_pressure': ambient pressure (Pa)
390                 'leaf_temperature': initial guess for leaf temperature (optional)
391                 'average_leaf_temperature': leaf temperature used for computing LWhet (optional)
392                 'radiative_conductance': radiative conductance used in computing LWnet (optional)
393             controls (dict):
394                 'energy_balance' (bool): True computes leaf temperature by solving energy balance
395                 'logger_info' (str)
396             leaftype (str): 'sunlit' / 'shaded'
397
398         Returns:
399             (dict):
400                 'net_co2': net CO2 flux (umol m-2 leaf s-1)
401                 'dark_respiration': CO2 respiration (umol m-2 leaf s-1)
402                 'transpiration': H2O flux (transpiration) (mol m-2 leaf s-1)
403                 'sensible_heat': sensible heat flux (W m-2 leaf)
404                 'fr': non-isothermal radiative flux (W m-2)
405                 'Tl': leaf temperature (degC)
406                 'stomatal_conductance': stomatal conductance for H2O (mol m-2 leaf s-1)
407                 'boundary_conductance': boundary layer conductance for H2O (mol m-2 leaf s-1)
408                 'leaf_internal_co2': leaf internal CO2 mixing ratio (mol/mol)
409                 'leaf_surface_co2': leaf surface CO2 mixing ratio (mol/mol)
410
411         """
412
413         Samuli Launiainen, Kersti Leppä, O-P Tikkasalo, Last edit 11/2025 / Open
```

System of coupled non-linear equations solved iteratively

... to get this far, one must have:

- Light regime inside canopy
 - Air temperature, moisture and CO₂ concentration
 - PlantType traits adjusted for soil or leaf water potential and seasonal phenology



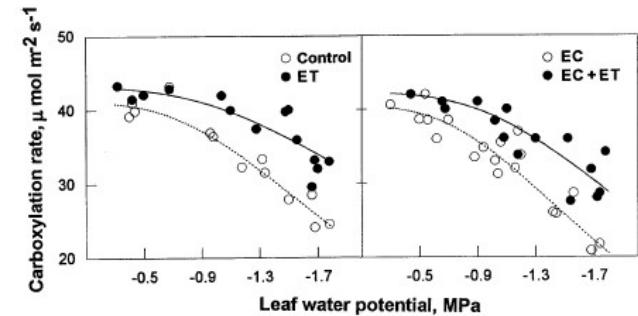
Here absorbed SW, Ta, ca, air humidy kept constant.

g_b – axis: vary wind speed and / or leaf size

g_s – axis: vary Vcmax, Jmax and/or g_1 (stomatal sensitivity to VPD)

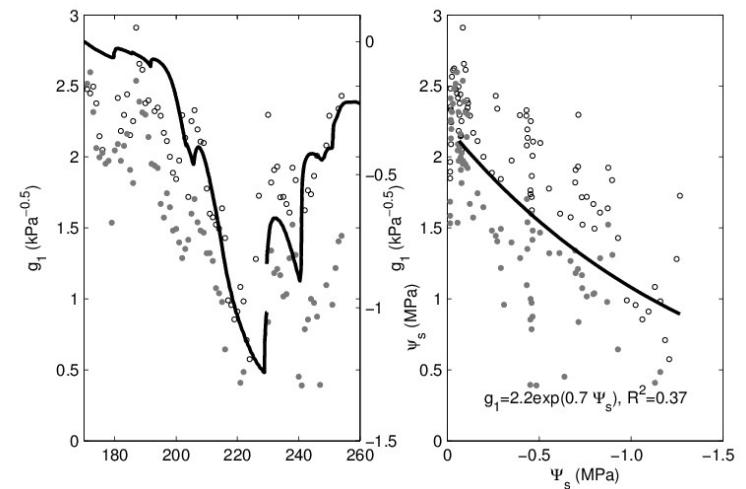
Soil to leaf feedbacks

Biochemical $\rightarrow V_{\text{cmax}}(\Psi_L), J_{\text{max}}(\Psi_L)$



Kellomäki & Wang (1996) Tree Phys.

Stomatal $\rightarrow g_1(\Psi_L), g_1(\theta), \dots$

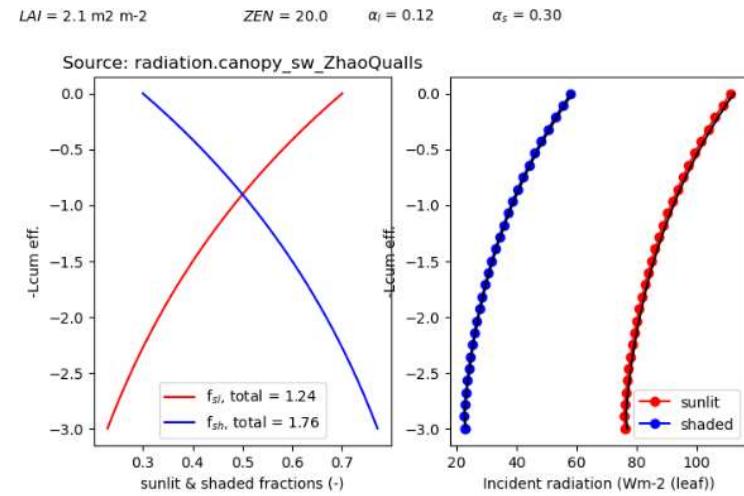


Launiainen et al. 2015

Canopy Radiative transfer

Treats canopy as horizontally homogeneous porous media

- PAR & NIR:
 - direct, diffuse, upward/downward scattered
 - with adaptations for clumped foliage & adjustment for within-shoot scattering
 - Multiple scattering among canopy layers (and forest floor)
 - Plant optical traits can vary across canopy depth or between species
- Thermal, two alternatives:
 - Black leaves (emissivity==1); ignores scattering
 - Non-black leaves & multiple scattering similar to PAR & NIR
- Zhao & Qualls (2005), Spitters et al, 1986; Campbell & Norman, 1998



```

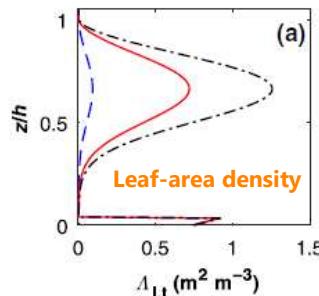
1 # import functions
2 from pyAPES.microclimate.radiation import canopy_sw_ZhaoQualls
3 from pyAPES.utils.constants import DEG_TO_RAD
4
5 # create stand with uniform leaf-area density
6 # stand 1-sided leaf-area index [m2 m-2]
7 LAI = 3.0
8 nlyrs = 30 # layers
9
10 # allocate LAI uniformly between nodes 1 and -1 (radiation models require at least one node with lad[i]=0.0 above canopy top)
11 laiz = np.zeros(nlyrs)
12 laiz[1:-1] = LAI / (nlyrs-2)
13
14 # optical parameters
15 p = {'clump': 0.7, # clumping index [-]
16       'leaf_angle': 1.0, # leaf-angle distribution [-]
17       'Par_alb': 0.12, # shoot Par-albedo [-]
18       'Nir_alb': 0.55, # shoot NIR-albedo [-]
19       'leaf_em': 0.98, # leaf emissivity [-]
20       'x': 1.0 # leaf-angle distribution parameter (1.0 == spherical)
21     }
22
23 # compute vertical PAR profiles for solar zenith angle ZEN = 20.0 deg
24 zen = 20.0 * DEG_TO_RAD
25
26 # the units are arbitrary here
27 rdir = 100.0
28 rdiff = 100.0
29
30 # call functions
31 Shb, Shd, Shu, Q_s1, Q_sh, q_s1, q_sh, q_soil, f_s1, alb = canopy_sw_ZhaoQualls(LAIz=laiz, Clump=0.7, x=1.0, Zen=zen,
32                                         IbSky=rdir, IdSky=rdiff,
33                                         LeafAlbedo=0.12, SoilAlbedo=0.3, PlotFigs=True)

```

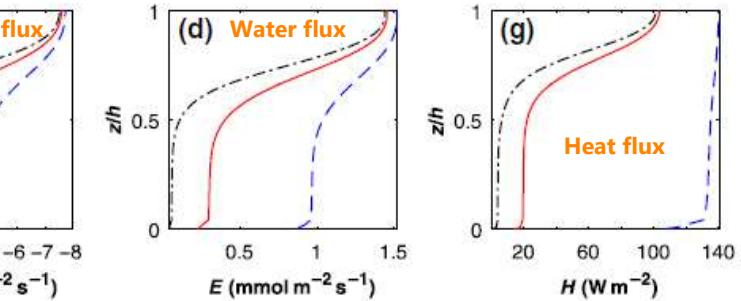
Upscaling from leaf to ecosystem scale

Example

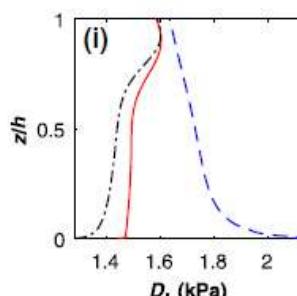
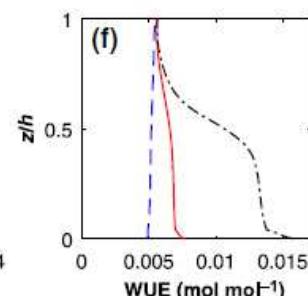
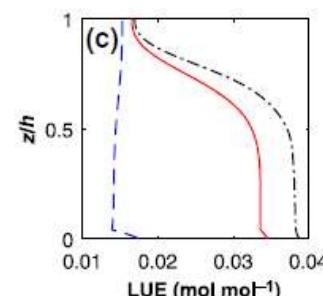
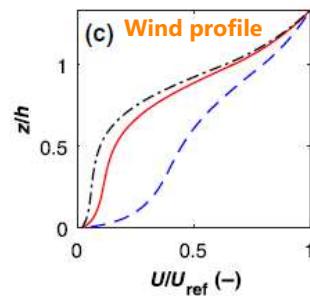
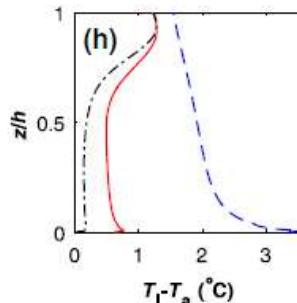
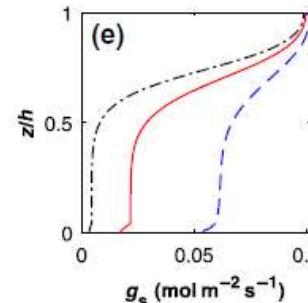
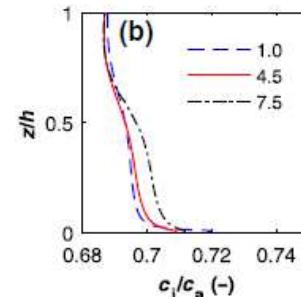
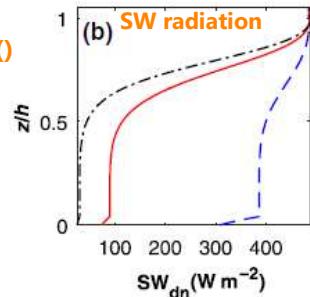
Vary canopy leaf-area density while keeping plant traits & environmental conditions the same



✗ multiply by amount of leaves



Leaf-level fluxes



$$K_m \frac{\partial^2 U}{\partial^2 z} + \frac{\partial K_m}{\partial z} \frac{\partial U}{\partial z} - C_d \Lambda_{p,t} U^2 = 0.$$

$$K_m = l^2 \left| \frac{\partial U}{\partial z} \right|$$

microclimate.micromet.Micromet. normalized_flow_stats()



Fig. 7 Modeled profiles of (a) leaf net CO₂ exchange, (b) leaf internal to external CO₂ mixing ratio, (c) light-use efficiency LUE, (d) transpiration rate E, (e) stomatal conductance g_s , (f) water-use efficiency WUE, (g) leaf sensible heat flux H , (h) local leaf-air temperature difference and (i) vapor pressure deficit D_l at leaf surface temperature. The profiles show layer-averaged values (accounting for sun-shade fraction) over dry-canopy daytime (10–17) conditions. The leaf-scale values in panels a, d, e and g are given per m² of leaf. The colors represent different LAI as in Fig. 6.

