”Searching for methods to analyze causality in environmental time series”

Can Mighty Matematicians help Miserable Micromeorologist?

Samuli Launiainen, 22.2.2019

Academy of Finland:
CLIMOSS (2016 – 2021)
SOMPA (2017-2022)
CCF-Peat (2017-2020)

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Content

- Eddy-covariance and flux data in brief
- Examples of ecosystem processes
- Case Hyytiälä: why annual carbon sink is increasing?
- Common questions
- Discussion & ideas!
- Slides + few papers at: https://github.com/LukeEcomod/AtMath

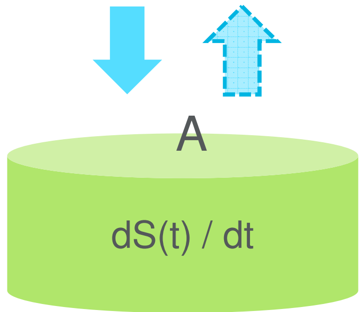
'Causality'

- Detto et al. 2012. Am. Naturalist:
  - "if some other series *X(t)* contains information in past terms that helps in the prediction of *Y(t)* and if this information is contained in no other series used in the predictor, then *X(t)* is said to cause *Y(t)*." (citing Granger, 1969)

- What (I think) we are interested on:
  - "which variables *X(t)* in their current and past terms *X(t, t-1, t-2, …)* explain variability in measured environmental time series *Y(t)*"? How much and what this tells about the system measured?
  - "how information on variables *X(t)* and *Y(t),* including their history, can be used to explain system state *S(t)*"?
- Point is not predicting *Y(t) per se* but understanding *S(t)* through *Y(t)* and *X(t)*

Flux and flux time series

$F_s(t) = dS(t)/dt$



A = ground area

Typical units:
kg J m^{-2} s^{-1}
Mol J m^{-2} s^{-1}
J m^{-2} s^{-1}

A = ground area or surface area of measured system

Eddy-covariance: ecosystem scale
3D sonic anemometer + IR gas-analyzer
10 Hz

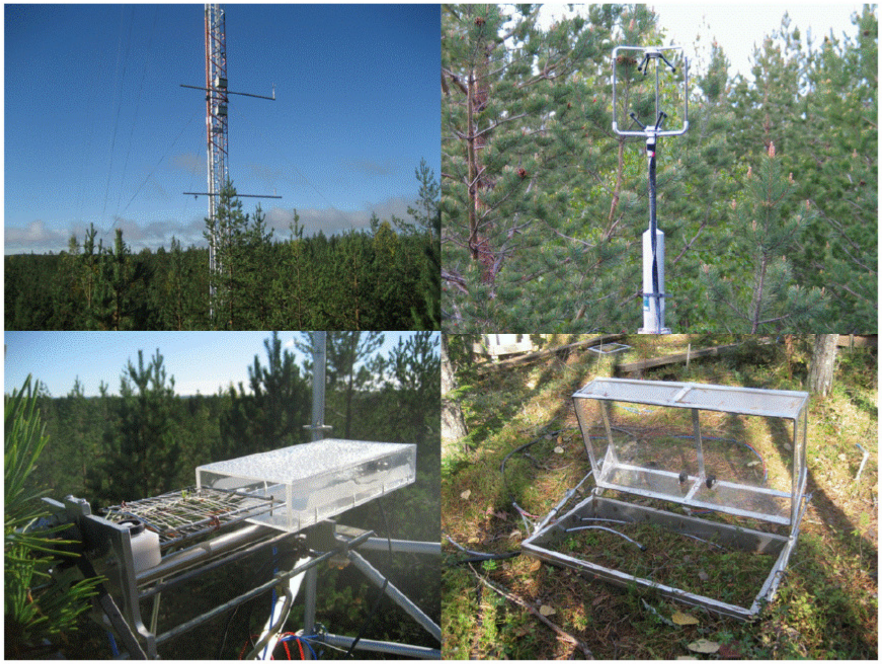
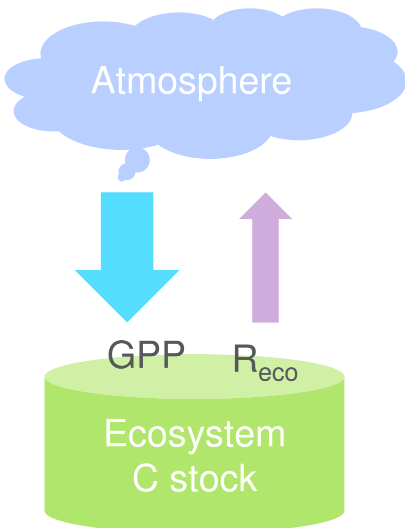


