Ecohydrology at Luke

”Process models and academic curiosity
for sustainable use of boreal ecosystems”

- Samuli Launiainen, Antti-Jussi Kieloaho, Kersti Haahti, Mingfu Guan, Aura Salmivaara

Content

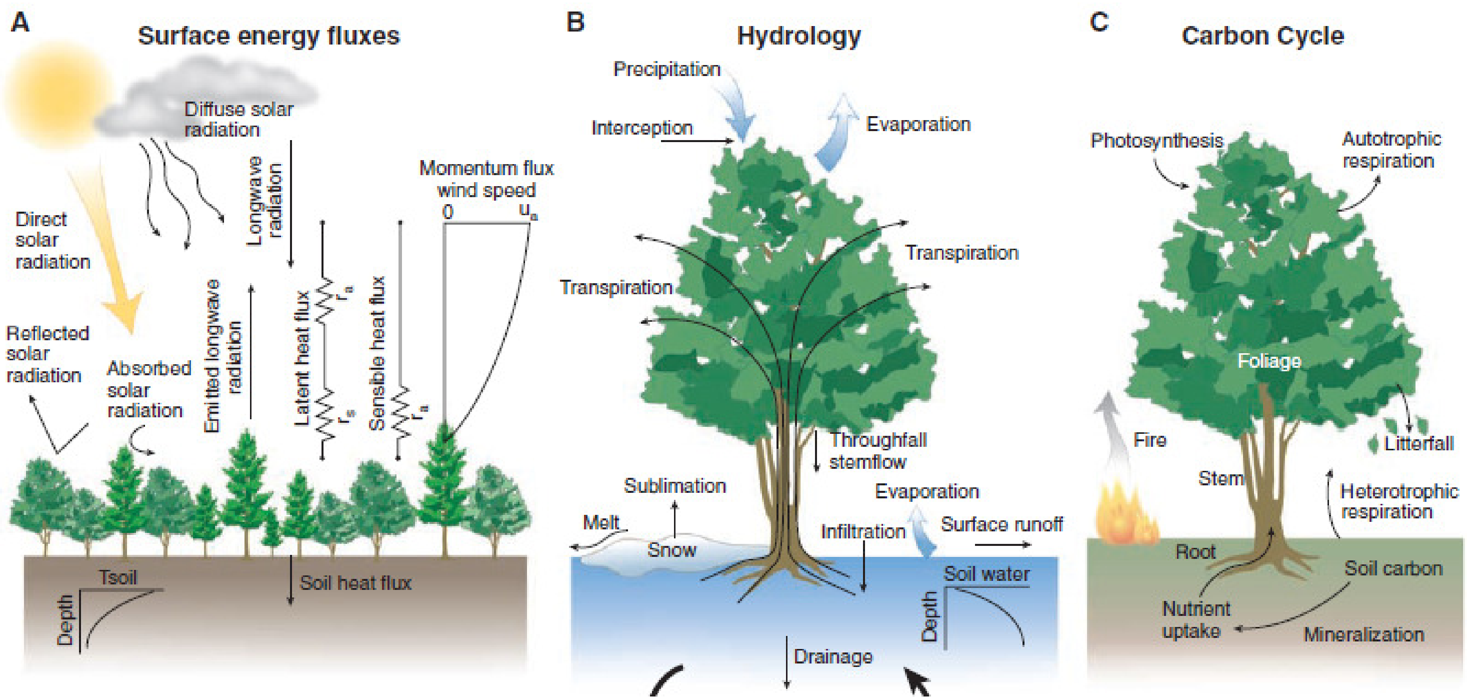
1) What we do in general: few current topics

2) ET and catchment hydrology: simple semi-spatial model using open GIS-data

3) Potential model applications

- Youtube:
  - spatial hydrology with topmodel: https://www.youtube.com/watch?v=quop7jZ3Bfk
  - Multi-layer APES –model: https://youtu.be/HQLuqT-qnFg

Water, carbon and energy cycles coupled



Bonan, 2008 Science.

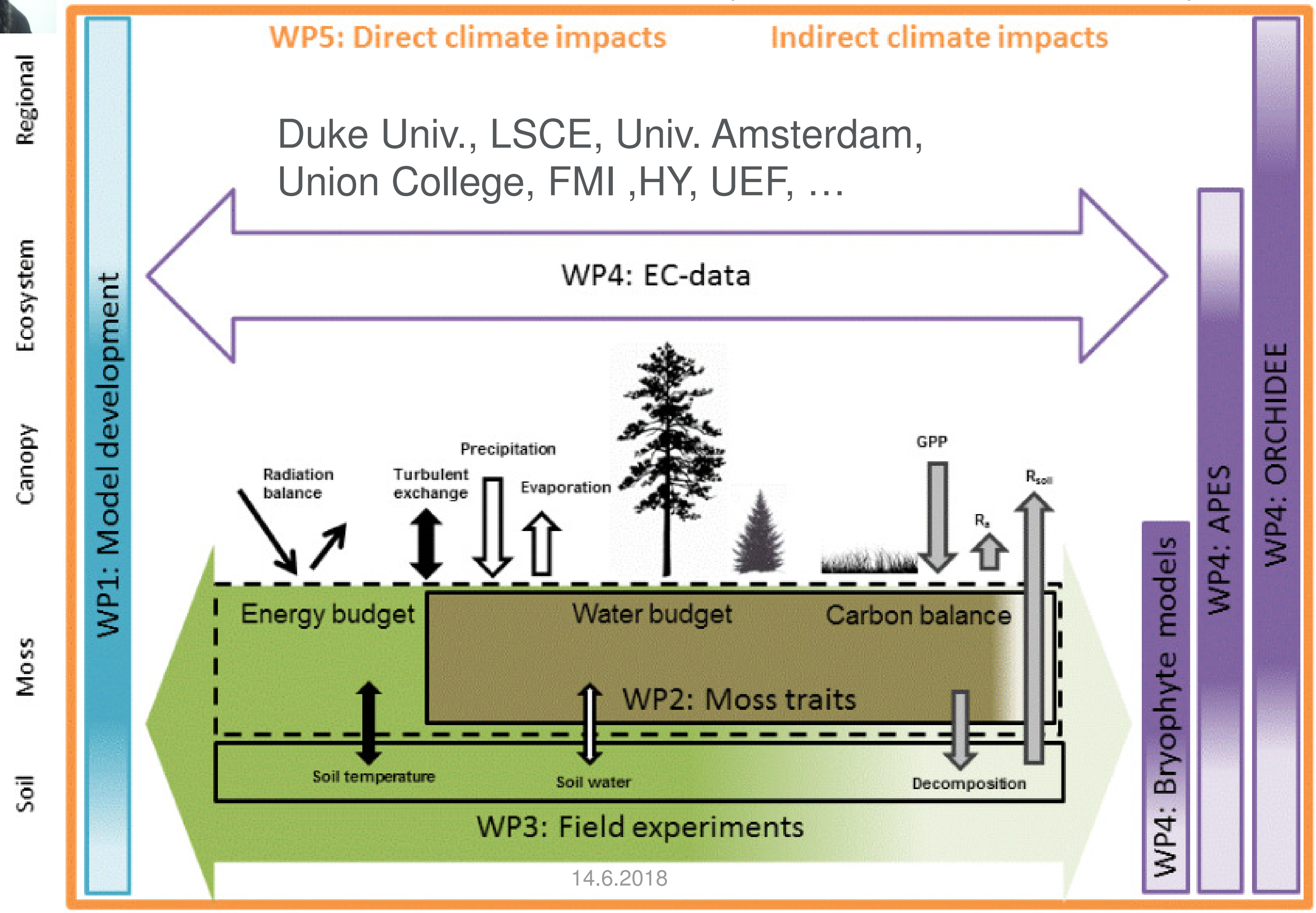
$$\boxed{E_i = \frac{1}{L_v}\,\frac{\Delta(R_{n,i}) + \rho_a c_p G_{a,i}\, D}{\Delta + \gamma(1 + G_{a,i}/G_i)}}$$

Penman-Monteith

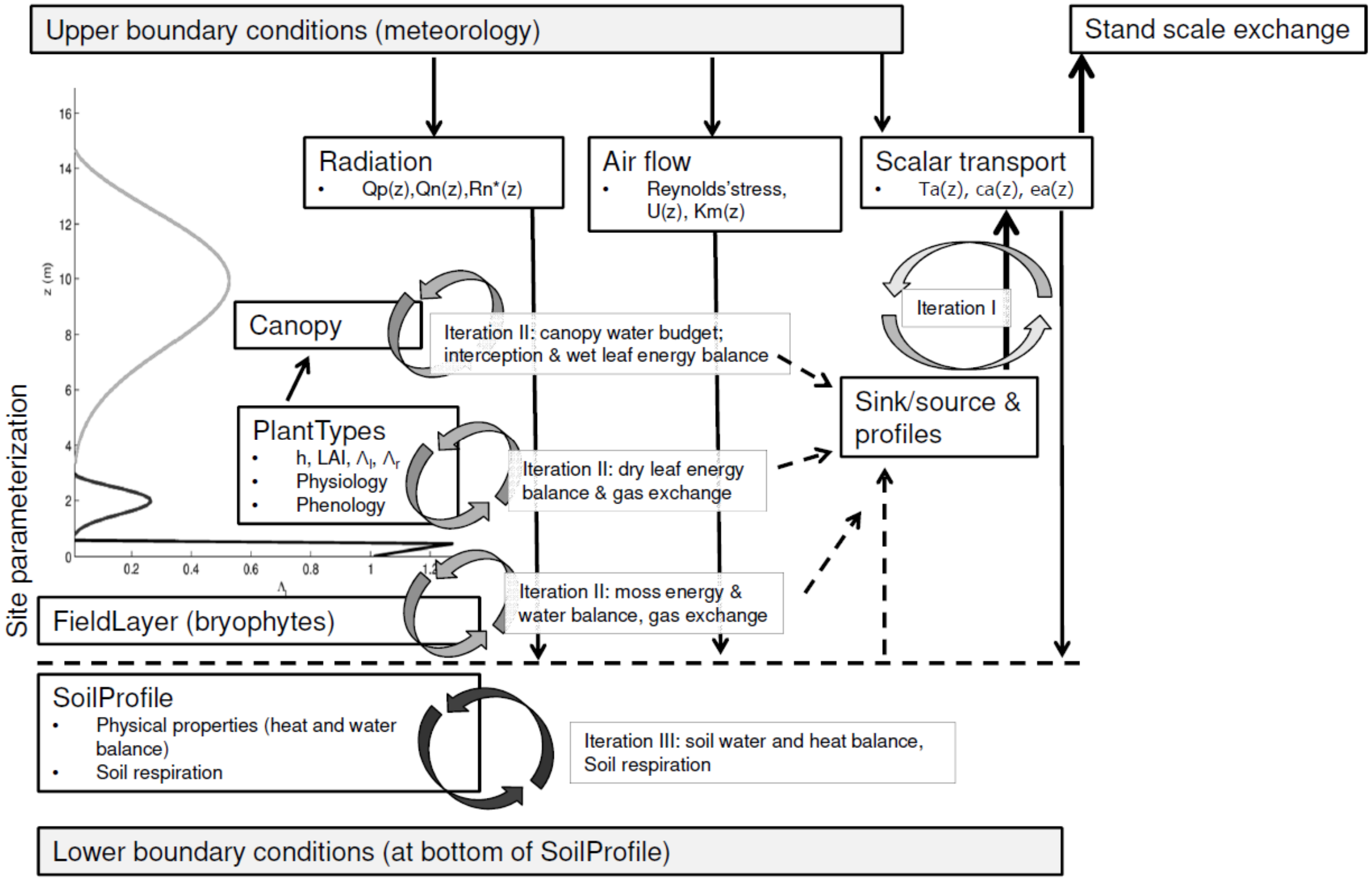
Antti-Jussi
Kieloaho

Climate impacts of bryophytes: from functional traits to global models

CLIMOSS (2016-2021, Acad. Finland)