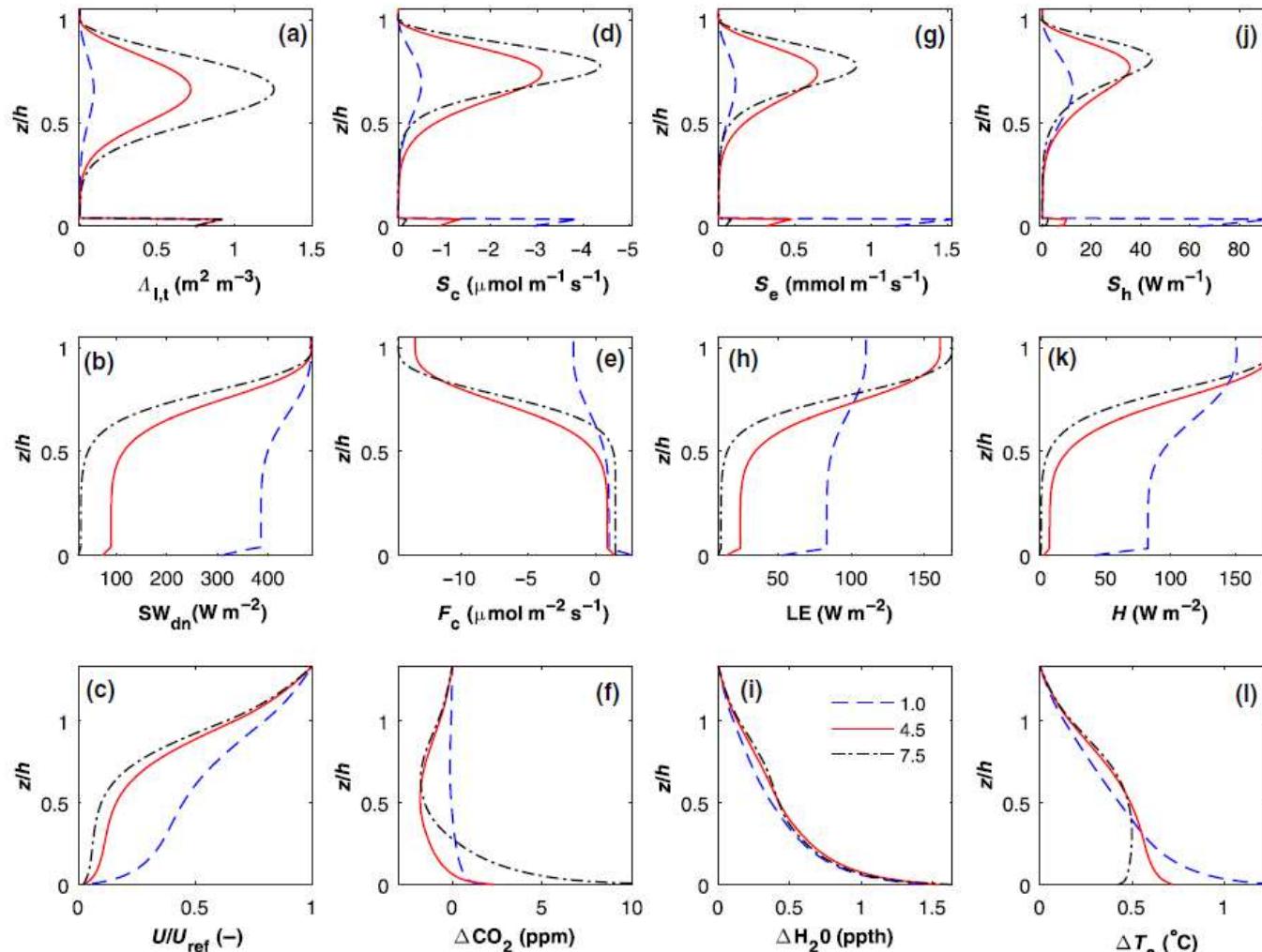
canopy.mlm_canopy.run()

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 $7.5 \text{ m}^2 \text{ m}^{-2}$).

Canopy sink/source profiles

Integrated flux profiles

Canopy microclimate
(in steady-state with
sinks /
sources)

$$K_s \frac{\partial^2 \bar{s}}{\partial z^2} + \frac{\partial K_s}{\partial z} \frac{\partial \bar{s}}{\partial z} + S_s(z) = 0,$$

microclimate.micromet.Micromet.scalar_profiles()**Sink/source and flux profiles**

Ecosystem responses

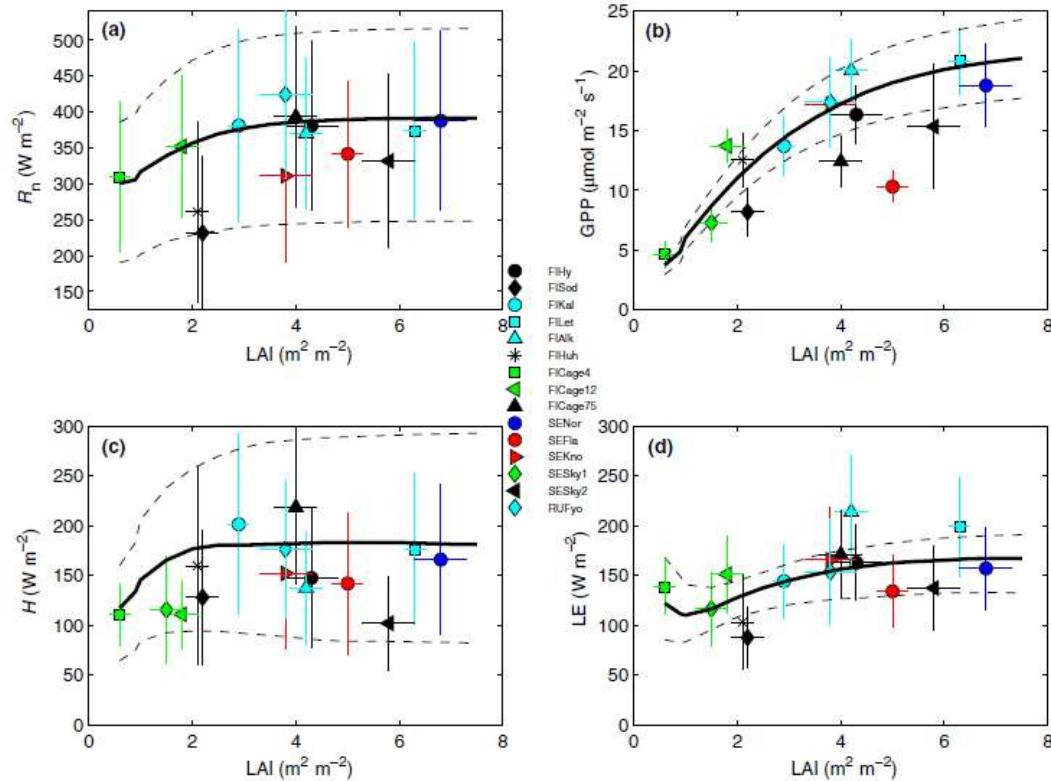


Fig. 1 Measured and model-predicted ecosystem-scale (a) net radiation (R_n), (b) gross primary productivity (GPP), (c) sensible heat flux (H) and (d) latent heat flux (LE) as a function of total (overstory + understorey) leaf area index (LAI). Symbols and vertical lines give measured daytime (10–17) 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.

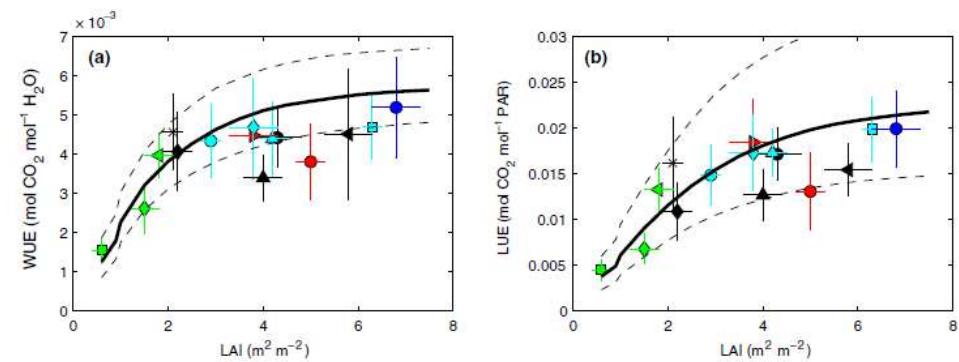


Fig. 5 (a) Ecosystem-scale water-use efficiency (WUE) and (b) light-use efficiency (LUE). The symbols and conditions are as in Fig. 1.