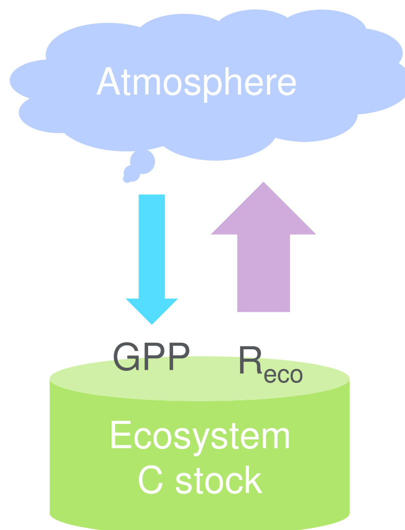
Figure 10: Measurement devices at SMEAR II. Top: Main mast where canopy scale fluxes and concentrations are measured; the 3D wind field is measured by sonic anemometer. Bottom: Chambers to monitor shoot gas exchange and soil CO_2 and H_2O fluxes.

Chambers: ecosystem component scale
Flow-through; dC/dt → flux
IR gas-analyzer, ~1 Hz

Ecosystem carbon stock and carbon balance



C stock increases



C stock decreases

Gross-primary productivity GPP

- Photosynthetic uptake of CO2 from the atmosphere

Ecosystem respiration R_{eco}

- decomposition & plant metabolism: release of CO2 to atmosphere

Carbon balance NEE = - GPP + R_{eco}

- Change in C stock
- Sign convention: - means atmosphere looses CO2
- $M(CO_2) = 12 + 2*16 = 44$ g/mol; $M(C / CO_2) = 12/44$

NEE(t) is measured by eddy-covariance
R_{eco}(t) inferred based on night-time measurements.
GPP computed as residual GPP(t) = - NEE(t) + R_{eco}(t)

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$$\underbrace{\frac{\partial \bar{s}}{\partial t}}_{change} = \underbrace{\sum_{i=1}^{3} \bar{u}_i \frac{\partial \bar{s}}{\partial x_i}}_{advection} + \underbrace{\sum_{i=1}^{3} \frac{\partial \overline{u_i ' s '}}{\partial x_i}}_{turb.\ flux\ divergence} \underbrace{+ \sum S_s}_{production/destruction}$$

Eddy covariance

Horizontal homogeneity, stationarity

$$0 = \frac{\partial \overline{w ' s '}}{\partial z} + \sum S_s(z)$$

Integrate with depth z

$$\overline{w ' s '}(z_{ref}) = -\int_{z=0}^{z_{ref}} S_s(z)$$

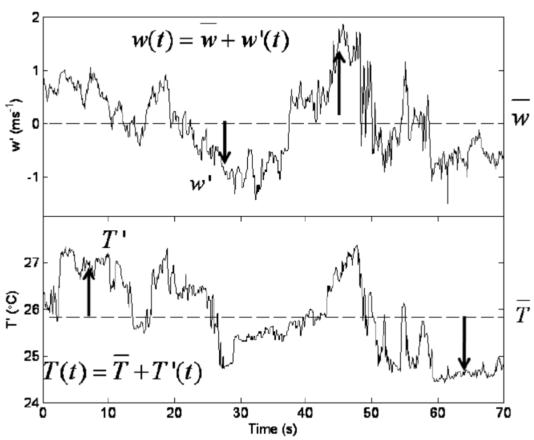

Figure 6: Turbulent time series of vertical wind (*w*) and temperature (*T*) measured on a clear sunny summer afternoon by a sonic anemometer at 23.3 m height, abound 8 m above a pine forest. The overbar represents time average and prime the instantaneous turbulent fluctuation around the mean (eq. 7). The mean values are denoted by dashed horizontal lines and fluctuating parts, at few occasions, by arrows. Note the ramp-like behavior of temperature signal and correlation with *w'*.