APES



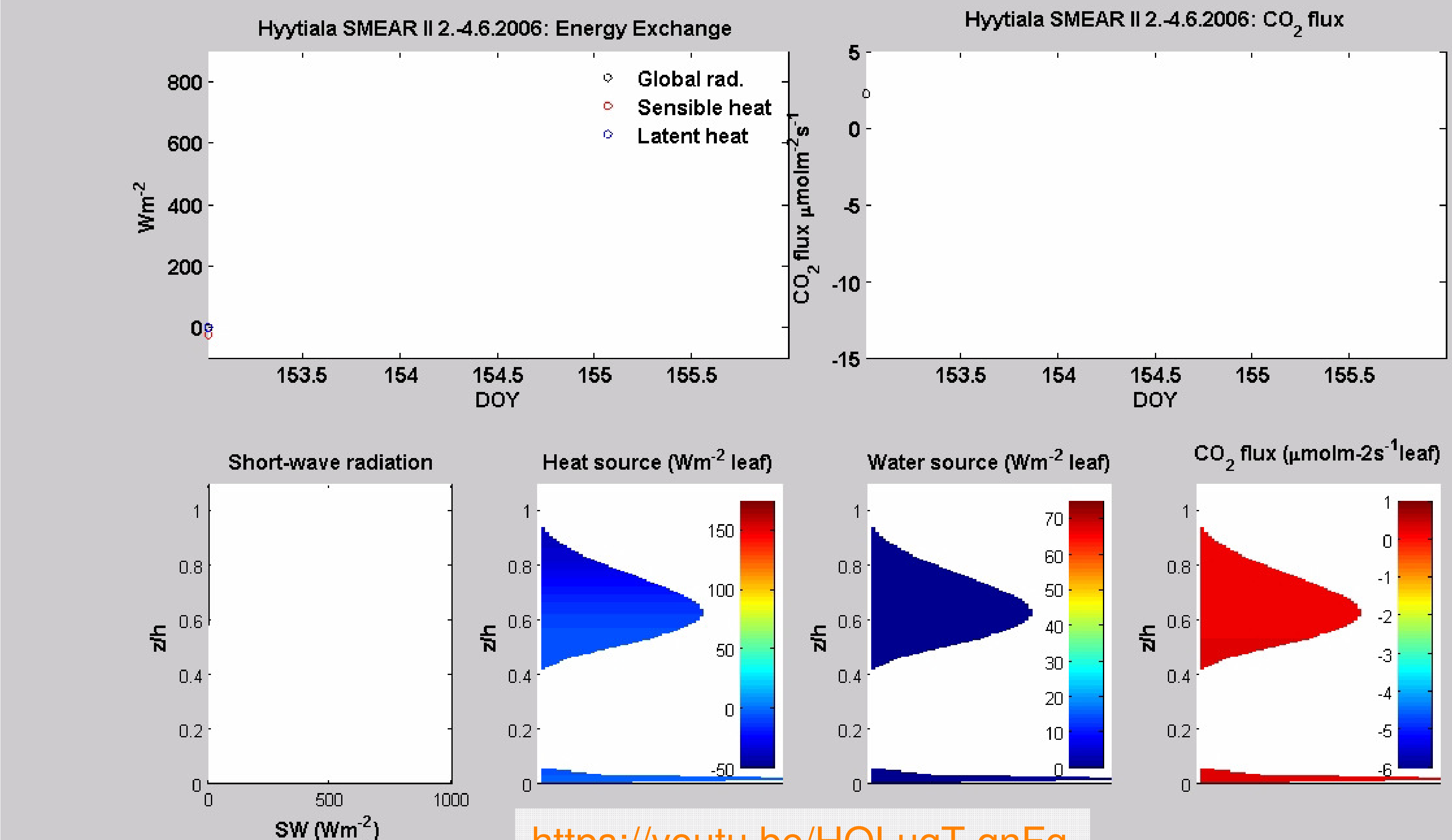
Water
Carbon
Energy
Wind flow

Atmosphere
Vegetation
Bottom layer
Soil

APES: Launiainen et al. 2015 Ecol. Mod., 2016 Global Change Biol.

https://github.com/LukeEcomod/APES_Jan2016

Heat, H2O and CO2 sinks/sources → ecosystem scale flows



https://youtu.be/HQLuqT-qnFg

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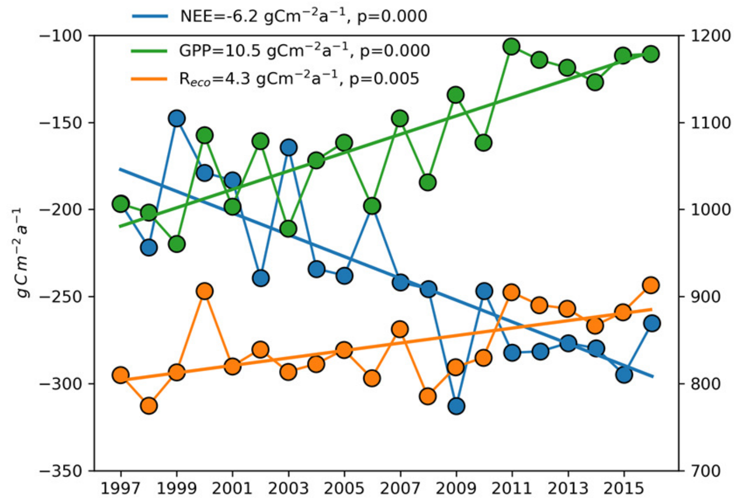
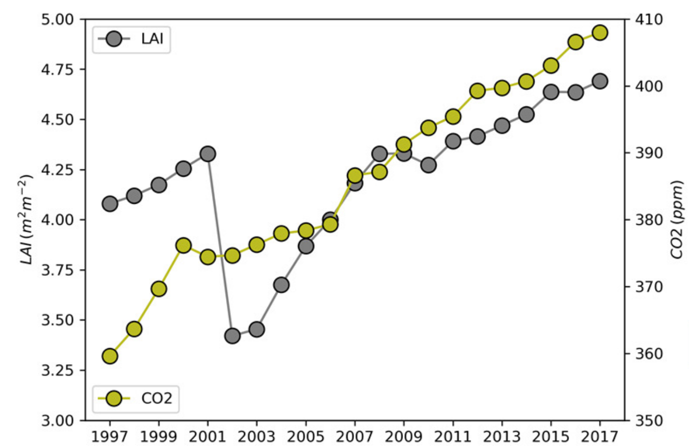
Why carbon sink increases at Hyytiälä Fluxnet site?

- Two decades of eddy-covariance data at Hyytiälä SMEAR II –site
- Increasing annual CO2 sink that is mostly due to enhanced productivity
  – NEE: from -180 to ~-200 g C m-2 a-1 (+53%)
  – GPP: from ~1000 to 1200 g C m-2 a-1 (+19%)
- Also annual ecosystem ET has increased (+22%)

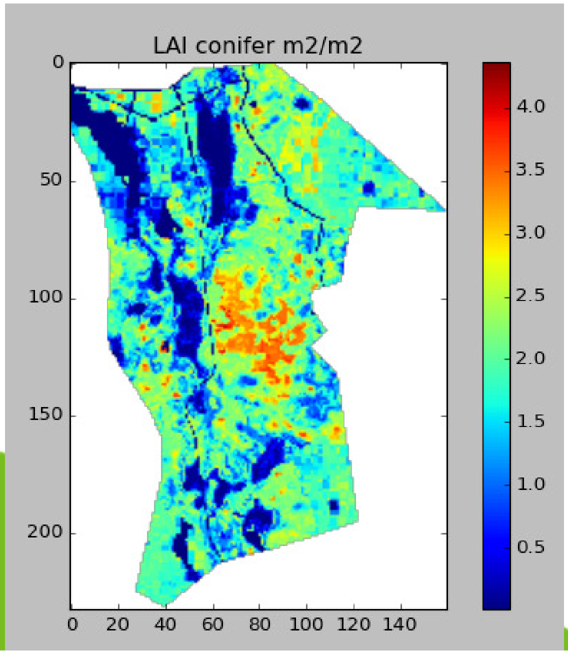


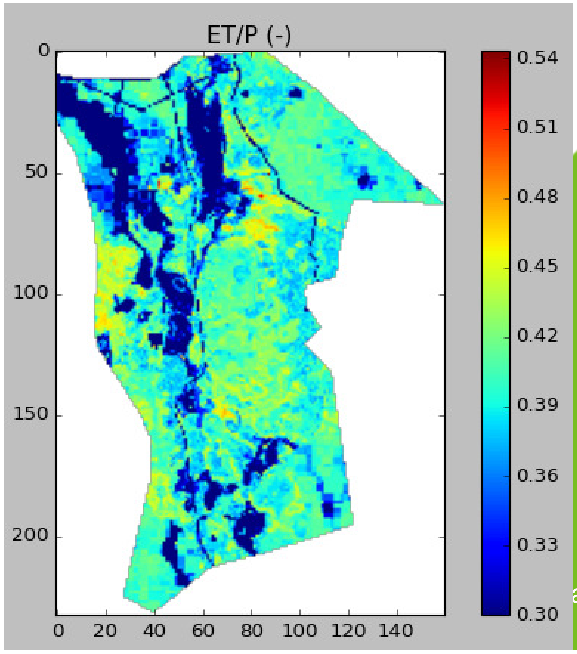
- Plausible explanations for increased productivity?
  – CO2 fertilization
  – Increasing T & longer growing season
  – Stand development
  – Footprint changes



Evapotranspiration in boreal forest catchments: upscaling by process models and open GIS data

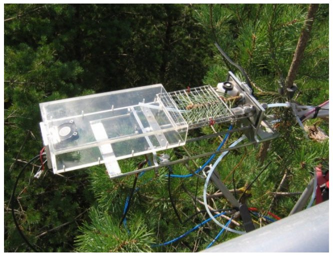
- Samuli Launiainen, Aura Salmivaara, Antti-Jussi Kieloaho, Mikko Peltoniemi, and Mingfu Guan

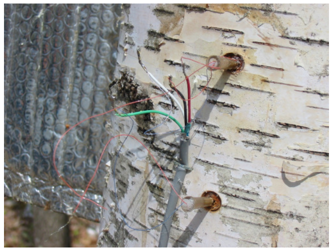


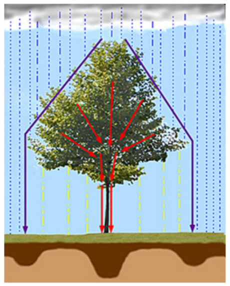


Measuring evapotranspiration and its components

- Leaf/shoot scale
  - gas-exchange by chambers
  - Transpiration, photosynthesis
  - From minutes to seasonal timescale
- Tree scale
  - sapflow –probes
  - Trunk diameter changes
  - Transpiration
  - Trunk water storage →
  - daily or longer timescales
- Stand/Ecosystem scale
  - Precipitation – throughfall = interception
  - Snow water equivalent
  - Eddy-covariance (total ET)
  - 30min to inter-annual
- Catchment scale
  - Catchment water balance: ET = P – Q
  - Hydrologic year







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Shoot gas-exchange: photosynthesis, transpiration and soil moisture

- Black dots: CO_2 exchange
- White dots: Transpiration
- Lower panel: volumetric water content θ
- Note how CO_2-flux and transpiration decrease during soil water stress

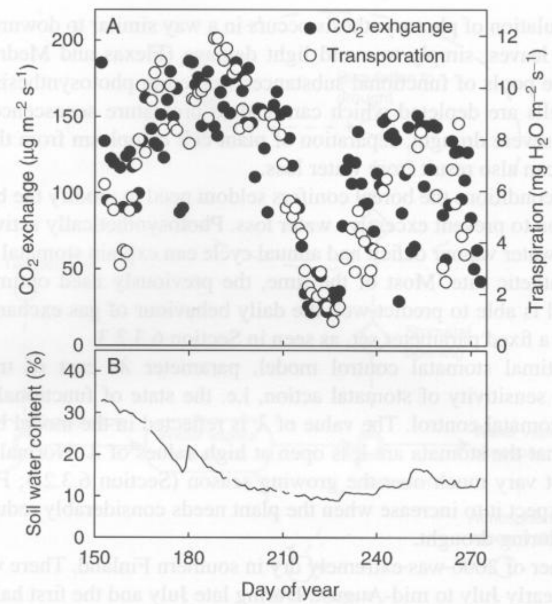
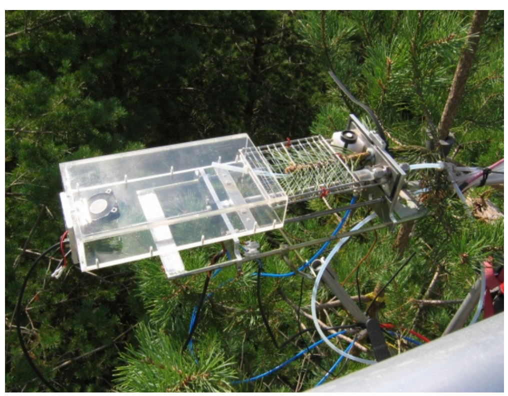


Fig. 6.3.55 CO_2 exchange (dots) and transpiration (circles) of Scots pine shoots (A) and soil water content (B) at SMEAR II in the summer of 2006. The fluxes are means of three shoots, averaged daily between 11:00 and 13:00 solar time



(Hari P. and Kulmala L. 2008)