Soil water and heat budgets

Class soil.Water()

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

- $R(z)$ root uptake, $D(z)$ drainage to ditches

Hydraulic properties = f(soil type, z_s , ψ_s)

- Water retention characteristics, hydraulic conductivity (van Genuchten – Mualem)
- Simple adjustment for macropore infiltration
- Upper BC: flux or head
- Lower BC: impermeable, free drainage or fixed

→ Water content and potential profile, vertical and lateral water fluxes

Class soil.Heat()

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

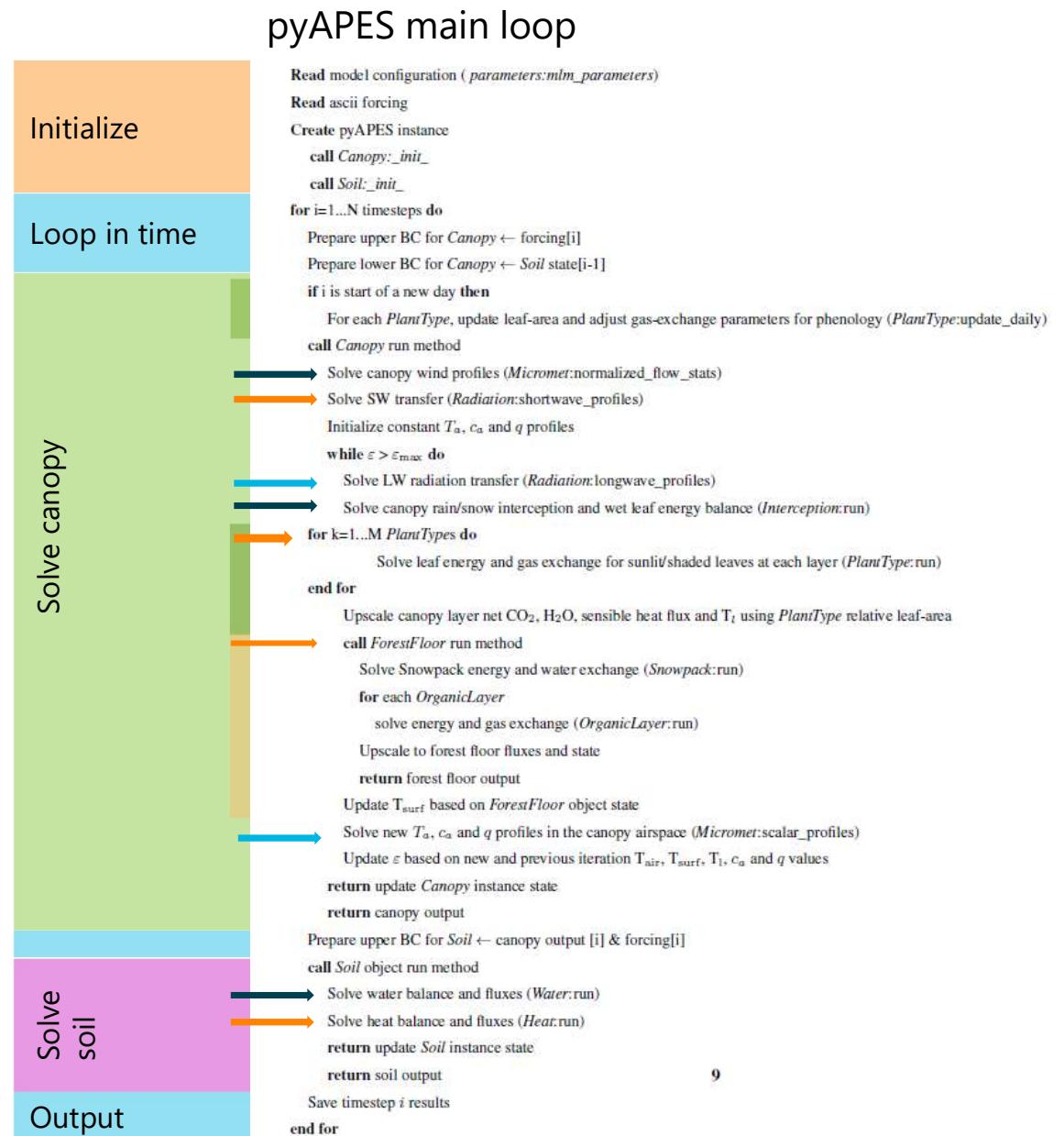


Hydraulic properties = f(soil type, z_s , ψ_s)

- Heat capacity C_p & thermal conductivity λ_h = $f(\theta, \text{soil minerals, soil org. matter})$
 - Soil freezing & phase changes
 - Upper BC: surface heat flux or $T(t)$
 - Lower BC: heat conduction through bottom or $T(t)$
- Temperature profile, ice and liquid water content, vertical heat fluxes

Solution strategy

- Timescale separation (fast vs. slow processes)
- Iterative solutions at multiple levels, e.g.:
 - Leaf temperature, photosynthesis, stomatal conductance
 - Forest floor and moss/litter temperature & moisture
 - Canopy sink/source profiles, thermal radiation & microclimate
 - Soil water potential & hydraulic conductivity
- Parameters and data flow between objects and functions via python *dictories*
- Outputs to NetCDF & log files



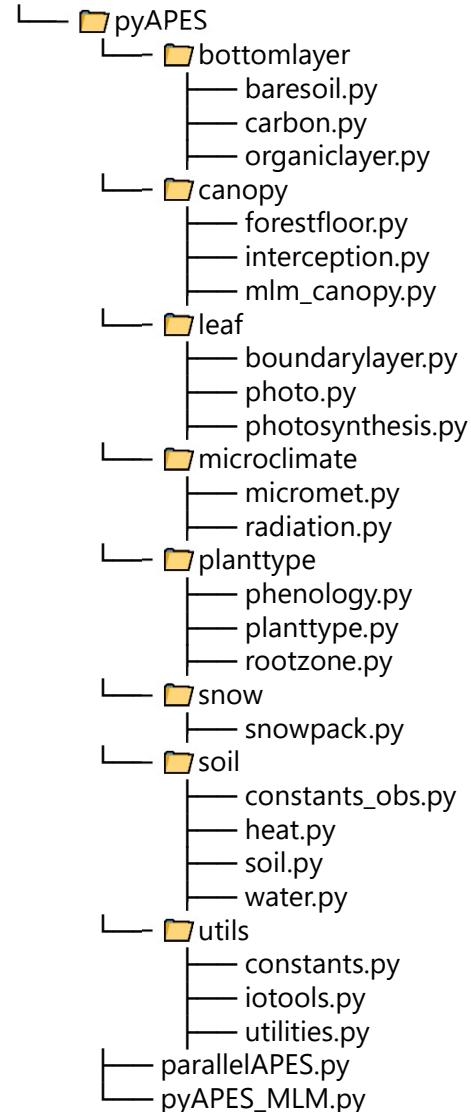
Modeling principles

Object-oriented

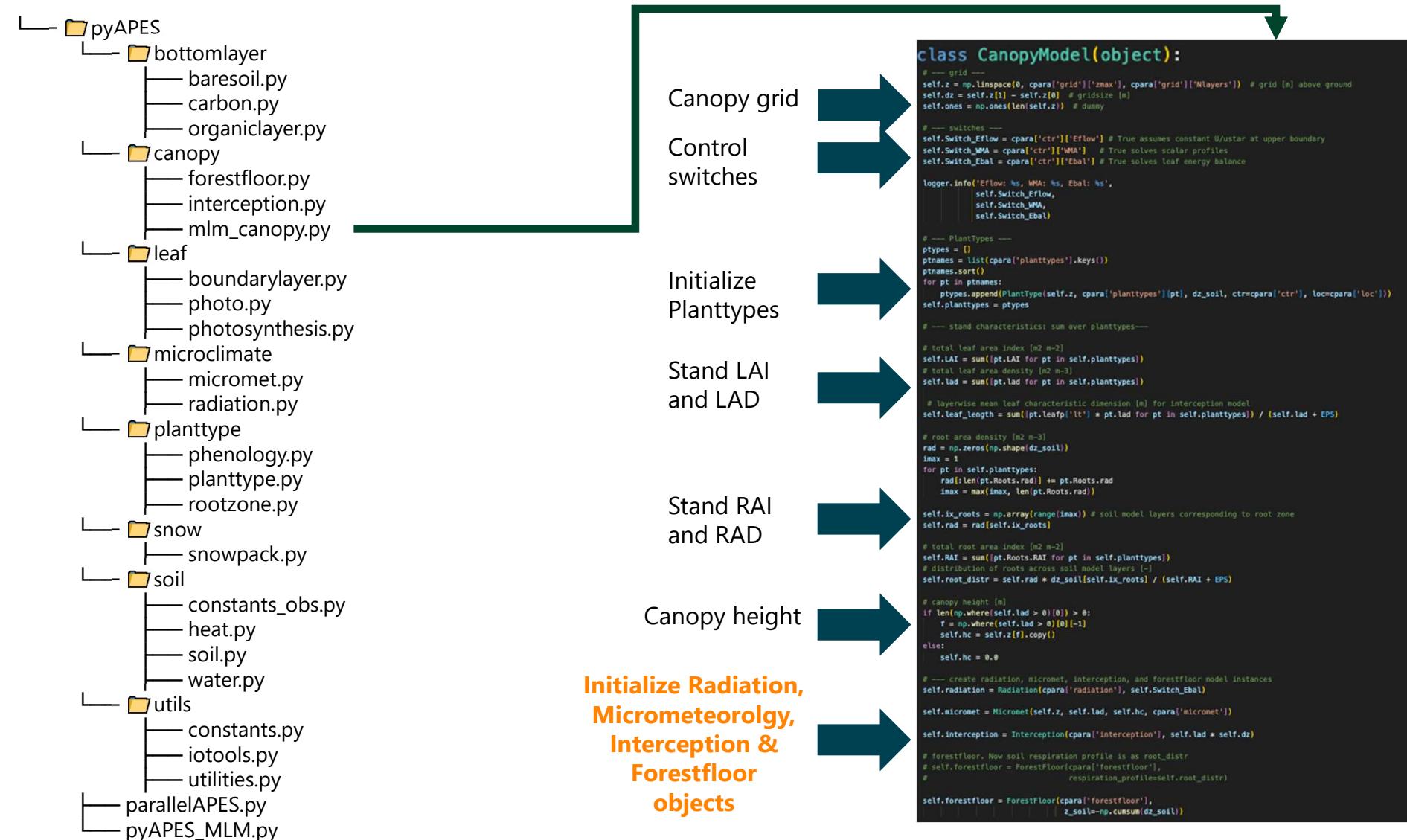
- Classes → parameterization → instances
 - Properties (structural, functional) ↔ parameters
 - Class functions ↔ processes
 - E.g., PlantType
 - → Structure
 - → Photosynthetic parameters
 - → Water use parameters
 - → Overstory pine with photosynthesis and transpiration

Modular, modifiable and reusable code

- Classes
 - System components (e.g. PlantType, OrganicLayer, Canopy, Radiation)
 - Stand-alone sub-models
- Packages
 - System compartments (e.g. leaf, plant, soil)

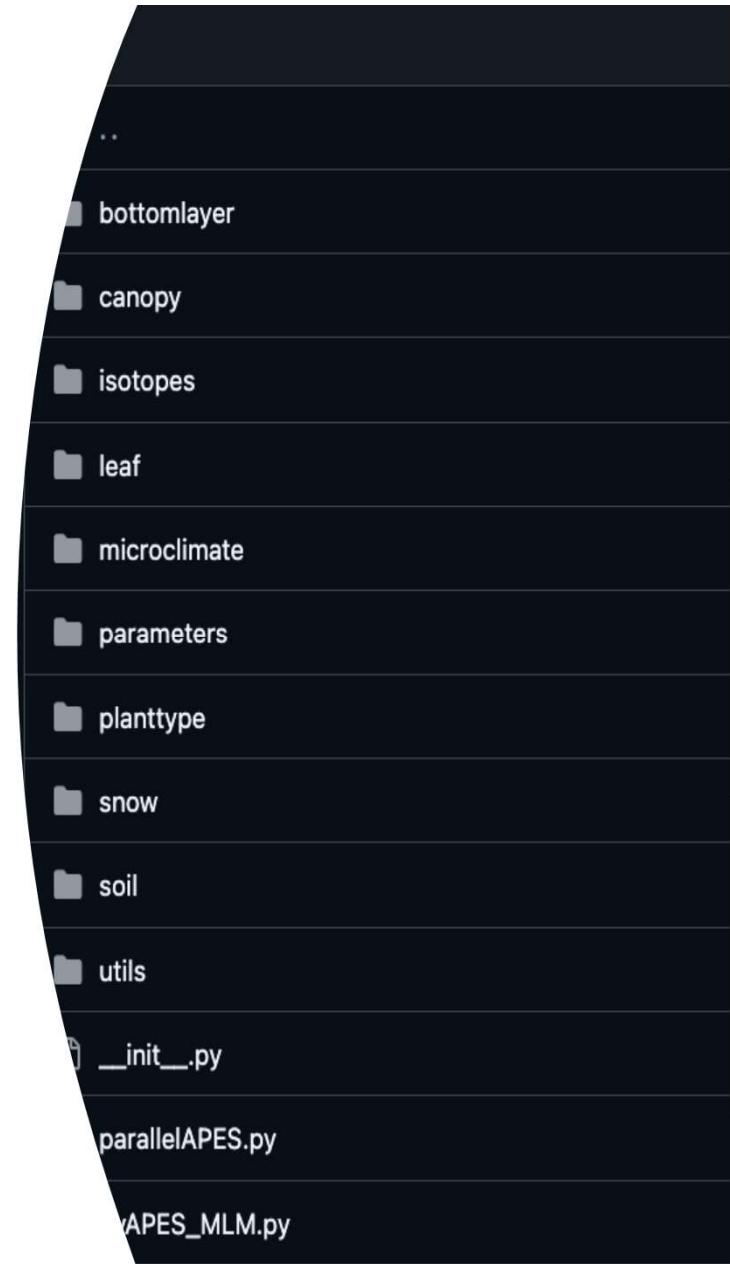


pyAPES source code structure



pyAPES version control

- Main repository maintained at GitHub
 - https://github.com/LukeEcomod/pyAPES_main/
- New features merged from specific branch
 - No pushing to main branch
- Forks or clones of the main repository can be made to tailor the code according to research needs
- We are constantly looking for best practices for model use and development
 - Please share your experiences after the presentation ☺

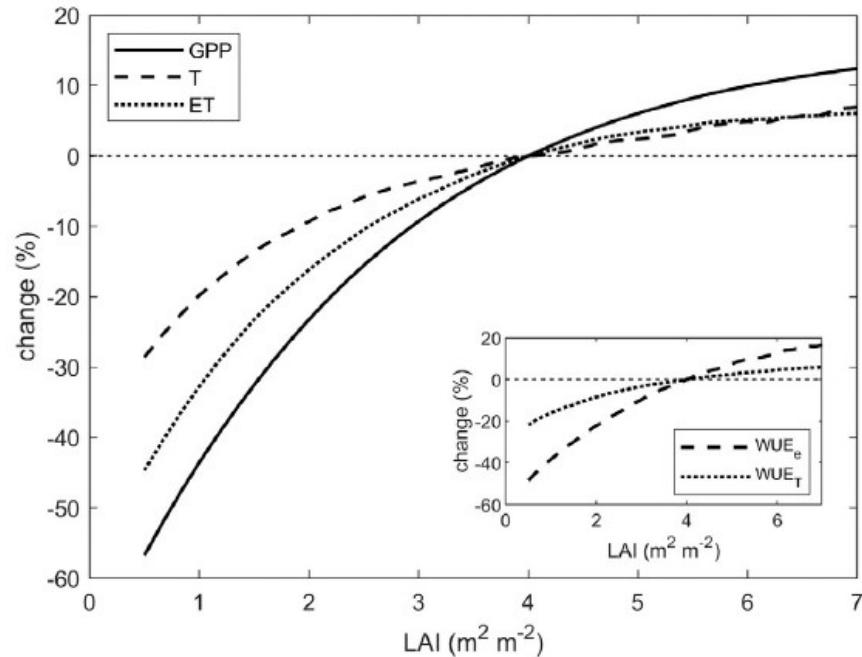


Case studies

Effect of LAI change on GPP, ET and transpiration

T. Aslan *et al.*

Agricultural and Forest Meteorology 353 (2024) 110061



Thinning impacts depend on:
 i) state before thinning
 ii) thinning intensity

Response flux-dependent

Fig. 11. Process-model predictions of the response of gross photosynthetic productivity (GPP), transpiration (T), and evapotranspiration (ET) as well as ecosystem water use efficiency (WUE_e) and stand transpiration use efficiency (WUE_T) for various thinning intensities. The figure shows the relative difference of each response variable with respect to the reference $\text{LAI} = 4.0 \text{ m}^2 \text{ m}^{-2}$.