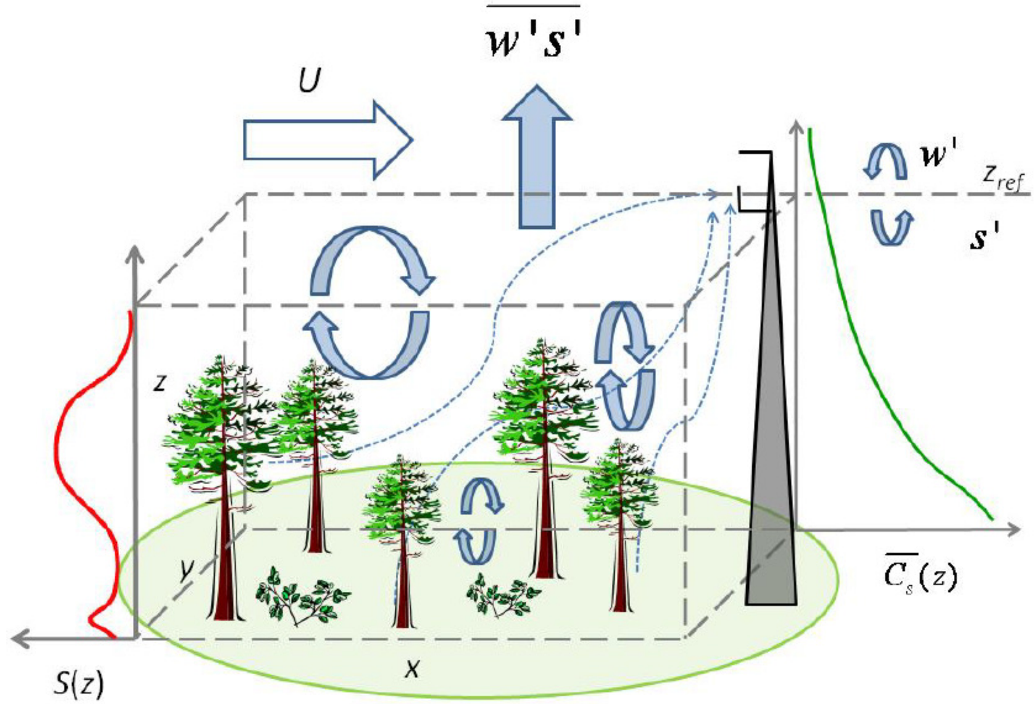

Figure 9: The principle of eddy-covariance is based on mass balance approach. In horizontally homogenous and stationary conditions the turbulent vertical flux at upper edge of the box (z_{ref}) should equal the integral over all sources and sinks, *S*(*z*), within the studied volume (eq. 10). Eddies 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 $\bar{C}_s(z)$ is shown in right.