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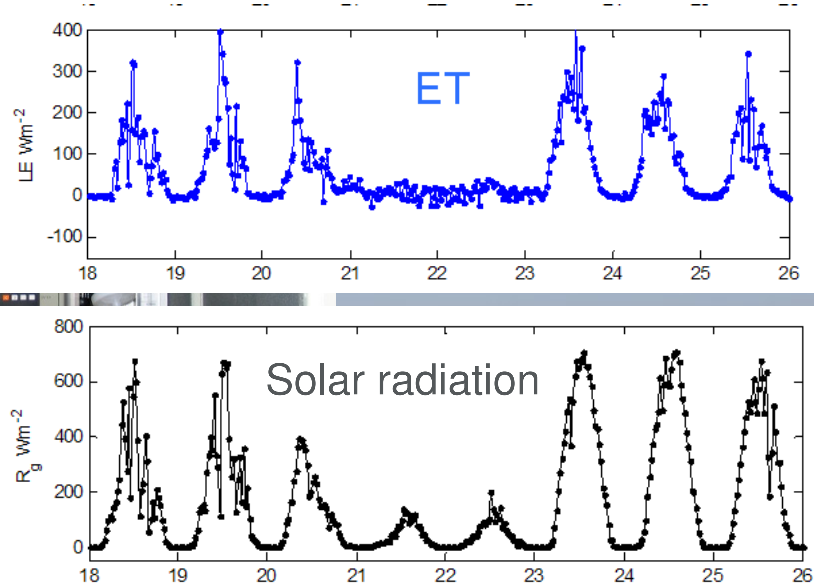
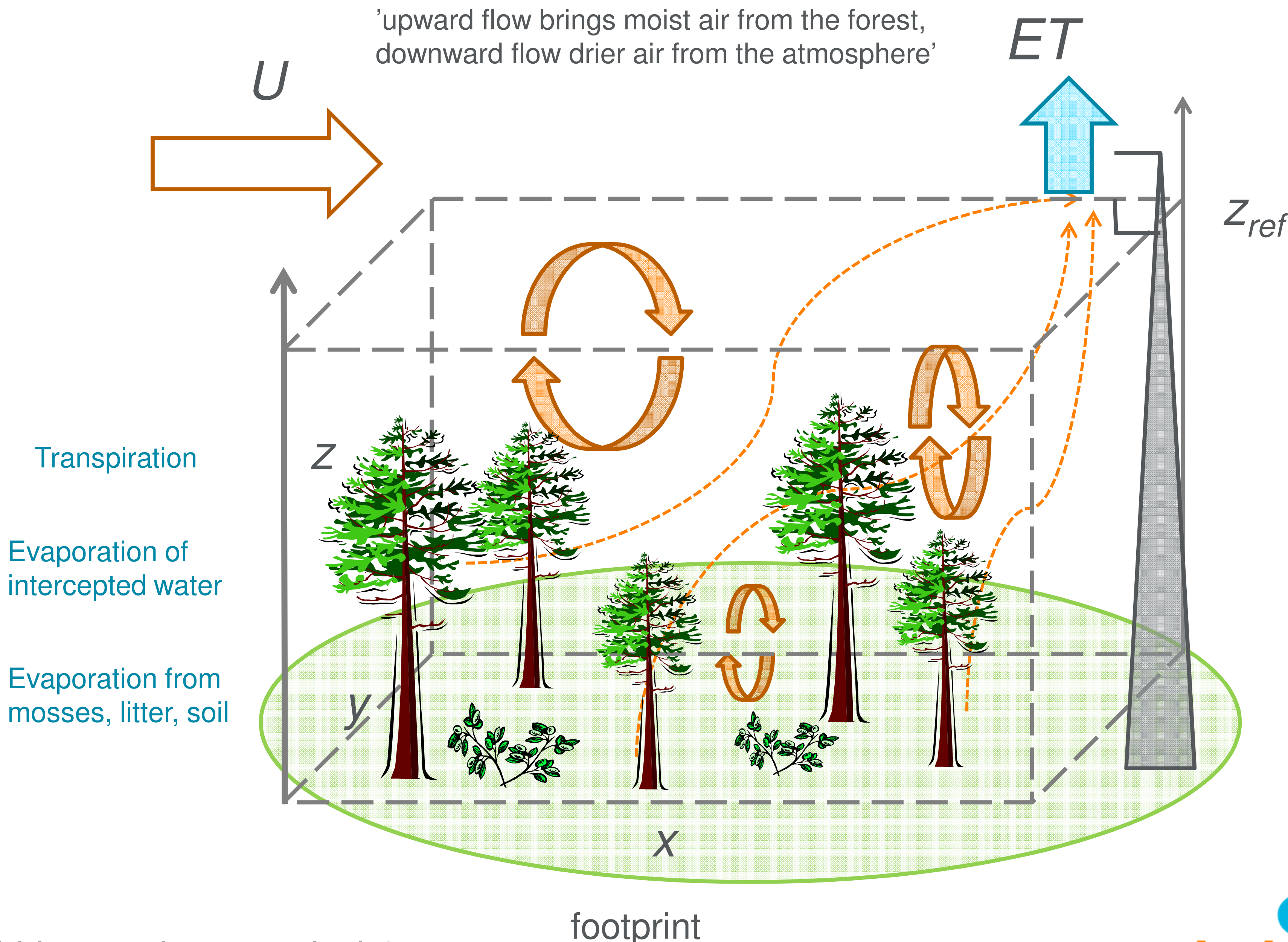
Eddy-covariance

- Direct method to measure H_2O, energy, CO_2, trace gas and particle exchange
- High-frequency (10-20Hz) 3D wind speed & concentration measurements
- Spatial scale: a forest stand (order of ha)
- Timescales: 1/2h → daily → monthly → annual, …



Hyytiälä, 8 days in July



Eddy covariance - principle

Background

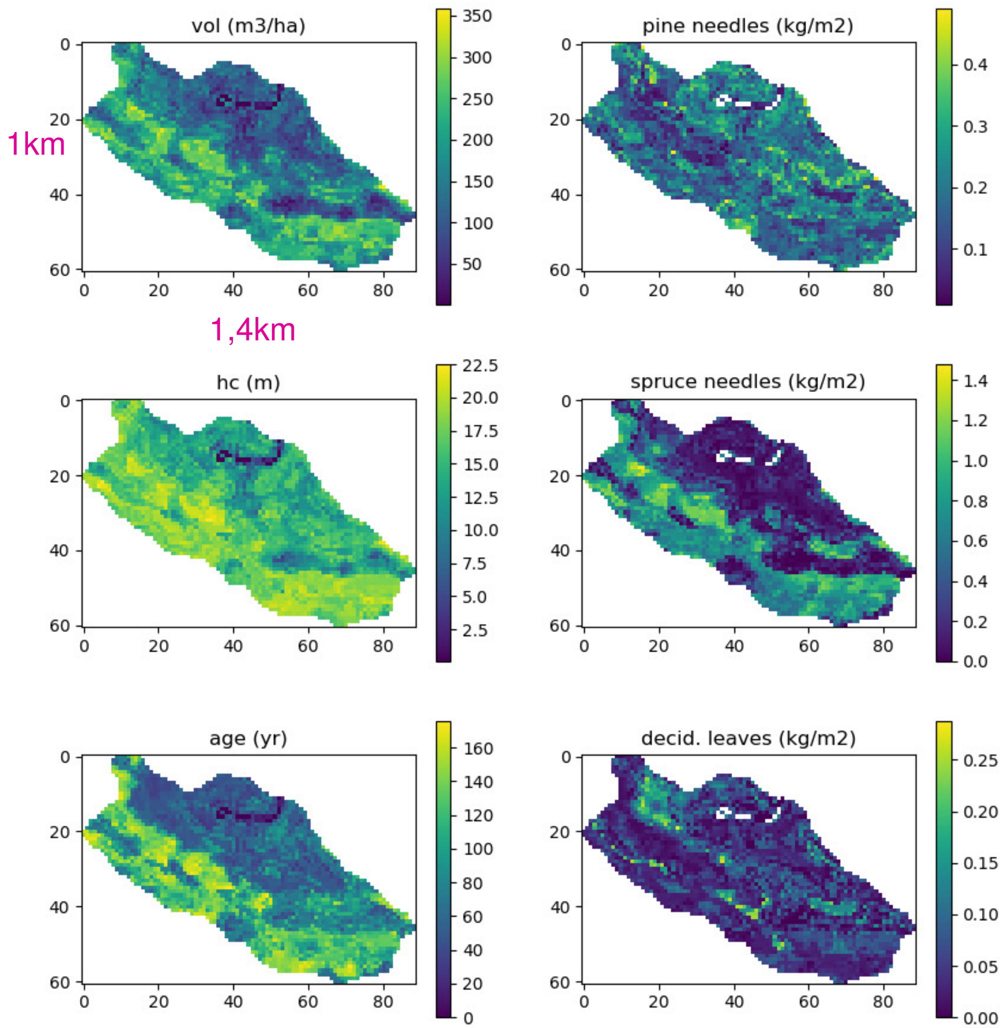
- Boreal mixed coniferous forests cover ~80% of land area in Finland
- Forest management creates mosaic landscape
- Why actual ET and its spatial variability?
  - Soil moisture & biogeochemical cycles, growth and climate feedback
  - Needs from practical forestry
  - Improved description of ET will reduce uncertainties in catchment models

Objectives:

1) Develop generic daily stand-level ET model
   - validate against eddy-covariance data
2) Upscale to landscape scale using open data
   - evaluate using annual ET from catchment water balance

"Simple, applicable at large scale, minimal calibration"

Multi-source National Forest Inventory (16 X 16 m)



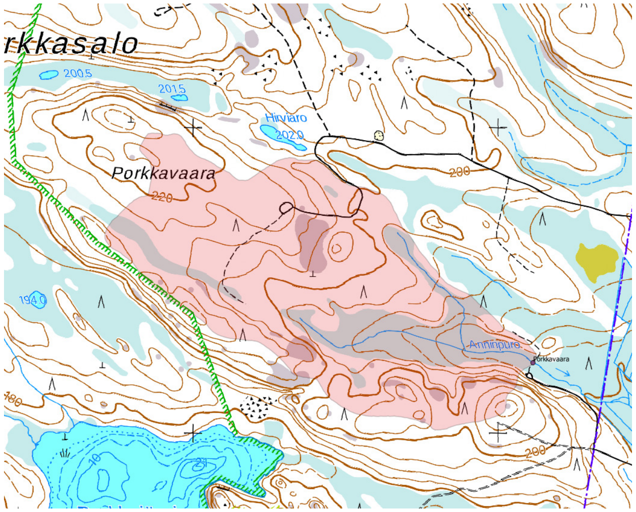
- 45 raster themes (geotiff)
- Open data, 3 year update interval
- > 80 0000 forest inventory plots
- Landsat + DEM, topographic basemap
- kNN –interpolation

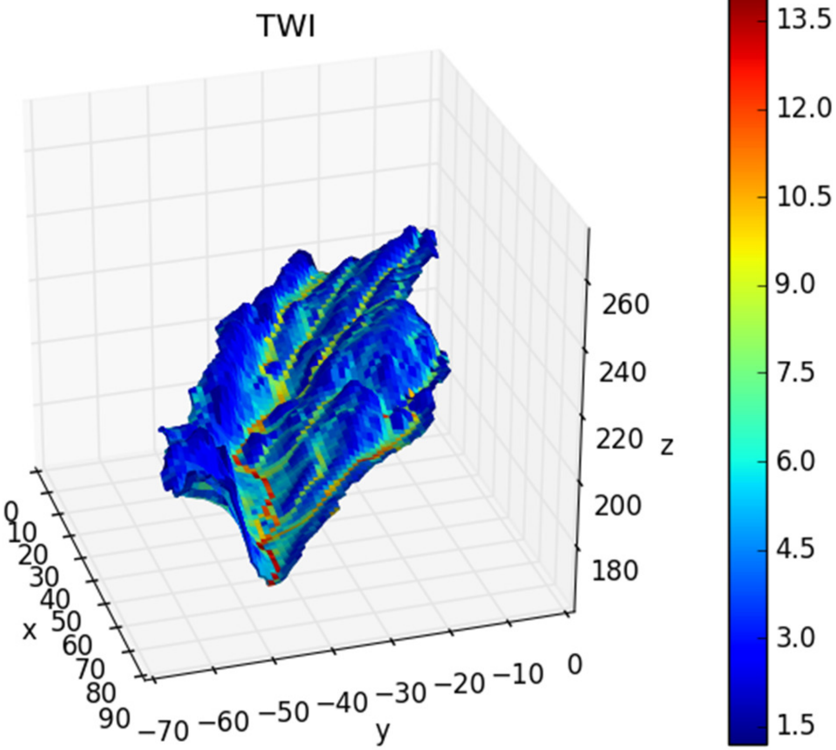
- Leaf-area index LAI (m2/m2) = M x SLA

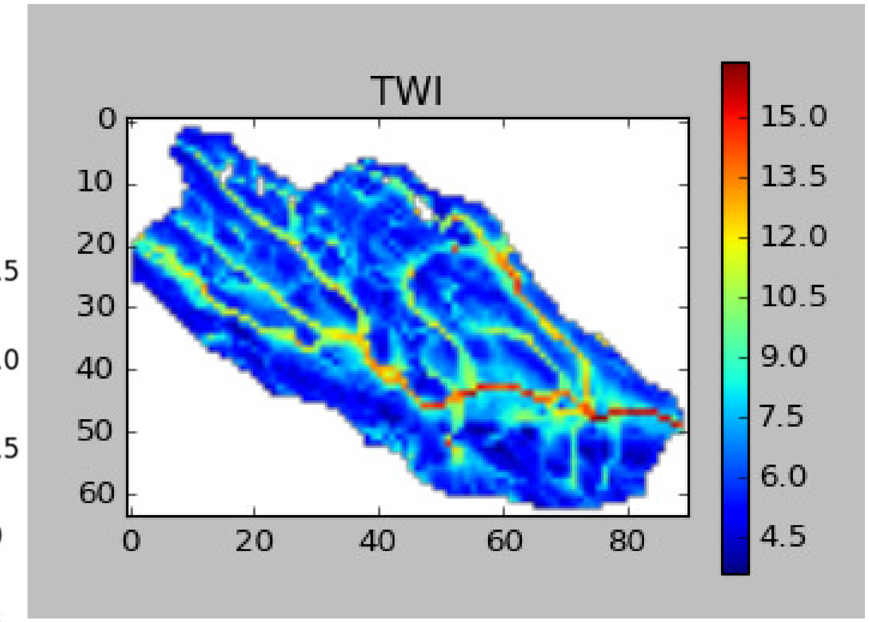
Comparison with MODIS LAI: Härkönen et al 2015 Bor. Env. Res. 20: 181–195