Increasing forest C sink – why?

Long-term FluxNet –site, 2001 – 2017

NEP increasing +1.4 – 1.8% a^{-1}

- Due to increasing GPP (+0.4 – 0.8 % a^{-1})
- GPP trend resembles that of CO₂
- No change in ecosystem respiration
- No change in evapotranspiration (ET)
- Statistically insignificant increase in WUE & LUE

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RESEARCH ARTICLE

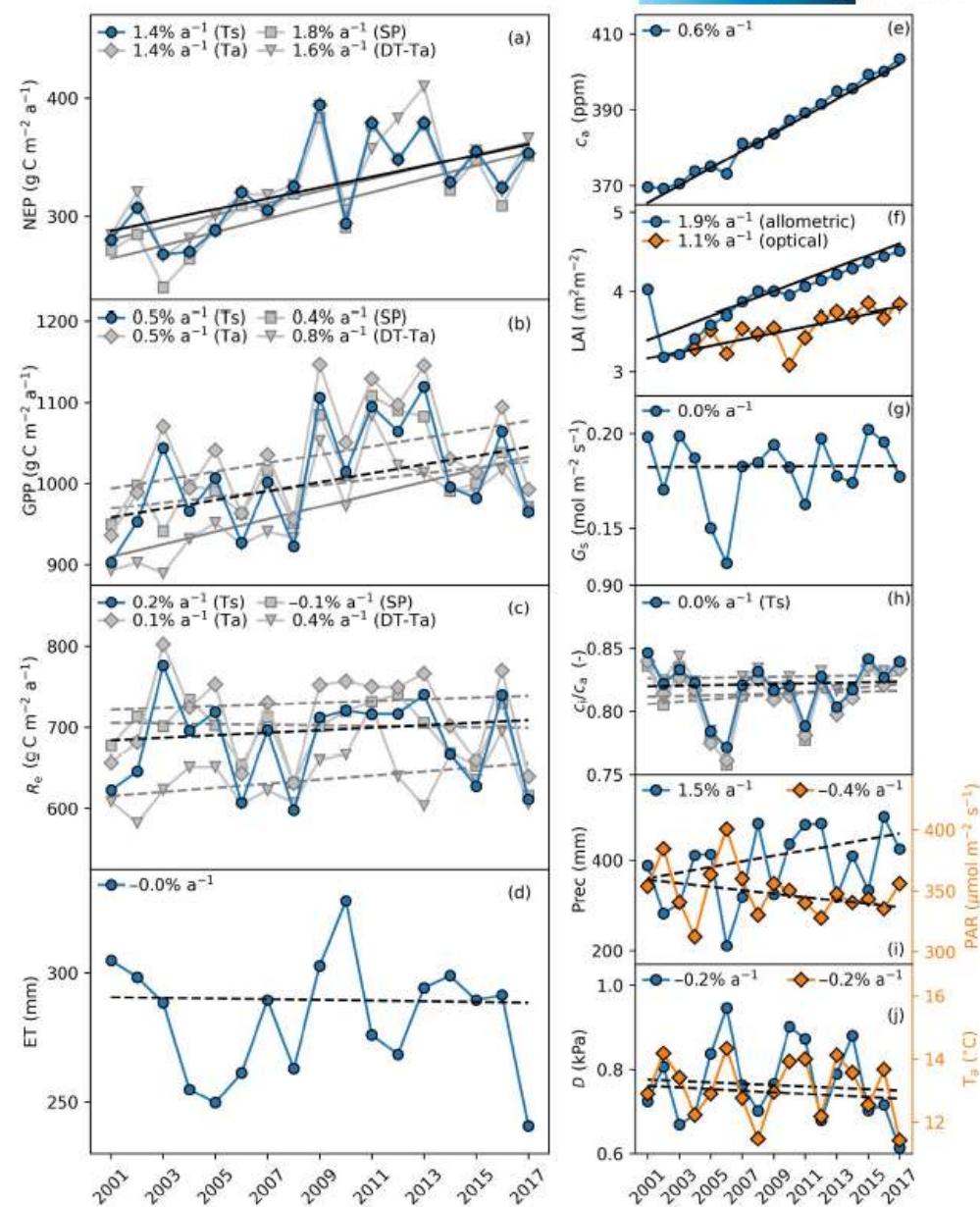
Global Change Biology WILEY

Does growing atmospheric CO₂ explain increasing carbon sink in a boreal coniferous forest?

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Abstract
The terrestrial net ecosystem productivity (NEP) has increased during the past three decades, but the mechanisms responsible are still unclear. We analyzed 17 years



Multiple factors can explain increasing GPP

GPP = f(light, CO₂, T, water availability, amount of biomass, ...)

Atmospheric CO₂ increase (+0.8 %a-1)

- More food available

Increasing biomass and LAI (+1.1 – 1.9 %a-1)

- More leaves eating the dinner

Increasing leaf nitrogen content (yes)

- hungrier leaves

Longer growing seasons (yes, spring advance, p>0.05)

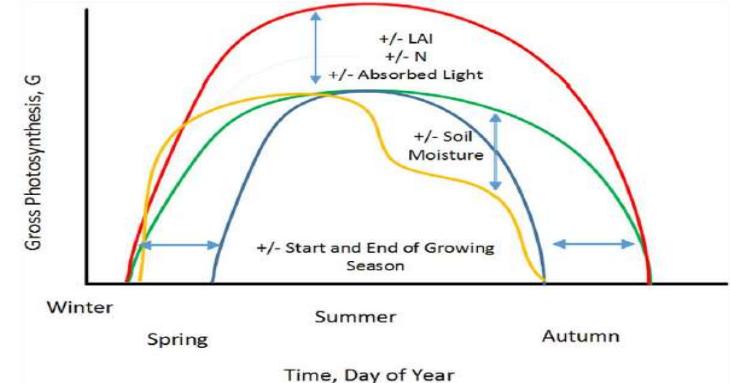
- More time for breakfast and supper

Increasing diffuse radiation (yes, p>0.1)

- Leaves deeper can eat more

Changing footprint (inevitably)

- The part of forest seen by EC gets smaller as trees get taller



Baldocchi et al. 2018. Agr. For. Met

All can occur simultaneously (and likely are)
Importance depends on timescale and env. conditions