Launiainen, 2011

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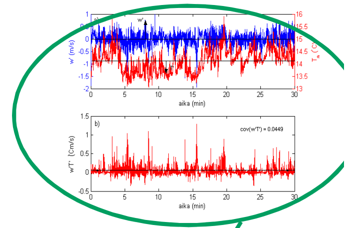
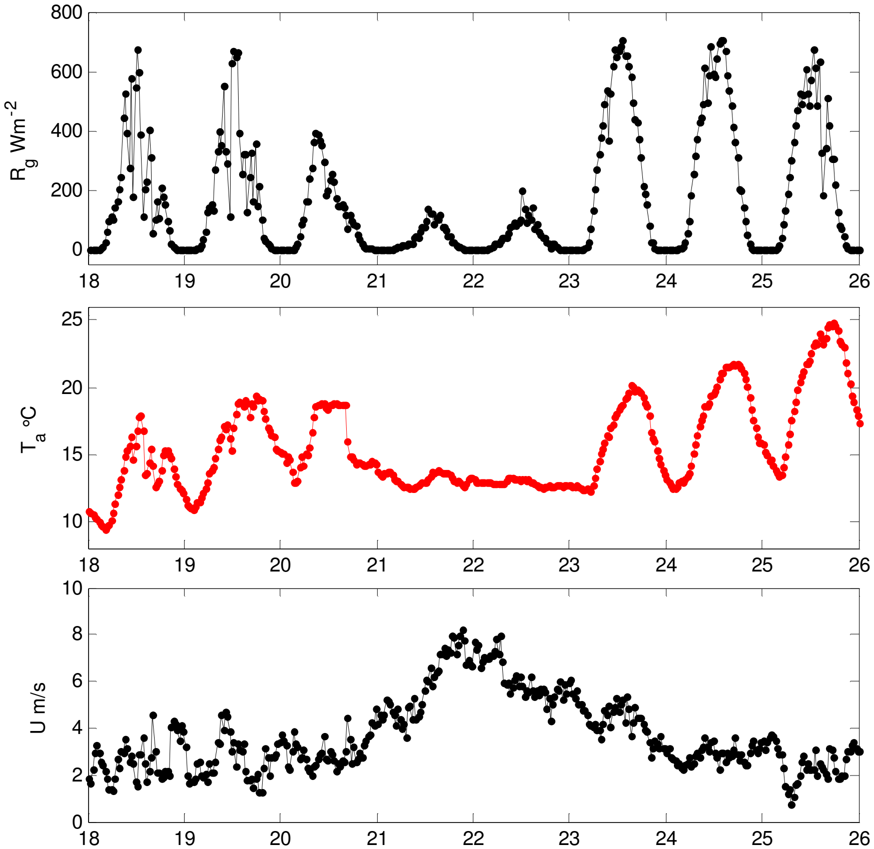
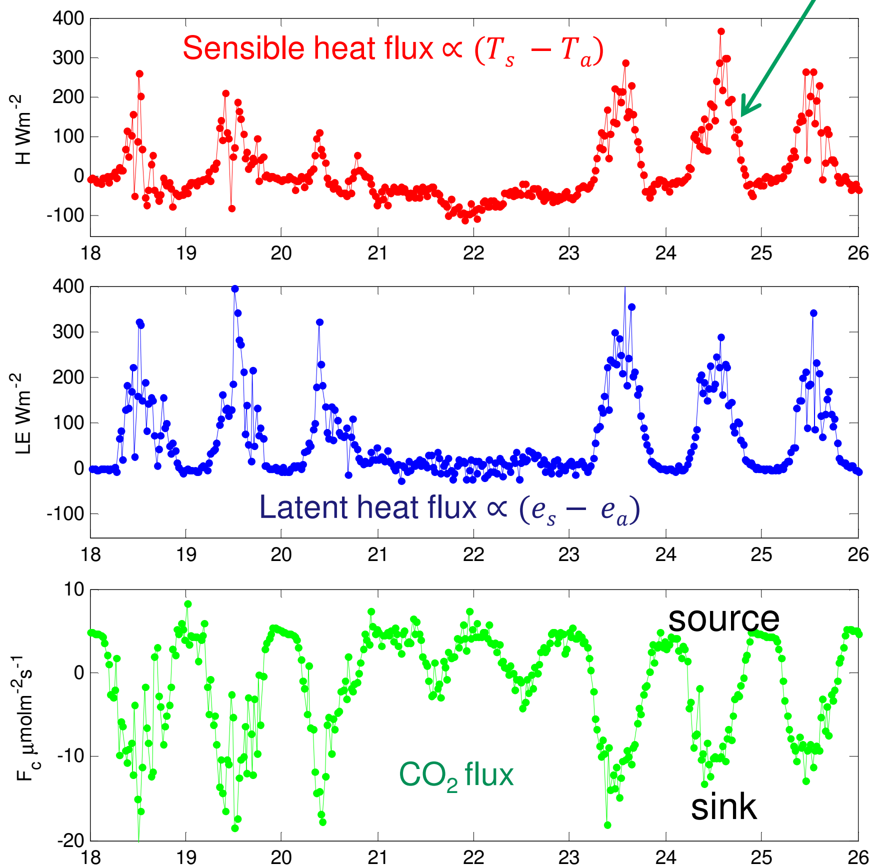