http://kartta.luke.fi/index-en.html

DEM → topographic wetness index





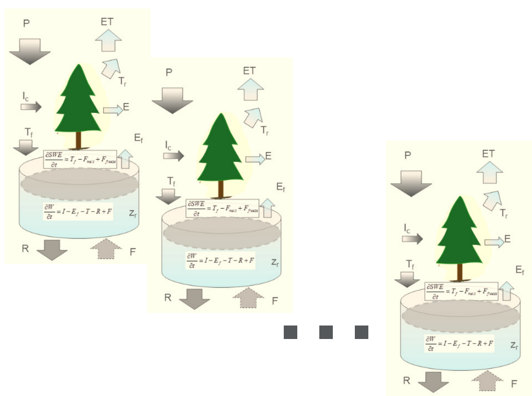


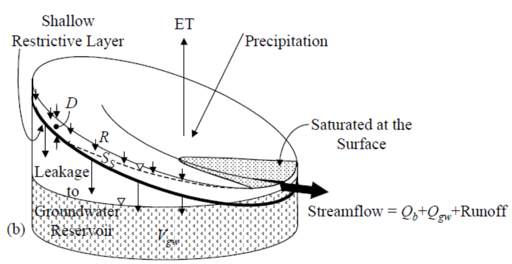
$$TWI_i = \ln\left(\frac{a_i}{\tan(\beta_i)}\right)$$

DEM + Topographic wetness index in color

Semi-distributed catchment model SpaFHy

Catchment → (n x m) grid of buckets





+ TOPMODEL for streamflow generation & returnflow

Launiainen et al. 2018, in prep.

INPUT 2D-GRIDS:

- Conifer & deciduous LAI, tree height
- Soil map, root zone organic layer depths
- Catchment boundaries
- Topografic wetness index TWI

DAILY FORCING

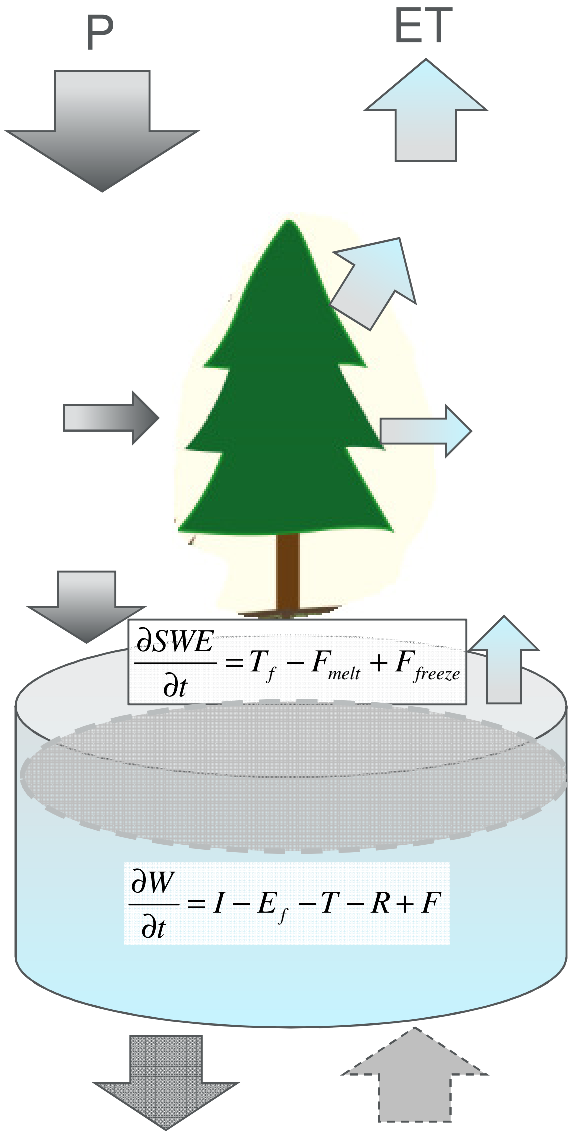
- Precip, SW radiation, temperature, RH (or VPD), wind speed

DAILY GRID-OUTPUTS:

- ET & components
- Snow water equivalent
- Organic layer & root zone moisture
- Drainage from root zone
- Saturation deficit (→ proxy of water table)
- Returnflow & dynamics of saturated area

CATCHMENT OUTLET

- Streamflow



Three-source Penman-Monteith

- Evaporation (sublimation) of canopy intercepted rain (snow)
- Canopy transpiration
- Evaporation from ground

$$\boxed{E_i = \frac{1}{L_v} \frac{\Delta(R_{n,i}) + \rho_a c_p G_{a,i} D}{\Delta + \gamma(1 + G_{a,i}/G_i)},}$$

Temperature-index snow model

Two-layer bucket model

- Organic layer
- Root zone

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Transport phenomena and controls of ET components

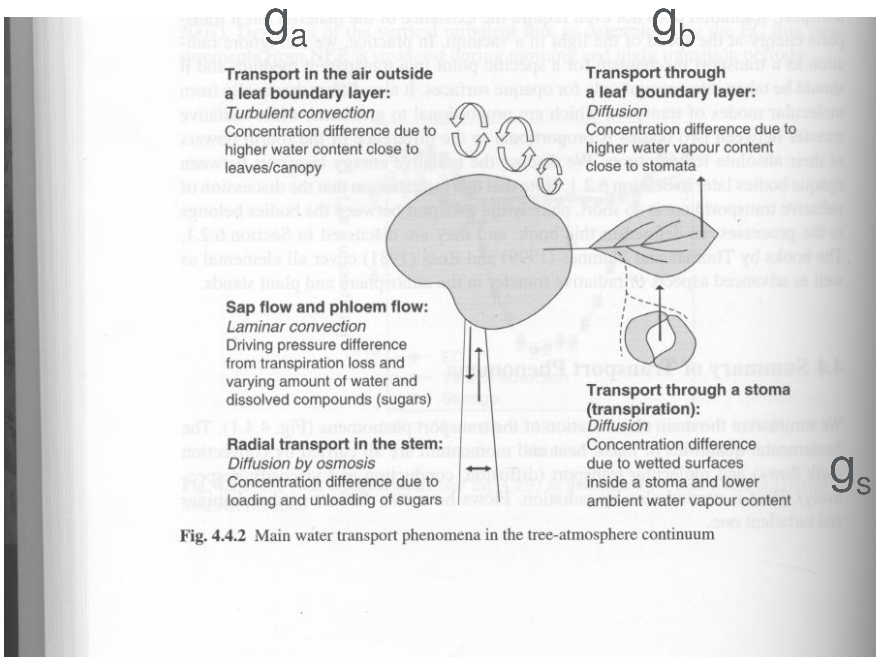

Fig. 4.4.2 Main water transport phenomena in the tree-atmosphere continuum

$g_a >> g_b >> g_s$

(Hari P. and Kulmala L., 2008)

- Evaporation from wet canopy and soil surface
  - Aerodynamic and boundary layer conductance (wind speed, geometry of canopy, roughness of surface)
  - Physical regulation
- Transpiration
  - Stomatal pathway: water movement from leaf interior through stomata to the leaf surface creates additional resistance
  - Physical + physiological regulation

Leaf to canopy stomatal conductance

$$g_s = g_o + 1.6\left(1 + \frac{g_1}{\sqrt{D}}\right)\frac{A}{C_a}$$

Medlyn et al. 2011
'USO'

scale-analysis & hyperbolic light-response

$$g_s \sim \frac{1.6\,(1+g_1)\;A_{max}}{C_a}\,\frac{PAR}{PAR+b}\,\frac{1}{\sqrt{D}}$$

g_{sref}

Exponential PAR within canopy

$$PAR(L) = PAR_o\,exp(-k_p L)$$

- A net photosynthesis
- g_1 depends on water use strategy
- g_{sref} light-saturated stomatal conductance at D = 1 kPa & const C_a

- Scots pine: g_{sref} ~2.5 mm/s (2.2 – 2.8), b ~30 – 50 Wm^{-2}
- Birch, aspen ~4.0 – 4.5 mm/s
- k_p ~0.6

$$G_c = \frac{g_{sref}}{k_p}\,ln\left(\frac{PAR+b}{PAR \times exp(-k_p LAI) + b/k_p}\right) \times \frac{1}{\sqrt{D}} \times f(\theta_{REW}) \times f_{CO2} \times f_S.$$

plant traits

Leaf → canopy

soil moisture

atm. CO2

phenology

Medlyn et al, 2011.
Global Change Biol. 17, 2134-2144

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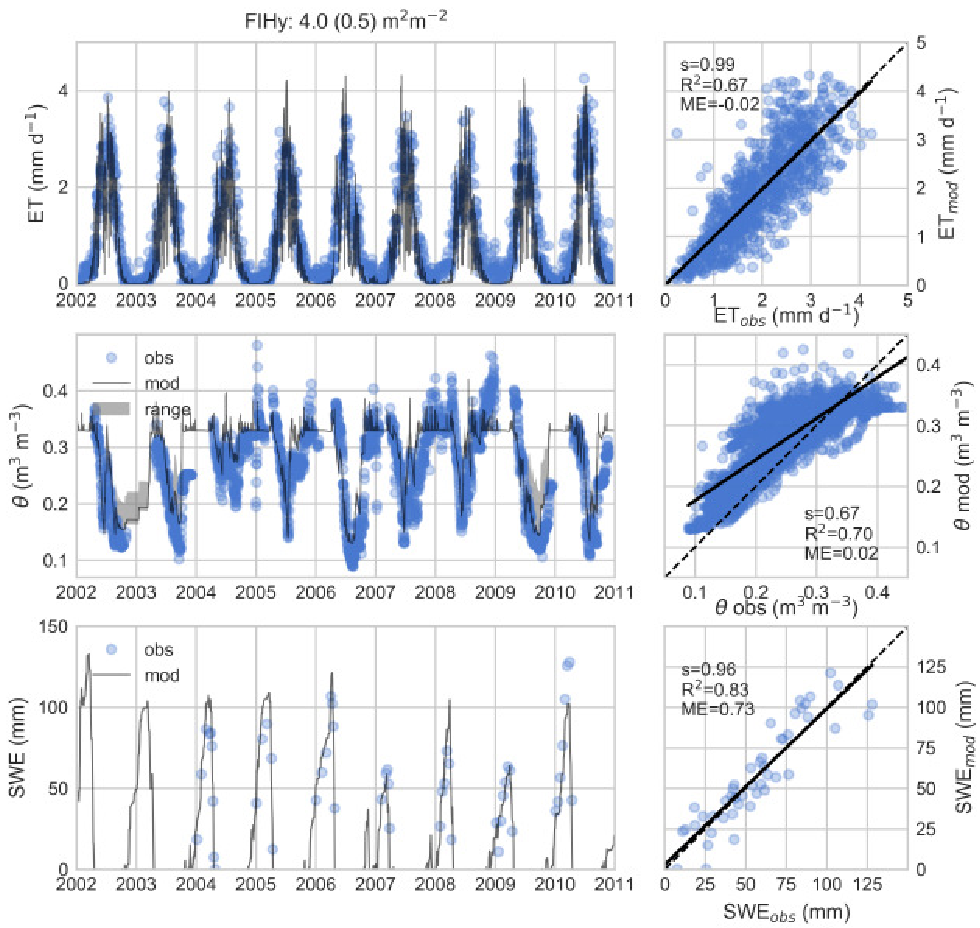
Parameterization of SpaFHy

- Mainly from literature
- Some parameters calibrated for single flux site, Hyytiälä, Southern Finland
- 1 for ground evaporation:
  - multi-layer SVAT –model APES
  - sub-canopy EC data
- 1 for transpiration
  - g_{sref} from leaf gas exchange
  - check against EC data
- 1 for interception of rainfall:
  - capacity = w x LAI, using throughfall data

APES: Launiainen et al. 2015 Ecol. Mod

Hyytiälä, Juupajoki Southern Finland



Daily ET

Soil moisture top 40 cm

Snow water equivalent

Figure 7. Modeled vs. measured dry-canopy ET at Hyytiala (top); and soil water content θ in root zone (middle) and snow water equivalent SWE (bottom). For periods when soil temperature was $le0$ θ was not shown due to soil freezing not included in the model.