N=1 → hard to assess causal mechanisms statistically

Numerical experiment



affect model parameters



External inputs X_n change

"Factorial design"

- $\boxed{\text{LAI}} + \boxed{\text{CO}_2} + \boxed{\text{Nleaf}} + \boxed{\text{Met}}$
- LAI + CO₂ + Met
- LAI + Nleaf + Met
- CO₂ + Nleaf + Met
- LAI + Met ← observed LAI trend
- CO₂ + Met ← observed CO₂ trend
- Nleaf + Met ← V_{cmax}, J_{max}, etc. = f(Nleaf)
- Met ← meteorological forcing (light, VPD, T, ...). Constant CO₂

Crank through number of runs, compute trends, compare to observed and interpret findings

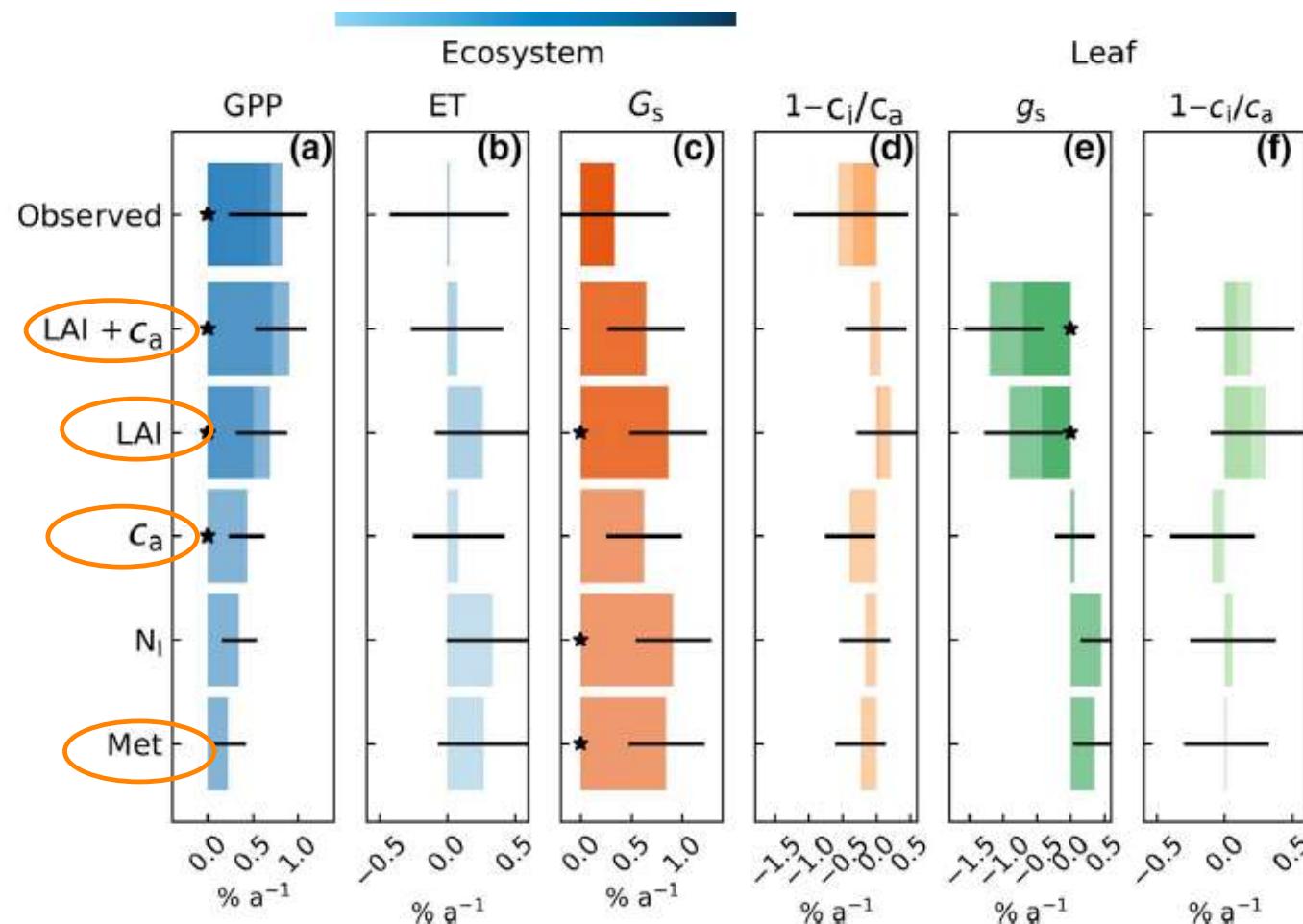
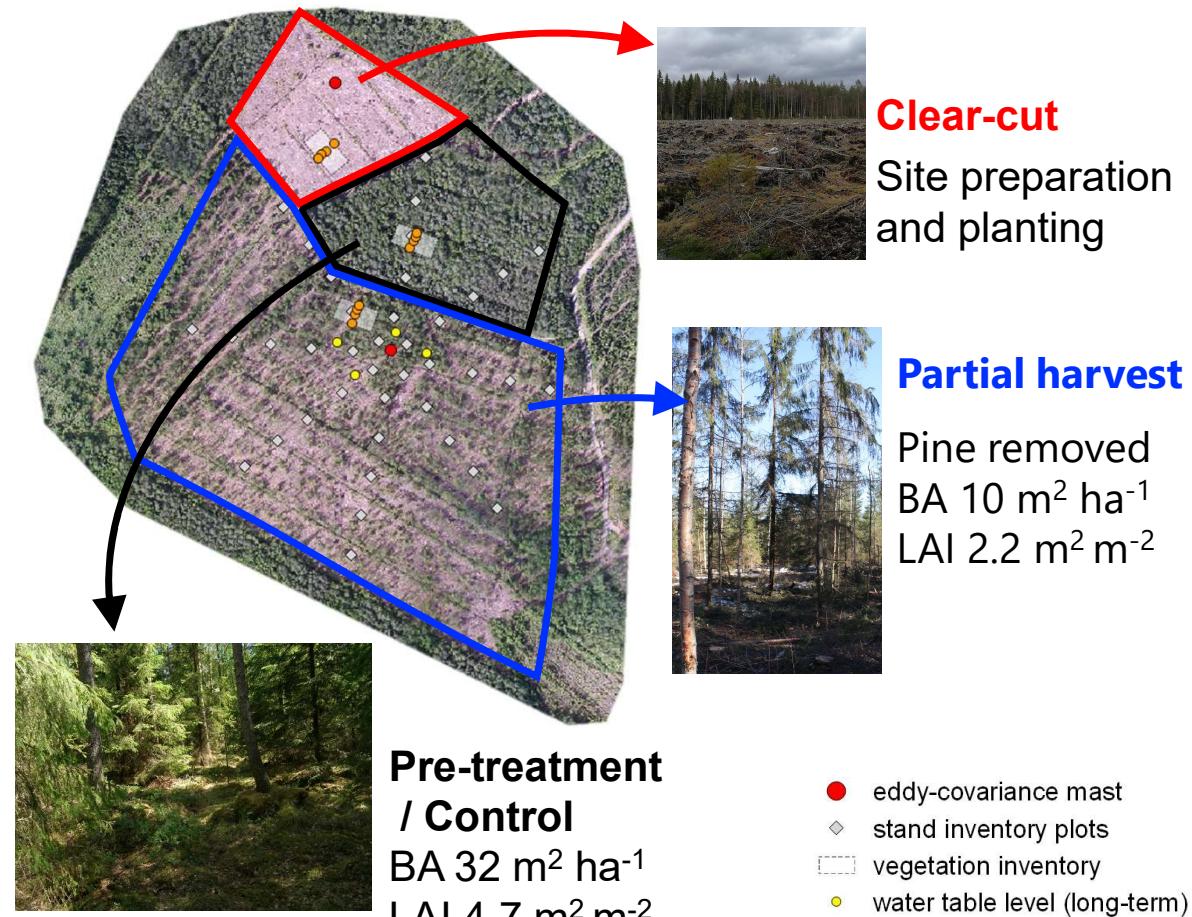
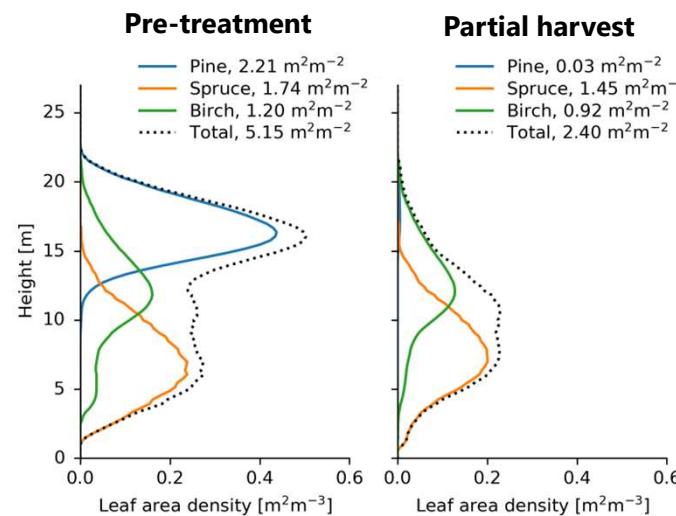


FIGURE 4 Observed and modelled trends in gross primary productivity (GPP, a), evapotranspiration (ET, b), ecosystem surface conductance (G_s , c) and C_i/C_a (d), and modelled trends in canopy mean stomatal conductance (g_s , e) and leaf c_i/c_a (f). The trends are slopes ($\pm SE$) of linear regression to yearly sums/averages of daytime dry-canopy conditions in May-September. Trends are shown as % of the 2001–2017 mean, and (*) denotes statistically significant ($p < .05$) slope. The relative trends in $\delta C_a/c_a = 0.6\% \text{ a}^{-1}$ and $\delta \text{LAI/LAI} = 1.1\text{--}1.9\% \text{ a}^{-1}$ (Figure 3). The shades correspond to different flux-partitioning and LAI-trend estimates

Met → no trend, explains inter-annual variability
 CO₂ → 1/3 of trend
 LAI → 2/3 of trend