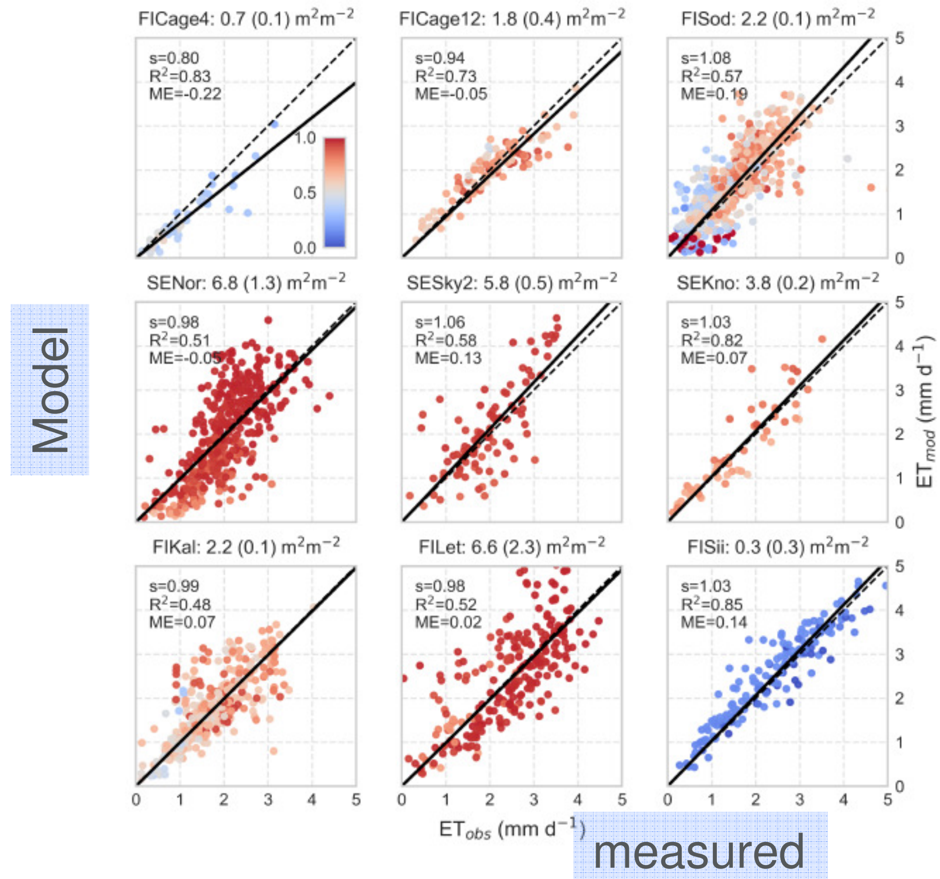
Site scale validation

- 9 EC sites from Finland & Sweden, 60 N to 68 N
- LAI (1-sided) from 0.2 to 6.8 m^2m^{-2}
- Pristine peatland … dense managed forests

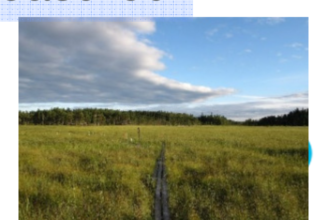
- Daily ET
  - dry-canopy conditions
  - Growing season (May-Oct)

- Independent comparison
- Color code: Transpiration / (Transpiration + Efloor)









https://github.com/LukeEcomod/EGU2018

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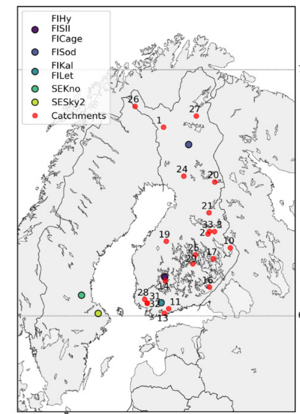
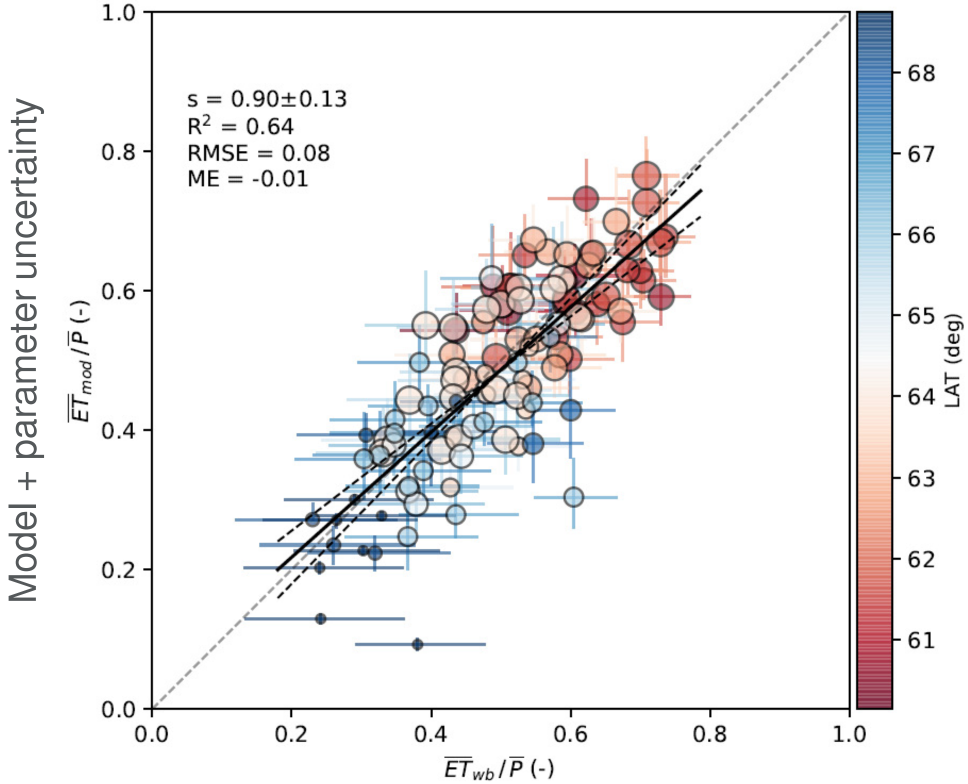
Annual evaporation ratio ET/P at catchment scale





Catchment water balance ET = P – Q

- 21 headwater catchments over Finland.
- Streamflow data 1 - 10 yr / catchment
- Independent comparison

- Across-catchment variability primarily due to north-south gradient:
  - E_{pot} / P
  - Length of snow-cover & annual snowfall
  - LAI

https://github.com/LukeEcomod/EGU2018

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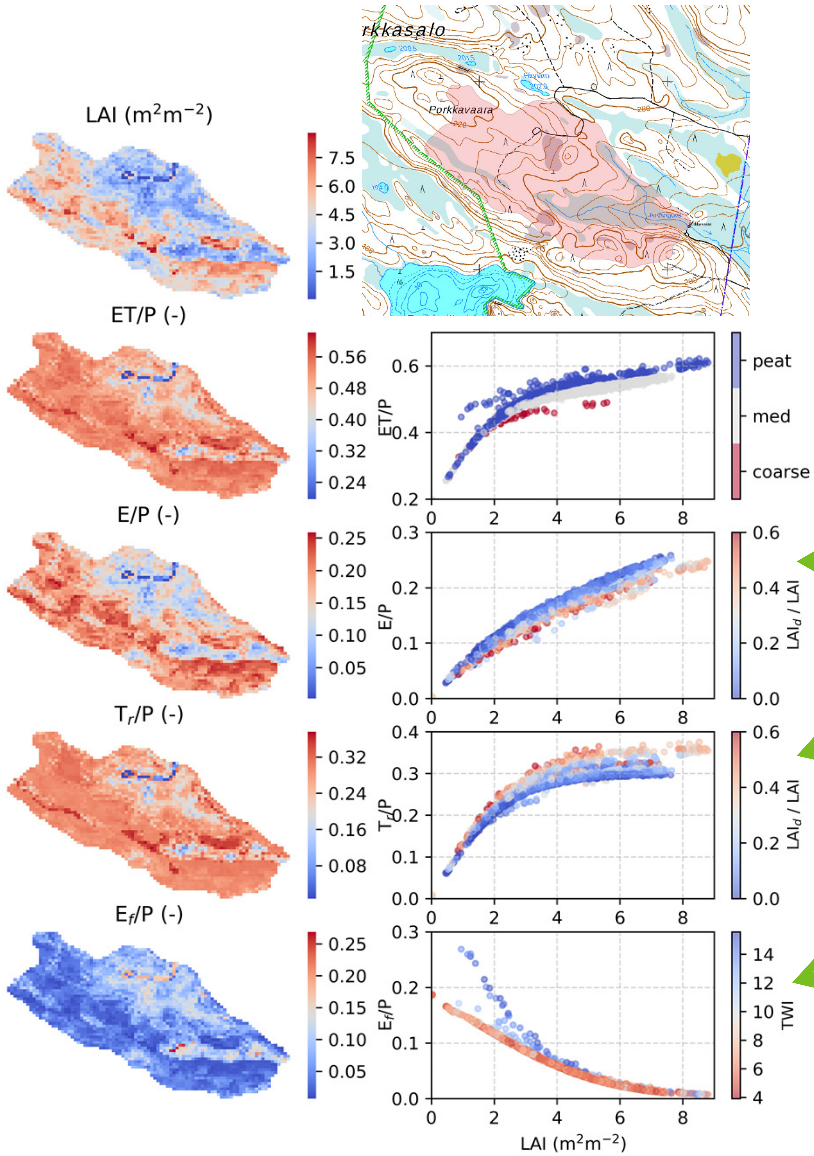
Spatial variability within catchment: model predictions



Porkkavaara catchment, Eastern Finland, 64ha, 16x16m grid

ET / P

- LAI –relationship non-linear; inflection point at LAI 2 to 3 m^2m^{-2}

Interception

- Capacity ~ a x LAI
- Snow interception

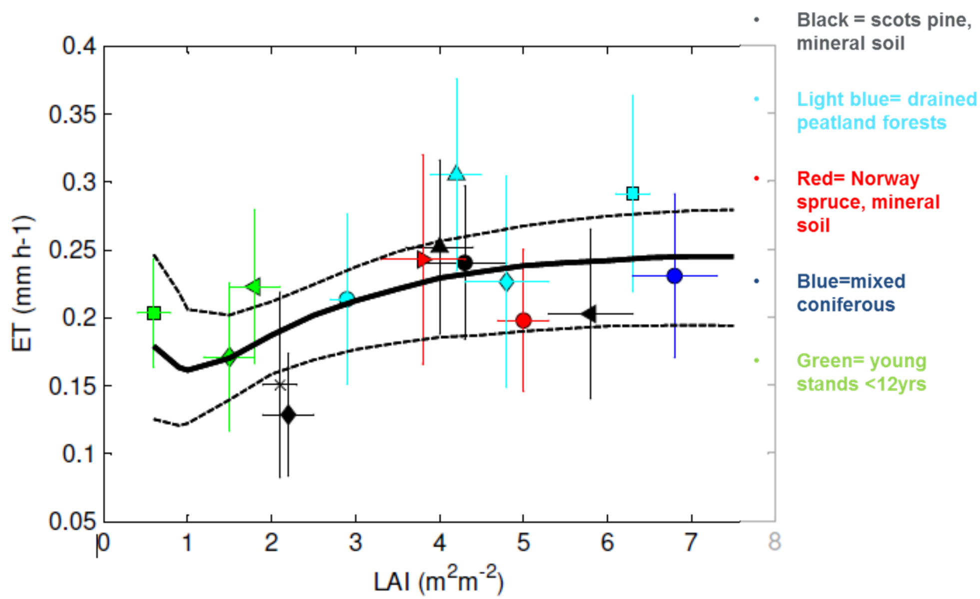
Transpiration

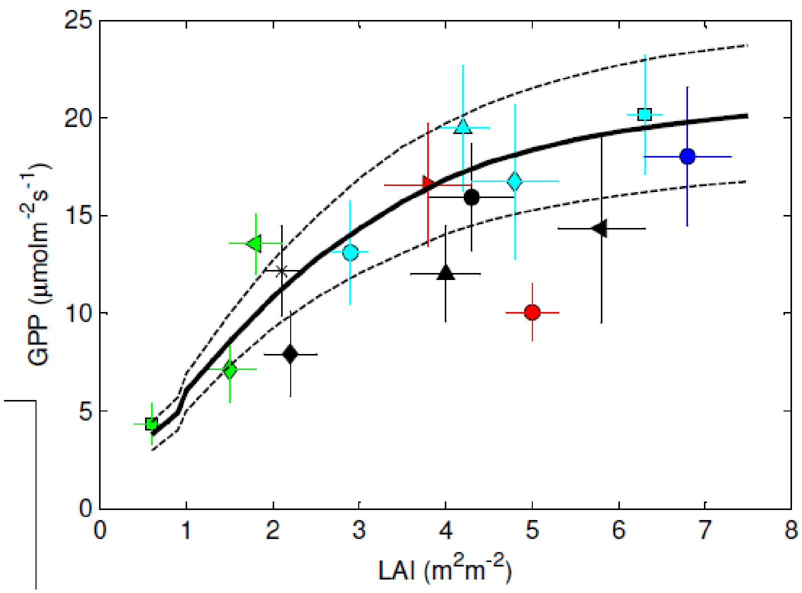
- Saturates due to light limitations
- Higher where deciduous dominant
- Drought stress at coarse soils

Evaporation from ground

- available energy
- Gridcells with high TWI receive returnflow & behave as wet surfaces: peatlands!

What does eddy-covariance data tell us? Dry –canopy ET



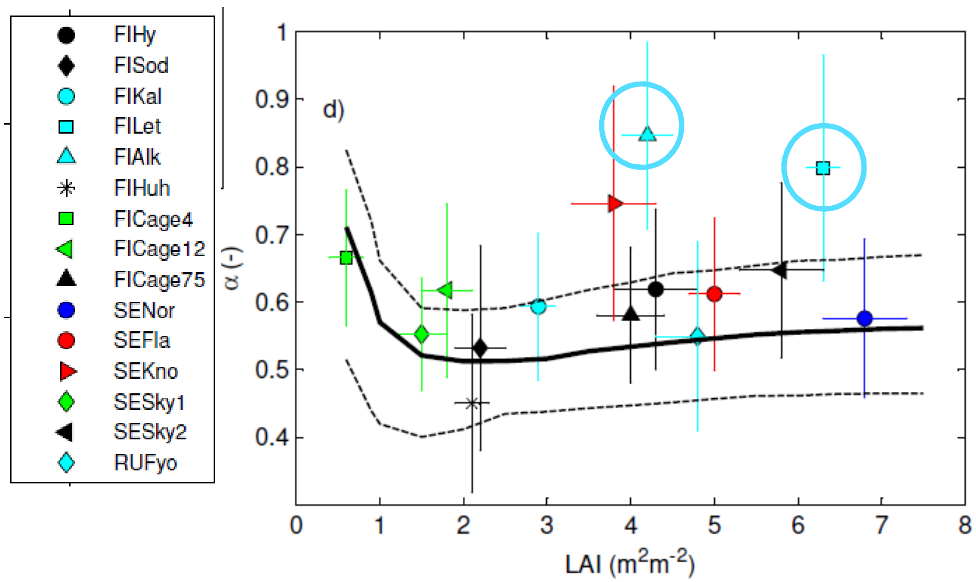


- Transpiration + forest floor evaporation is rather conservative over wide range of LAI
- Site-specific differences!

- … especially compared with photosynthetic CO_2 uptake that scales non-linearly with LAI

Launiainen et al. 2016 Global Change Biol.

Dry-canopy ET compared to 'equilibrium ET'



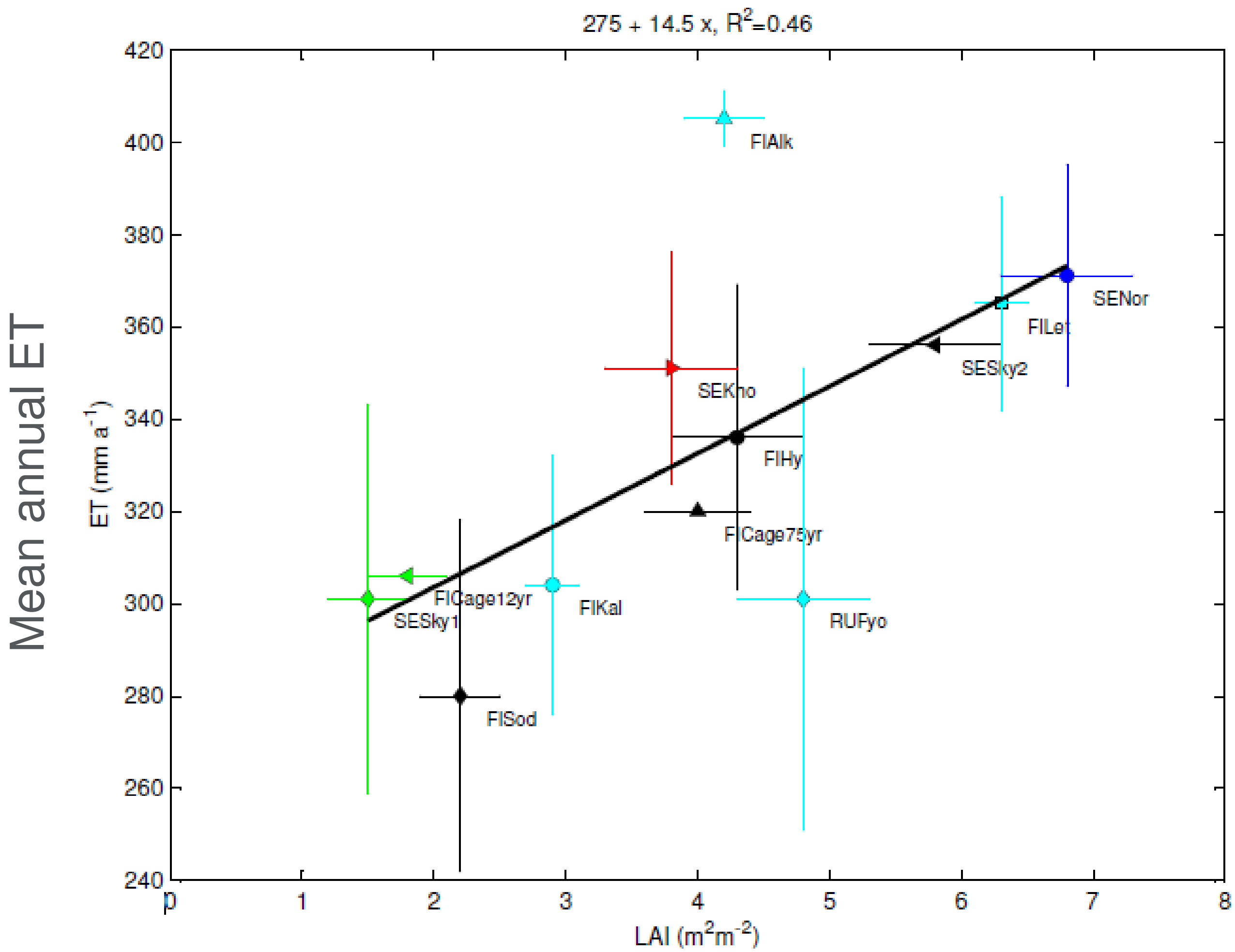
$$\alpha = \frac{ET}{ET_{eq}}$$

ET_{eq} is 'reference ET' determined by net radiation and temperature.
For well-watered short reference crop α~1.28

- FIAlk (Alkkia, Scots pine)
  - Drained peatland with agricultural history (very fertile)
  - Vigorous deciduous understory
- FILet (Lettosuo, mixed conif.)
  - Fertile drained peatland forest
  - LAI: 30% pine, 35% spruce, 35% birch
- Species have different water use strategies!

Alkkia
(photo:Tuomas Laurila)

Nordic forests, eddy-covariance data: annual ET



Leaf-area index (hemi-surface, canopy + understory)

- **Black = scots pine, mineral soil**
- **Light blue= drained peatland forests**
- **Red= Norway spruce, mineral soil**
- **Blue=mixed coniferous**
- **Green= young stands <12yrs**

Note: EC-data Likely underestimates ET during and after precipitation events!

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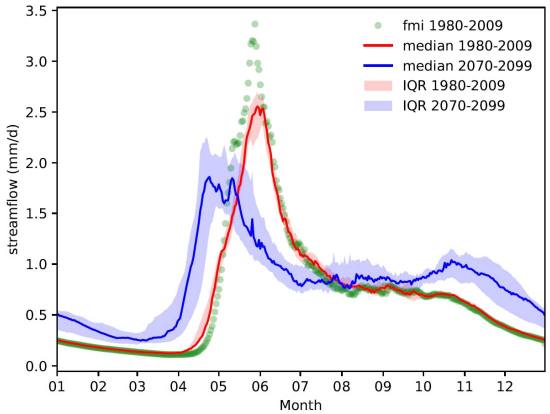
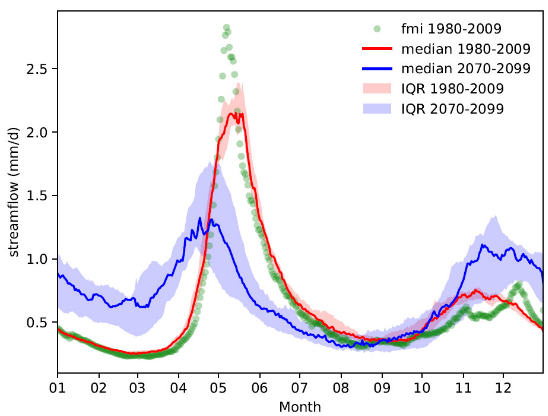
Applications & work in progress

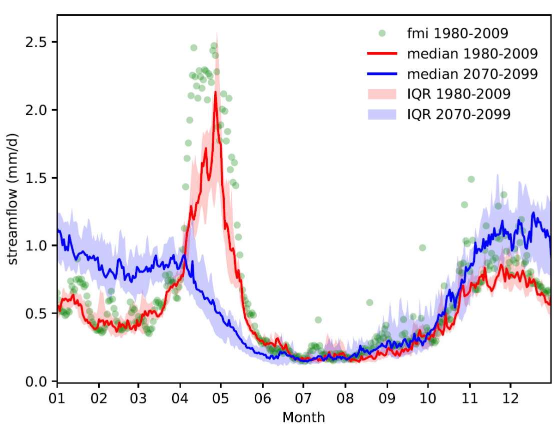
Climate projections: RCP 4.5 & 8.5 degC



Lompolojänganoja, Muonio

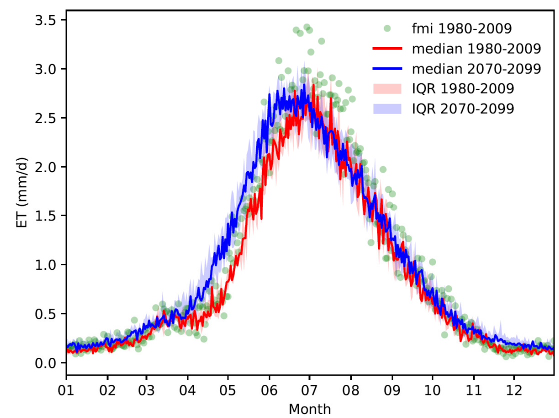


Porkkavaara, Sotkamo



Paunulanpuro, Orivesi

ET



- Larger evaporative demand
- Increasing ground evaporation
- Higher wintertime interception
- Transpiration:
  - Increases in spring & early summer
  - Drought-induced decrease in July-August

https://github.com/LukeEcomod/EGU2018

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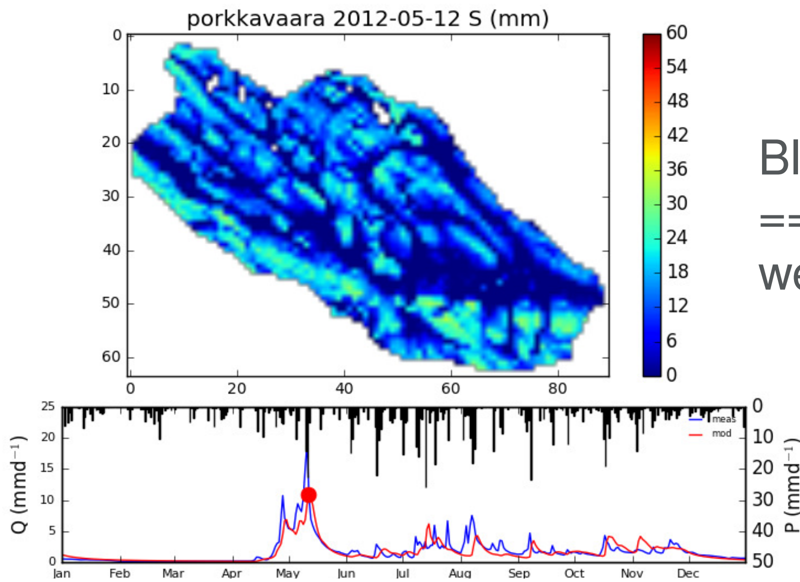
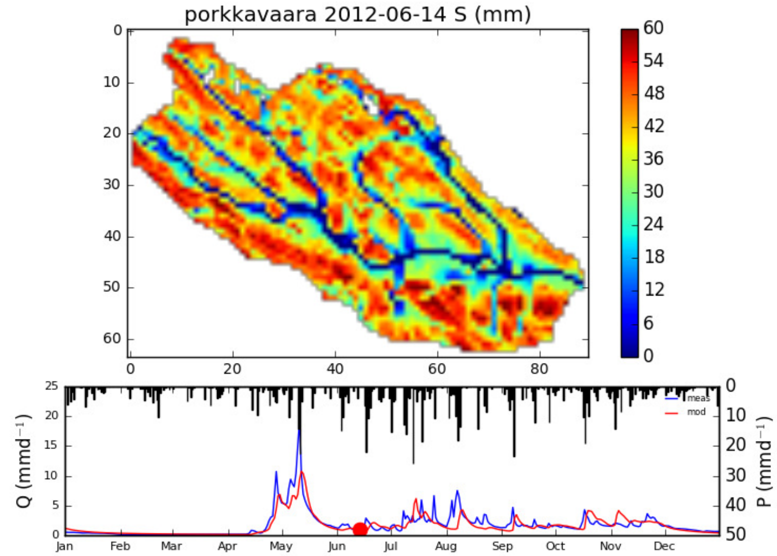
Topmodel saturation deficit: dynamic 'TWI' 16x16m