LAI + CO₂ → true trend + realistic change in WUE

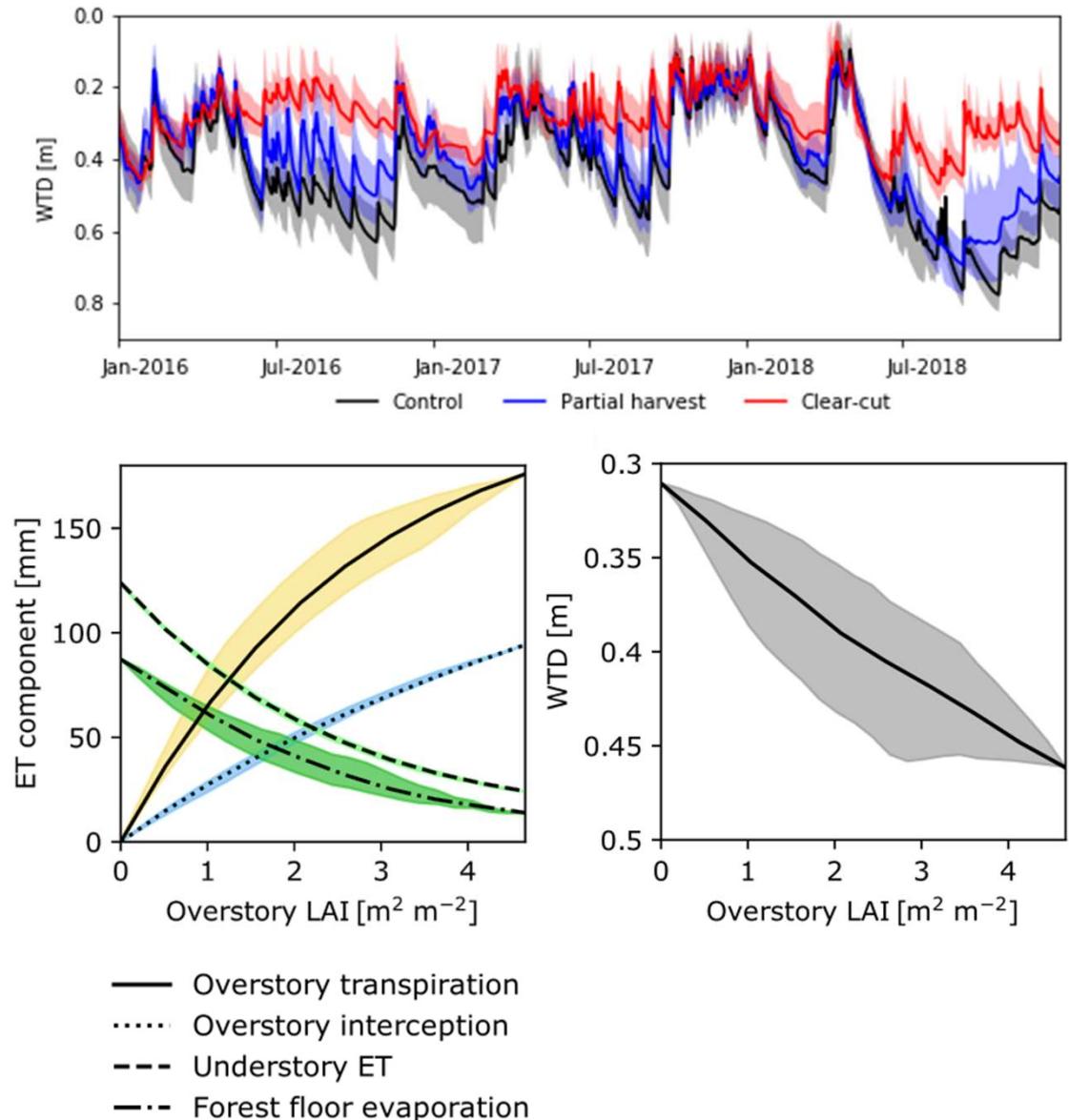
Lettosuo-case: Impact of harvesting on water and energy balance

- Motivation: optimizing WTD using stand density for multiple ecosystem services
- Measurements (WTD, EC) tell **what** changed, pyAPES answers **why**



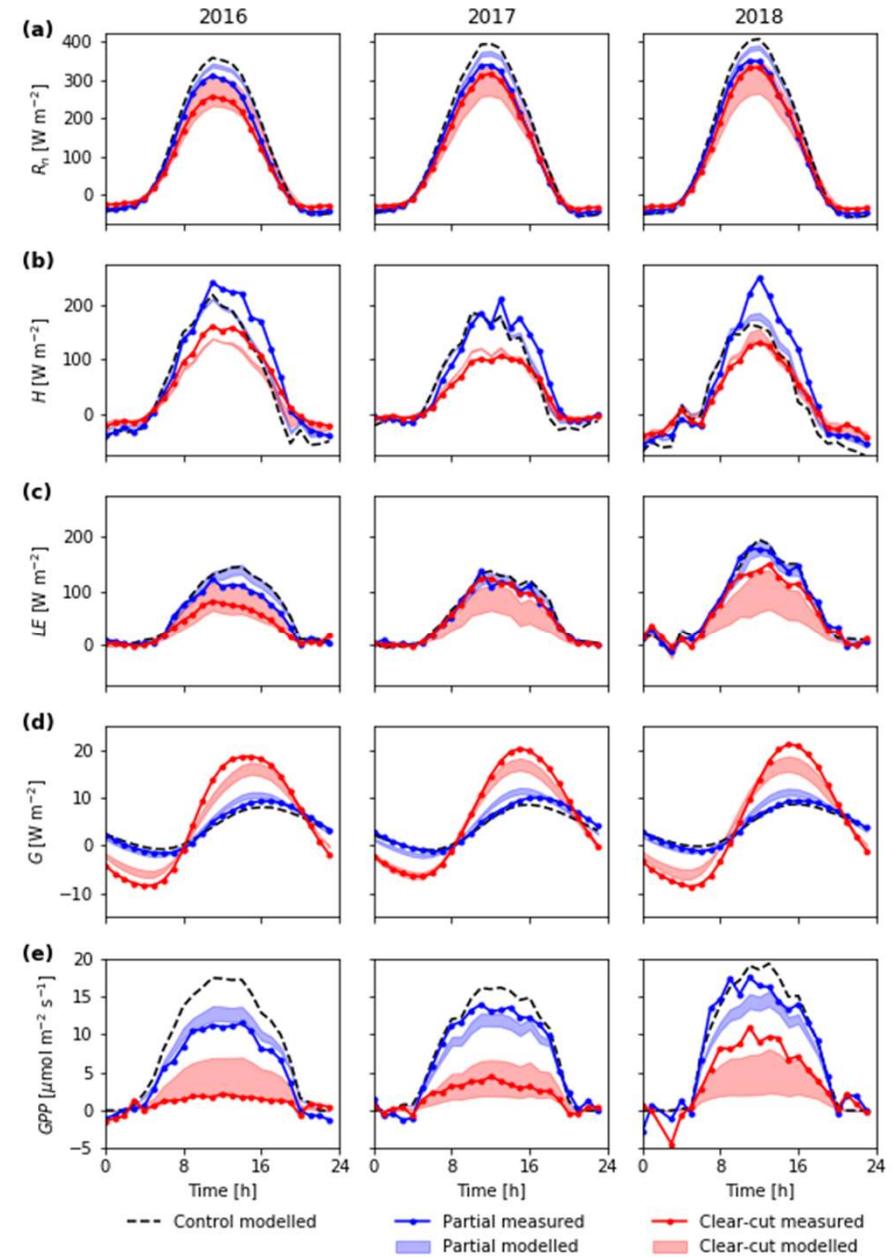
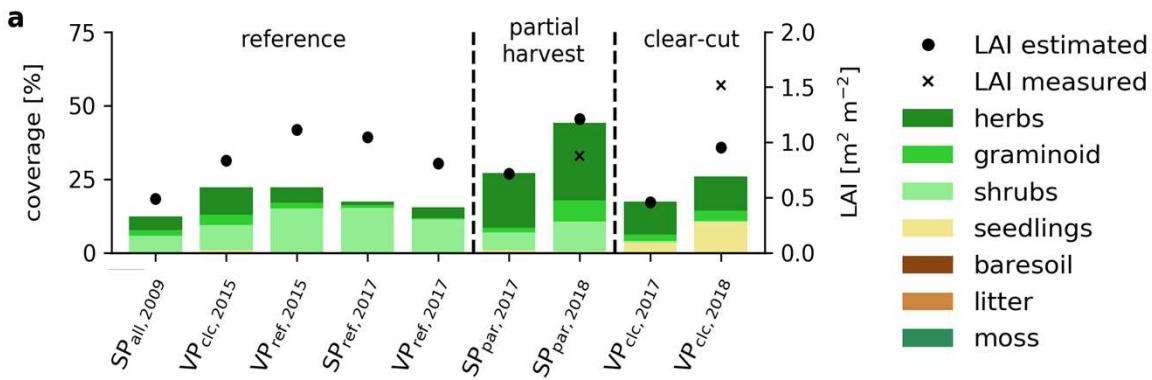
Results WTD

- Minor changes at partial harvest but clear changes at clear-cut
 - Non-linear relationship between overstory transpiration and LAI, especially when remaining species less conservative water users
 - Understory and forest floor evapotranspiration compensates largely for removed stand



Results ecosystem fluxes

- Again, minor changes at partial harvest and evident changes at clear-cut
- Recovery indicated at both sites (LE, GPP, clear-cut R_n)
 - Model runs using increasing understory vegetation LAI (observed) mostly resolve this

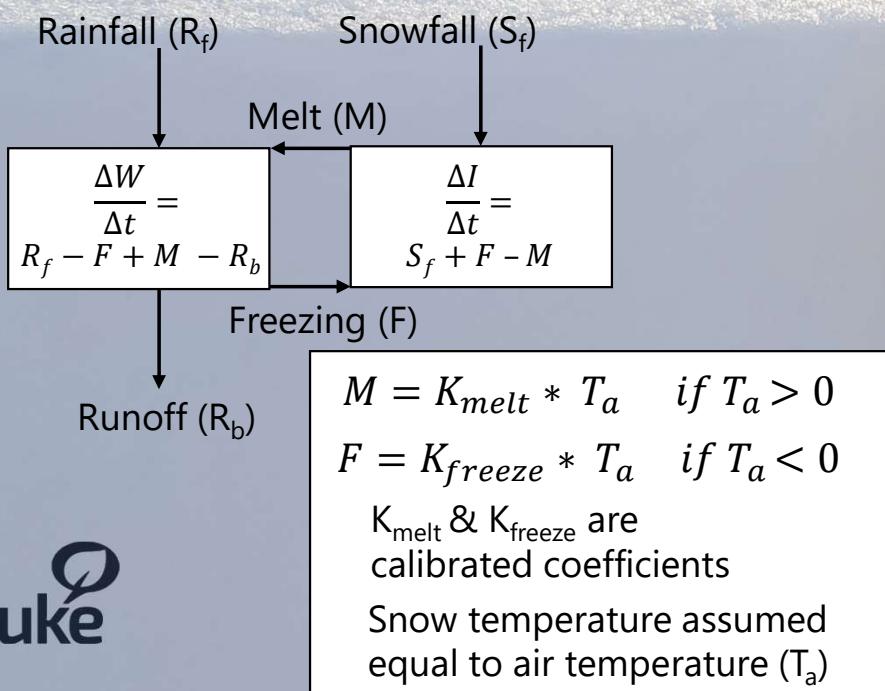


Current development & research

Snowpack – from conceptual to process-based approach

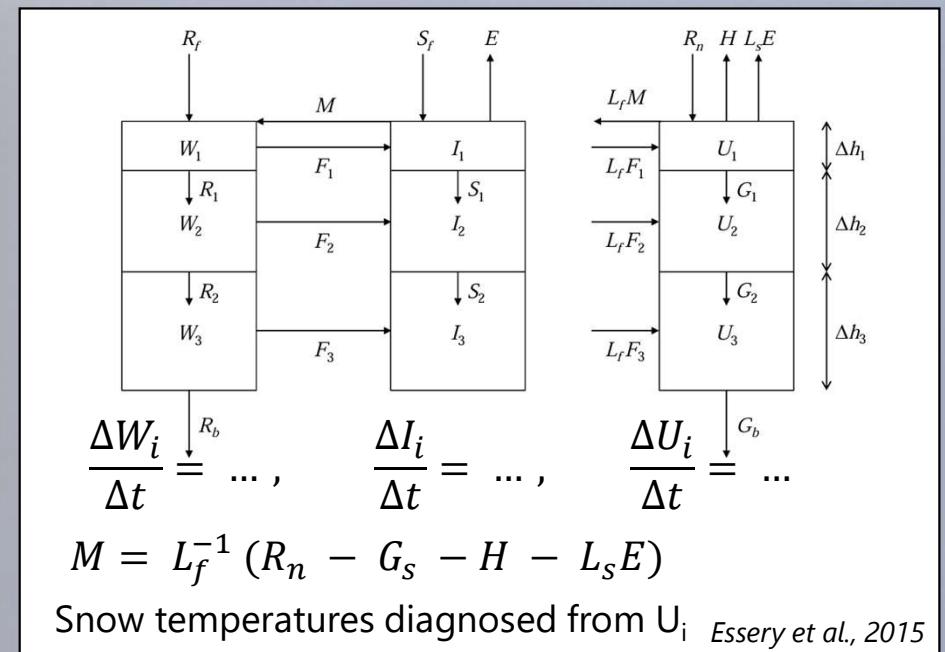
Temperature-index model

- Zero-layer snowpack
 - Liquid (W) and ice (I) storages
- Snow processes
 - accumulation, melt, refreezing and runoff



Energy-balance model

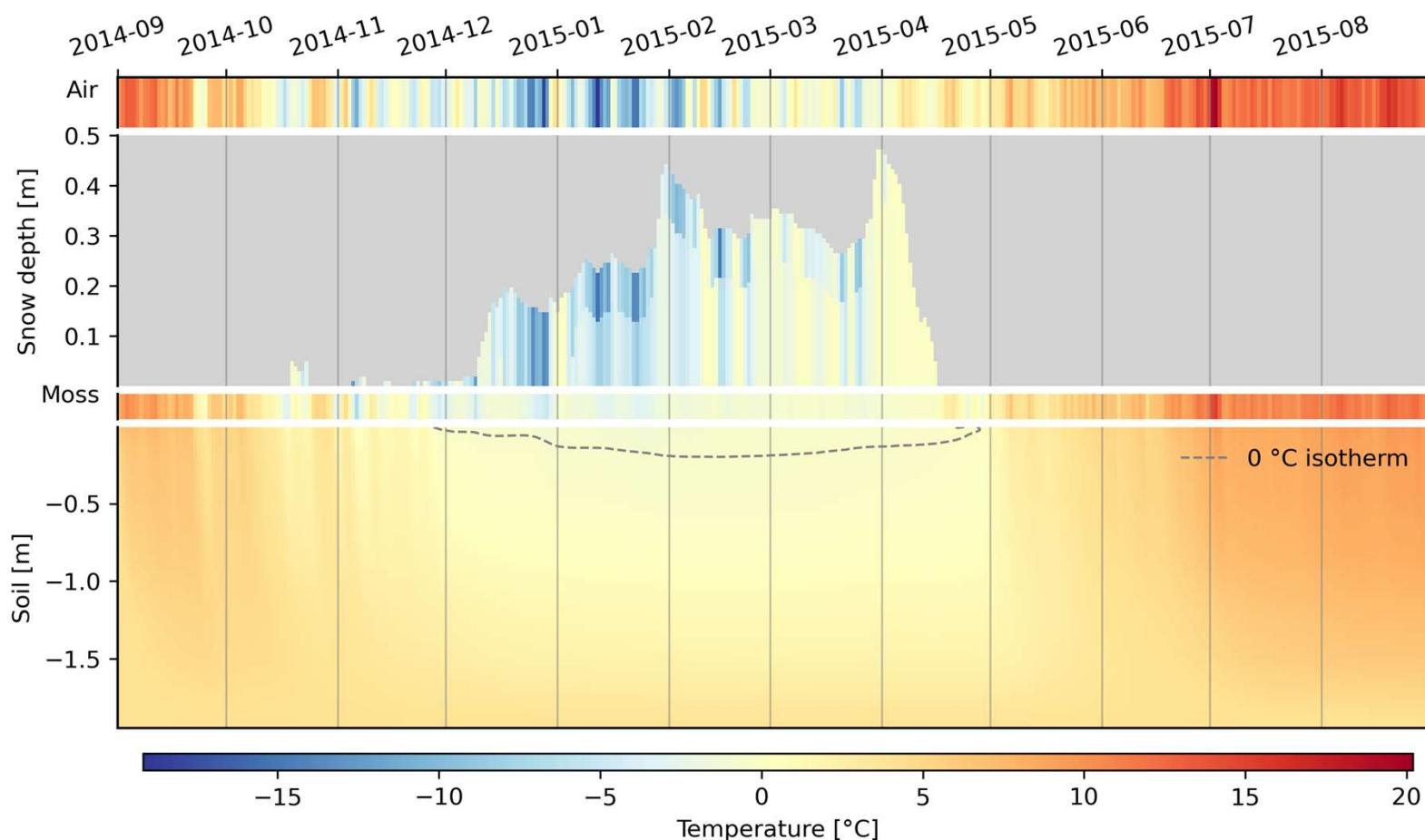
- Three-layer snowpack
 - Liquid (W_i), ice (I_i) and energy (U_i) storages
- Snow processes
 - accumulation, albedo, surface energy balance, heat conduction, compaction, melt, liquid water percolation, refreezing and runoff



Demonstration of energy-balance snow modelling

© Luke

- Heat conduction via snow-moss-soil continuum
- Expected improvements
 - Enable realistic full-year simulations
 - Initial conditions for the growing seasons
 - Effect of snow on growing season water availability
 - Better future predictions (no calibrated coefficients)



Dynamic model for tree water transport & storage

Current module

$$Tr_i \sim g_{s,i}[f(\text{env})] \cdot VPD_i$$



$$\sum RWU_i = \sum Tr_i$$

New module

$$Tr_i \sim g_{s,i}[f(\Psi_i)] \cdot VPD_i$$



$$RWU_i \sim K_{s,r,i} \Delta \Psi_{s,r,i}$$

Stem water content

Sap flow

$$\frac{\partial V_s(z)\theta_p(z,t)}{\partial t} = -\frac{\partial q_p}{\partial z} dz$$

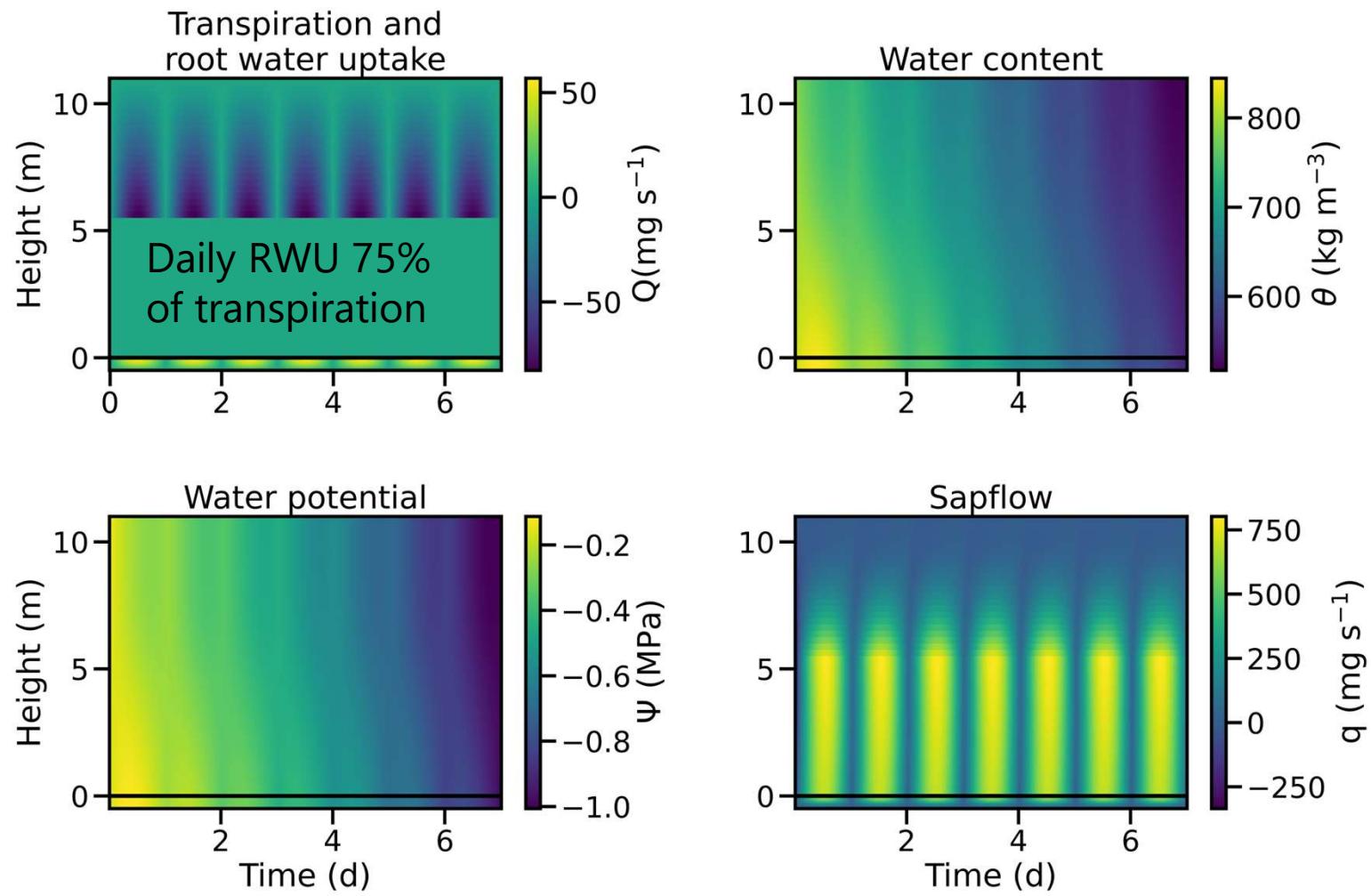
$$q_p = -A_s(z)K_p(\theta_p) \frac{\partial \psi_p}{\partial z}$$

$$\psi_p = \phi_p + \rho gz,$$

Huang et. al., 2017 New Phytol.

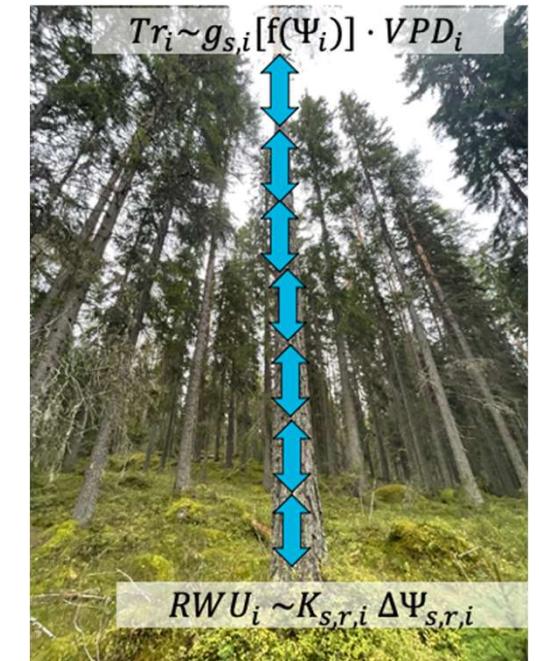
Stem water potential

Dynamic model for tree water transport & storage



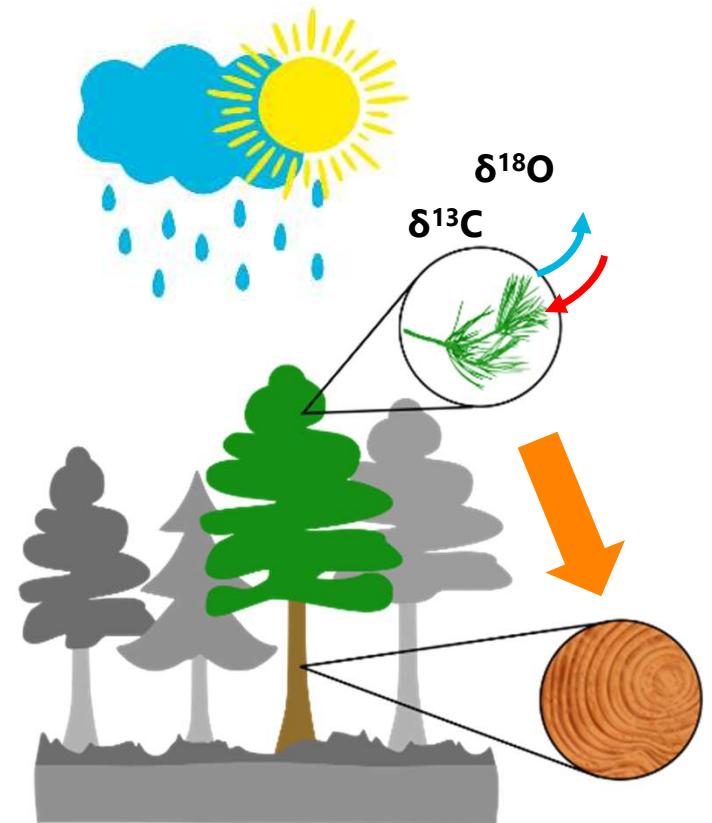
Stand drought risk characterization with water transport module

- How stand attributes affect water availability and tree functions?
 - Small vs. large trees
 - Dense vs. sparse canopy
 - Mono vs. multispecies stands
 - Role of stem water storage – how long the reserves last?
- What happens if the environmental conditions change?
 - Drought risks at different site types
 - Drought risks in future climate projections
- What are our mitigation possibilities?