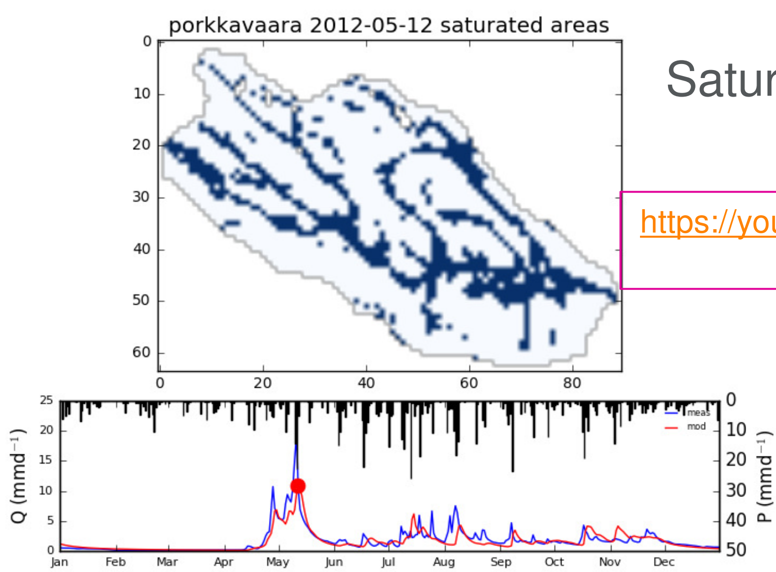
During snowmelt

Dry summer conditions



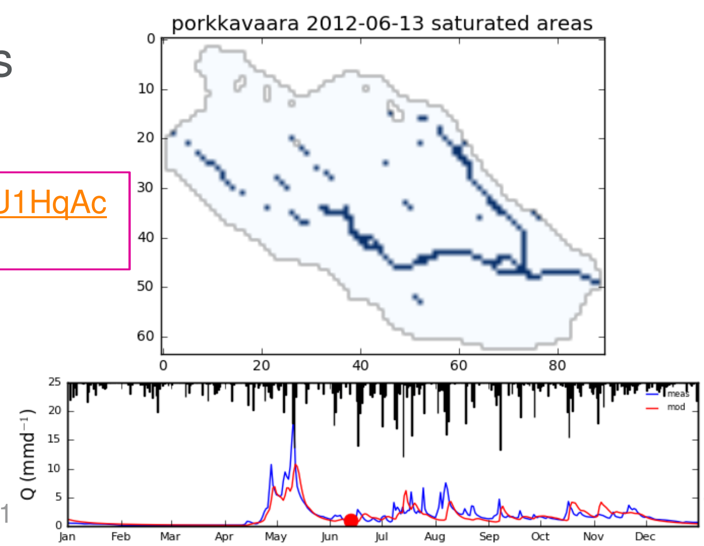
Blue == wet!





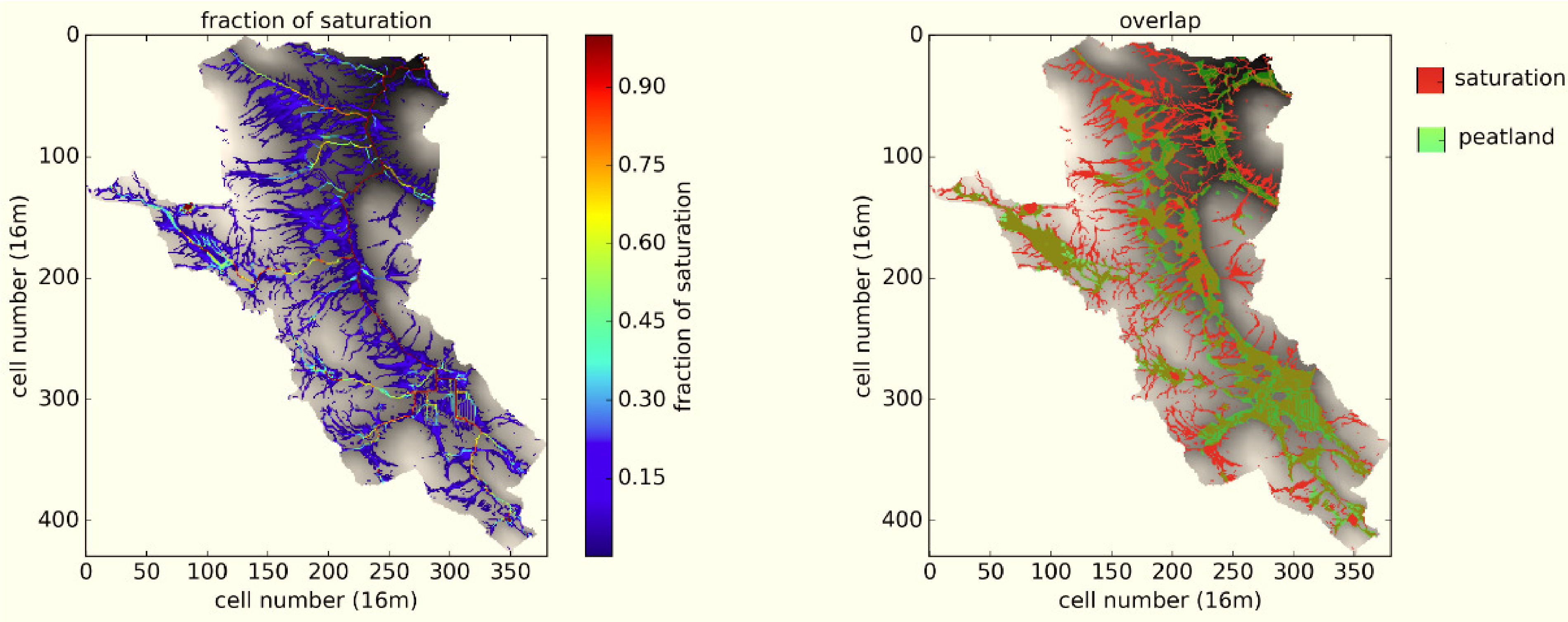
Saturated soils

https://youtu.be/kuzJRU1HqAc



Location of saturated areas vs. peat soils

- Fraction of time gridcell saturated (ground water at surface)
- Compared to peatland extent from topographic database



https://github.com/LukeEcomod/EGU2018

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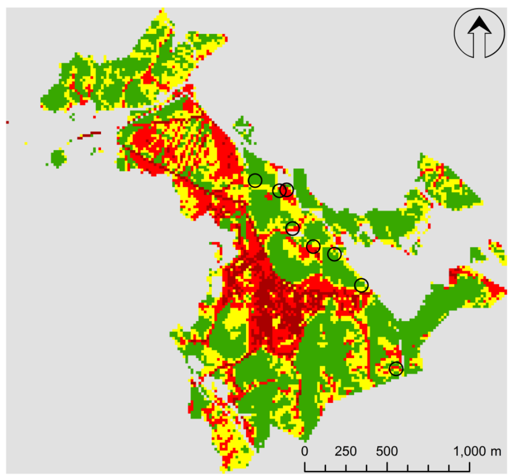
VISION: Google maps for forest machines

Luke
NATURAL RESOURCES INSTITUTE FINLAND
Turun yliopisto
University of Turku

DATA fusion:
1. Open data
2. Spatial hydrology model Spathy
3. STireTrack (Kulju et al.)
4. CAN channel & Sensors in forest machines (Ala-Ilomäki, Sirén et al.)

➢ **DYNAMIC TRAFFICABILITY FORECASTING**

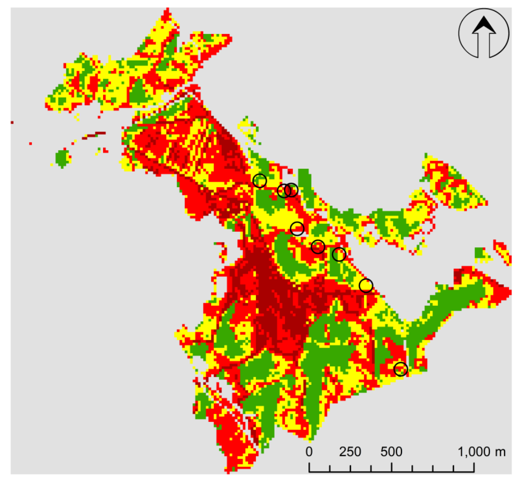
Vihdin kokeessa selittävät tekijät
Dynaaminen TWI (Hydrol. Malli),
juurten määrä (mNFI),
Rinteen suunta (DEM)
harvesterin kulkuvastus



Predicted rut depth in "dry" conditions (19.11.2016) [cm]

< 5
5 - 10
10 - 20
20 - 40

Kuiva tilanne



Predicted rut depth in "moist" conditions (18.5.2016) [cm]

< 5
5 - 10
10 - 20
20 - 40

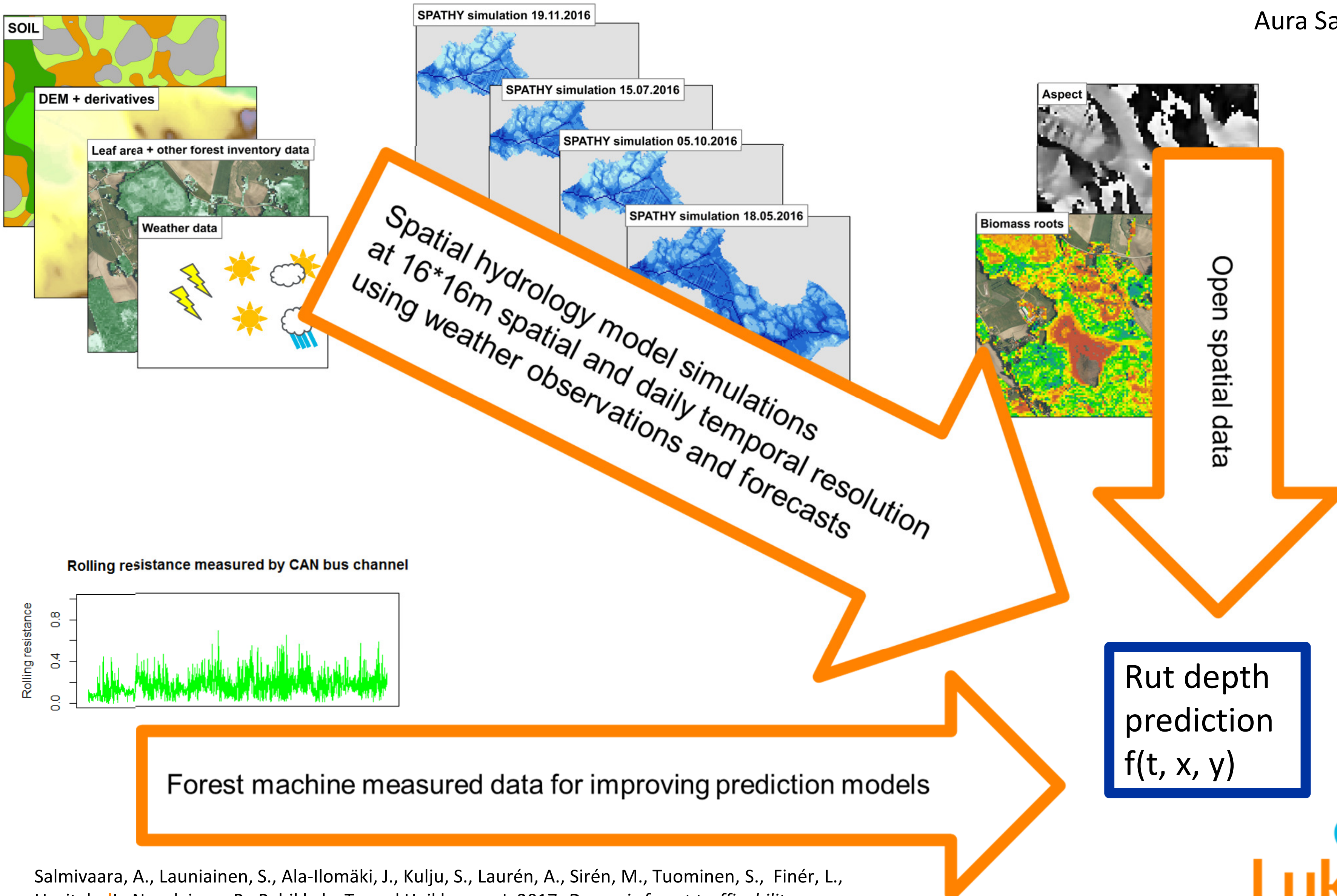
Kostea tilanne

In ”moist” conditions the area with ruts >10 cm covers 45% of the total area, while in ”dry” conditions this proportion is 26%.

Luke
NATURAL RESOURCES INSTITUTE FINLAND

Dynamic forest trafficability prediction by fusion of open data, hydrologic forecasts and harvester-measured data

Aura Salmivaara



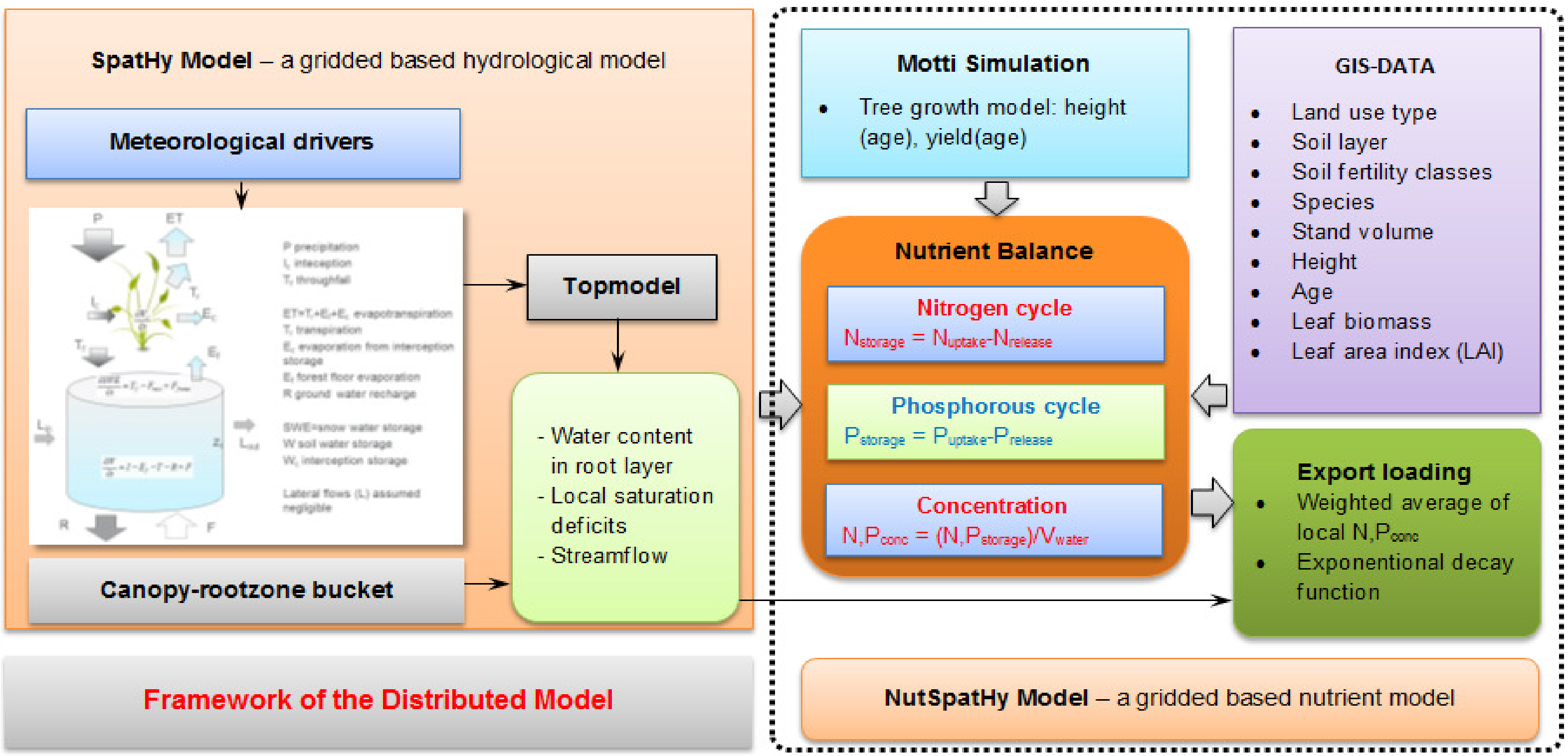
Salmivaara, A., Launiainen, S., Ala-Ilomäki, J., Kulju, S., Laurén, A., Sirén, M., Tuominen, S., Finér, L., Uusitalo, J., Nevalainen, P., Pahikkala, T., and Heikkonen, J. 2017. *Dynamic forest trafficability prediction by fusion of open data, hydrologic forecasts and harvester-measured data. Poster.*

NutSpatHy

- **A grid-based distributed nutrient model for predicting nitrogen (N phosphorous (P) leaching in forested catchments**
- **Model key features:**
  - Grid-based nutrient balance (Δstorage = release - uptake)
  - Nutrient concentration prediction (conc = storage/water_volume)
  - Export loading simulation based on SpatHy runoff prediction
  - Spatiotemporal modelling of nutrient dynamics

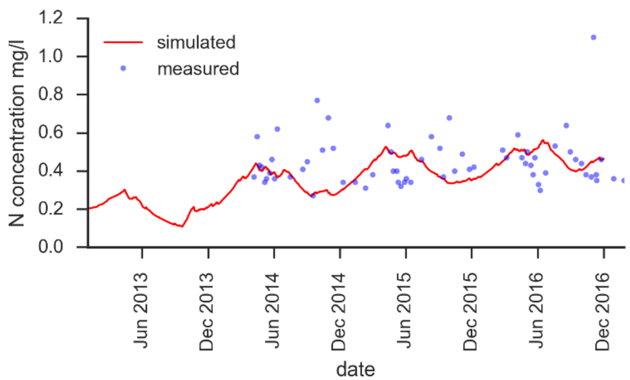
Mingfu Guan

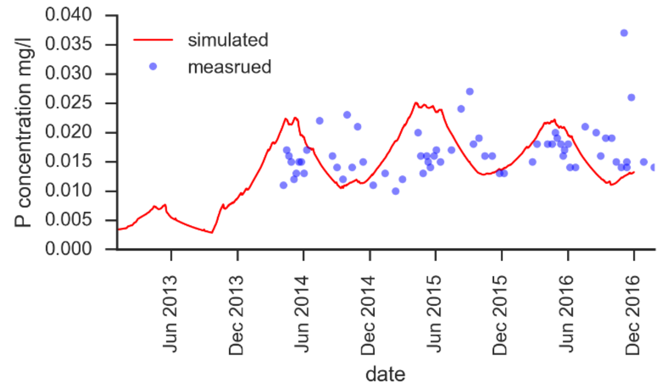
Ari Lauren



- **N and P concentration**

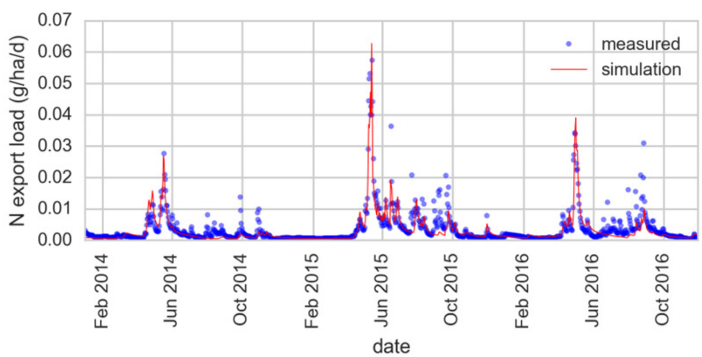
Nutrient concentration is reasonably predicted considering the complex chemical process and a series of uncertainties of parameters and input data.

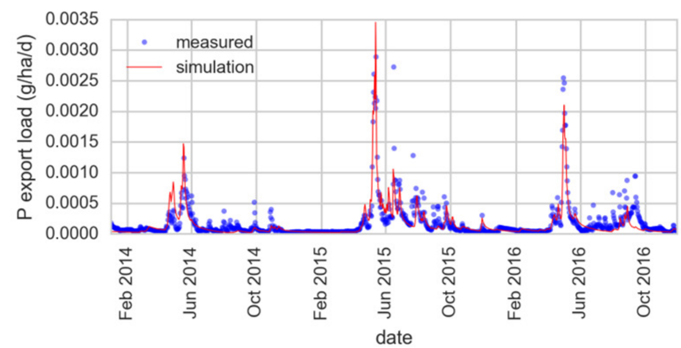




- **Daily and monthly N and P export loading**

Good performance in the prediction of export loading verifies the controlling role of hydrology on nutrient transport processes.

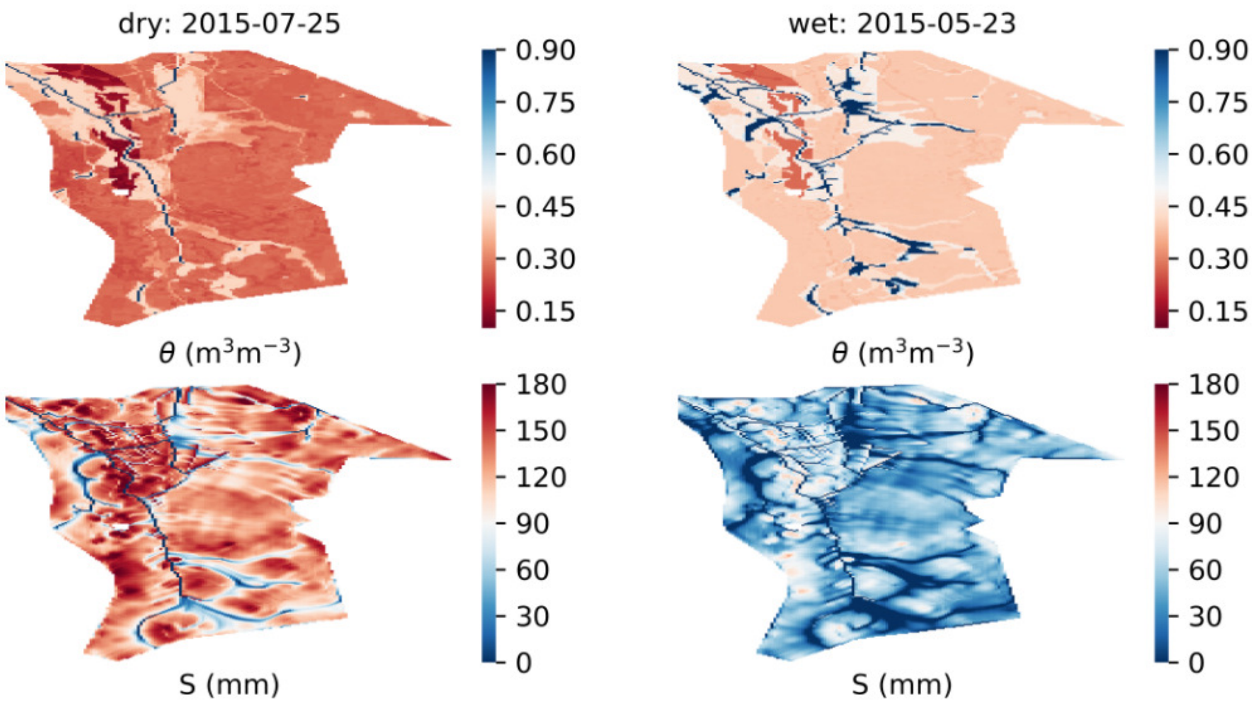




Daily N and P export loading: NSC = 0.76, correlation coef.= 0.81

Lompolojängänoja, Pallas

Root zone vol. moisture and Topmodel saturation deficit S during dry and wet periods



https://github.com/LukeEcomod/EGU2018

Thank you!

contact: samuli.launiainen@luke.fi

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