 - How managing stand attributes can change drought risks



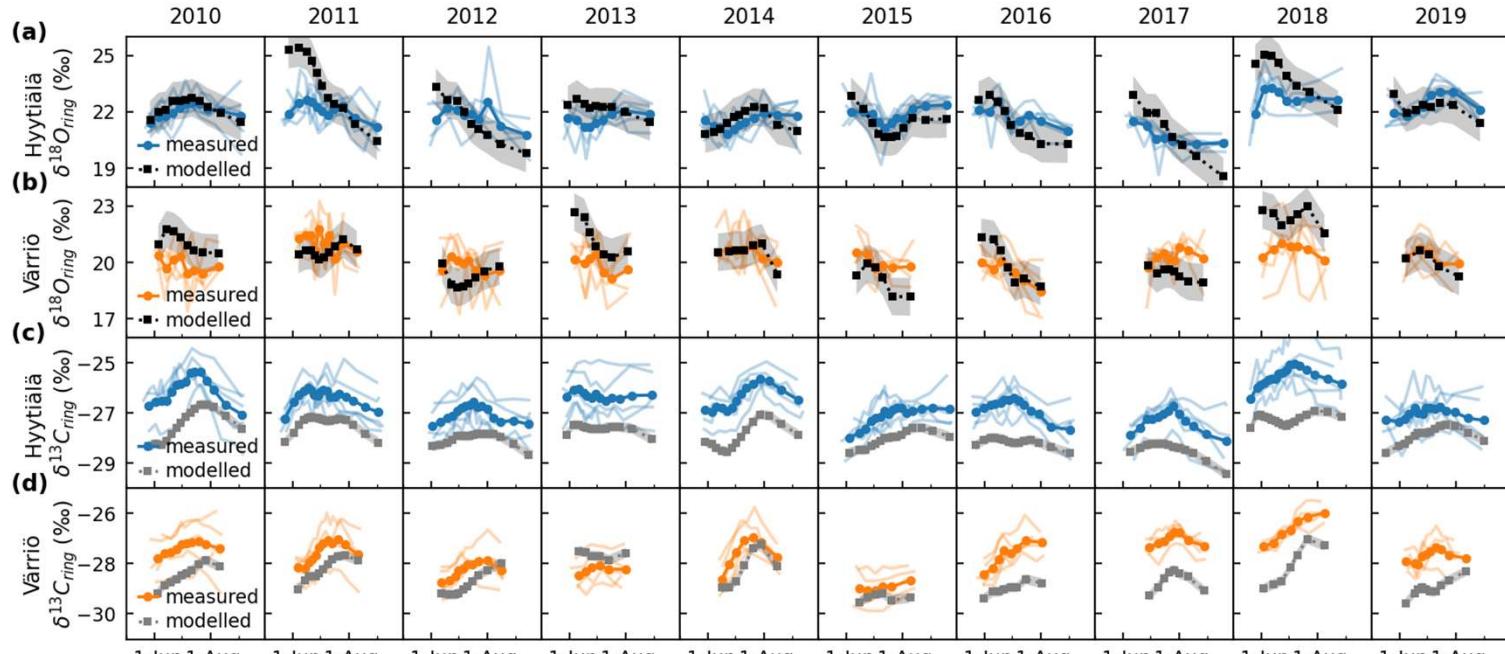
Stable carbon and oxygen isotopes ($\delta^{13}\text{C}$ and $\delta^{18}\text{O}$)

- Tree ring $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ – valuable records
 - $\delta^{13}\text{C}$ proxy for ci/ca, ^{12}C favored in non-stressed conditions (more open stomates)
 - $\delta^{18}\text{O}$ records RH (^{16}O evaporates more readily) and source water $\delta^{18}\text{O}$
- Isotope-enabled models
 - Test and advance process understanding
 - Explicitly account for different spatial and temporal scales (needle – tree, seconds – decades)
 - Isotope records provide additional constraints to models
- Stable Isotope Laboratory of Luke (SILL)



Modelling $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$

- Simplified version
 - Leaf-level model + carbon pool and assignment to tree rings (xylogenesis)
 - Leaf-level (*Leppä et al., 2022, New Phytol.*)
 - Intra-annual tree-ring (*Leppä et al., revised, Tree Physiol.*)
- Integration to pyAPES (in-progress)
 - Explicitly addressing vertical gradients, effect of surrounding canopy (*Tikkasalo et al., 2024, Tree Physiol.*)
 - Resolving multiscale iWUE records derived from shoot chambers, tree-ring $\delta^{13}\text{C}$, EC



Summary

What for and what not?

What pyAPES is and enables?

- Modular toolkit rather than a fixed model
- Way to learn, understand and explore ecosystem functions
- Research tool to integrate physiology, isotopes, mixed forests, climate change and management
- Melting pot of knowledge across scales, research disciplines
- Asking "what if" & "how"!

What pyAPES is not?

- Growth model, forest simulator or dynamic vegetation model – and should not become one
 - ... but can provide support to feasible simplifications
 - ... but see Metzler et al. (2024)
- Computationally extremely efficient
- Simple to use tool for non-experts ☺

New description paper in prep (Tikkasalo et al. 2026, Geosci. Model. Dev.)

Jupyter notebook tutorials

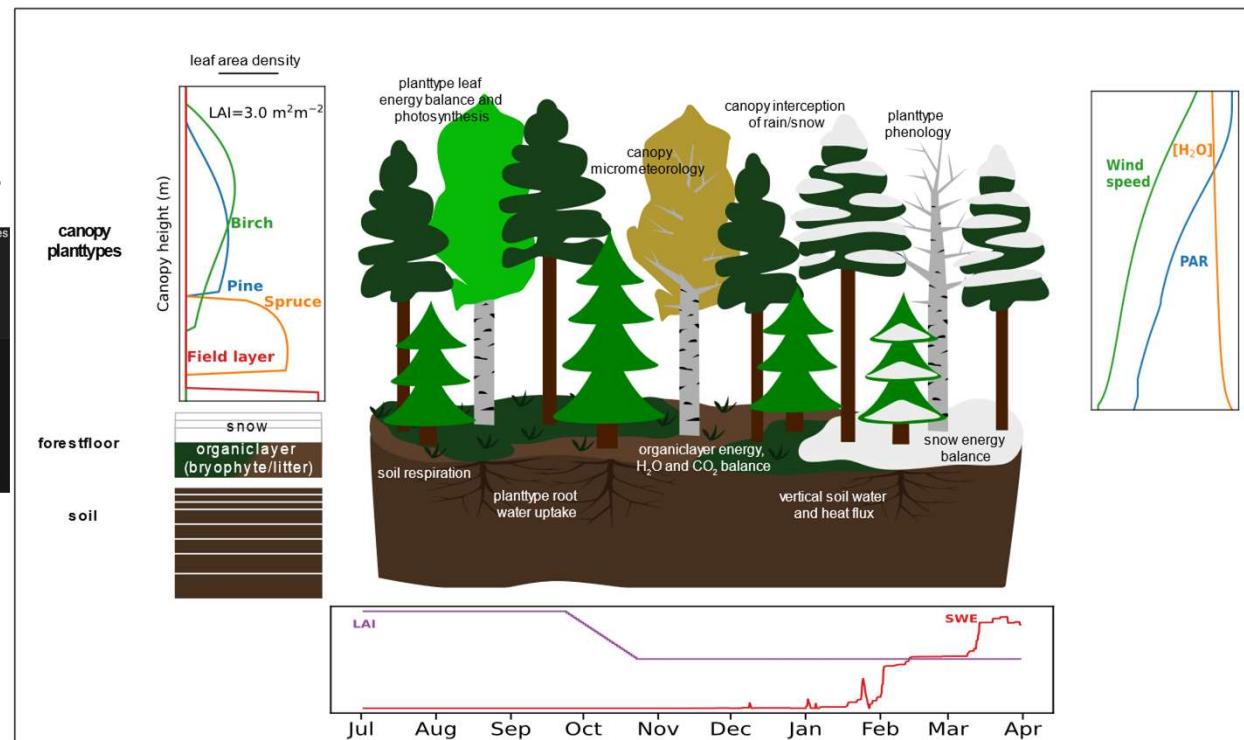
Micromet -class: sub-model for turbulent canopy flow & scalar (T , H_2O , CO_2) profiles

- canopy flow (eq. 1-5) pyAPES.microclimate.micrometclosure.T_U0
- scalar profiles: pyAPES.microclimate.micromet_closure_t_scalar()
- called from sub-daily loop of pyAPES.canopy.mim.canopy_run()
- saves normalized flow statistics & previous scalar profiles as state variables

Define parameters (similar to pyAPES.mim_parameters)

```
# define model parameters
# --- Turbulent flow & scalar transport in air-space: pyAPES.microclimate.micromet.Micromet
micromet = {'zest': 0.01, # forest floor roughness length [m] — not used
            'dHdx': 0.0, # horizontal pressure gradient [unitless]
            'Utop': 0.0, # ensemble Ustar at top boundary [-]
            'Ubott': 0.0, # flow at lower boundary [-]
            'Sc': ('T': 2.0, 'H2O': 2.0, 'CO2': 2.0) # turbulent Schmidt numbers in canopy flow
            }

# create grid
grid = {'maxz': 25.0, # height of grid from ground surface. Corresponds to height of forcing data [m]
        'Nlayers': 101 # number of layers [-]}
```



Scientific documentation

10.2 Model framework

The modelled ecosystem is depicted in Fig. 1a. In pyAPES, the coupled plant-soil system (later referred as 'stand') is described through interlinked objects, which represent different structural hierarchies or functional compartments of the stand. The physical domain of the model consists of the soil and canopy objects. The canopy object can have PlantType instances that are defined by their ecophysiological parameters and vertical leaf area distribution (Fig. 1d). The soil instances are made of the computational grid and soil parameters. A separate ForestFloor instance resides between soil and canopy instances. ForestFloor instance can consist of bryophyte(s), litter or bare ground instances which are defined by their respective parameters and coverage value (Fig. 1c).

In addition to the physical domain and their associated parameters, the user needs to define upper and lower boundary conditions. The upper boundary conditions are the prevailing meteorological conditions at the top of the canopy (see Table 20 AX) and the lower boundary conditions define how the heat and water flow are treated at the lowest grid element.

The pyAPES code is hierarchically organized as packages according to Fig. 2. The interlinkage of packages and instances can be described by Alg. 1 showing the pseudocode, which shows how the main loop of the model operates.

- Describe model output

Model availability improvement



Version control & Open code base

pyAPES_main Public

1 main · 12 Branches · 0 Tags

Go to file Add file · Code · About

No description, website, or topics provided

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Packages

Alternatives Photo gm (4) Photo gm (X) 409 Comments

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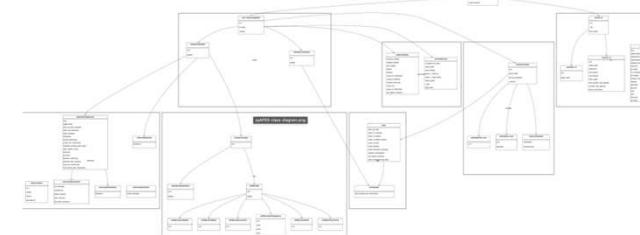
pyAPES Photo gm (4) 6 months ago

pyAPES_utilities jan 8th, 2024 2 years ago

ignore Updated ignore (4) 8 months ago

README.md cleaning repo 8 months ago

Technical documentation



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Thank you!



luke.fi

<https://github.com/LukeEcomod>
https://github.com/LukeEcomod/pyAPES_main/



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