Environmental variables



Day in July 2008

Ecosystem – atmosphere fluxes



Day in July 2008

Sign convention:
+ net flux to atmosphere

External forcings

$$X(t_0) = [x_1(t_0) \\ x_2(t_0) \\ \ldots \\ x_n(t_0)]$$

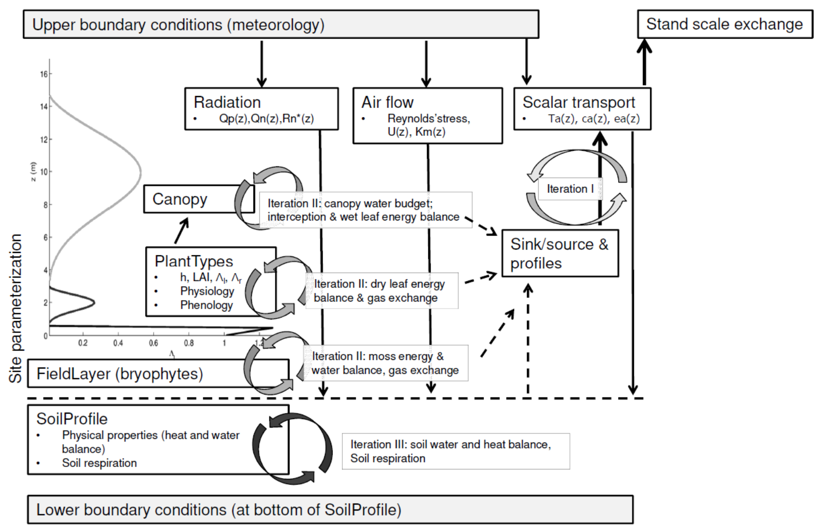
System

Processes ~ functions

System components = class instances (objects)

Parameters ~ object properties; depend on current conditions and/or history

States ~ object state variables; depend on history



Fluxes between system and the environment

$$Y(t_0) = [y_1(t_0) \\ y_2(t_0) \\ \ldots \\ y_m(t_0)]$$

Launiainen et al. 2015. Ecol. Mod; 2016 Global Change Biol.

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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

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

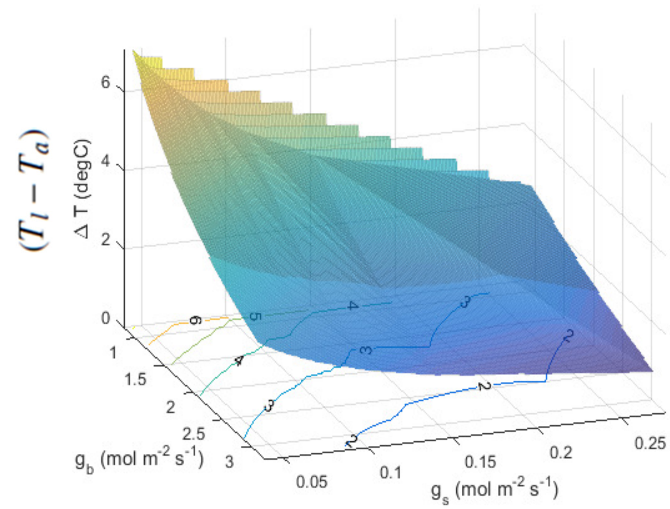
$$A_1 = V_{cmax}\frac{c_i - \Gamma_*}{c_i + K_c(1 + O_a/K_o)}$$

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

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

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

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



leaf properties

$\alpha,\ \epsilon,\ d,\ a_3$

External inputs

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

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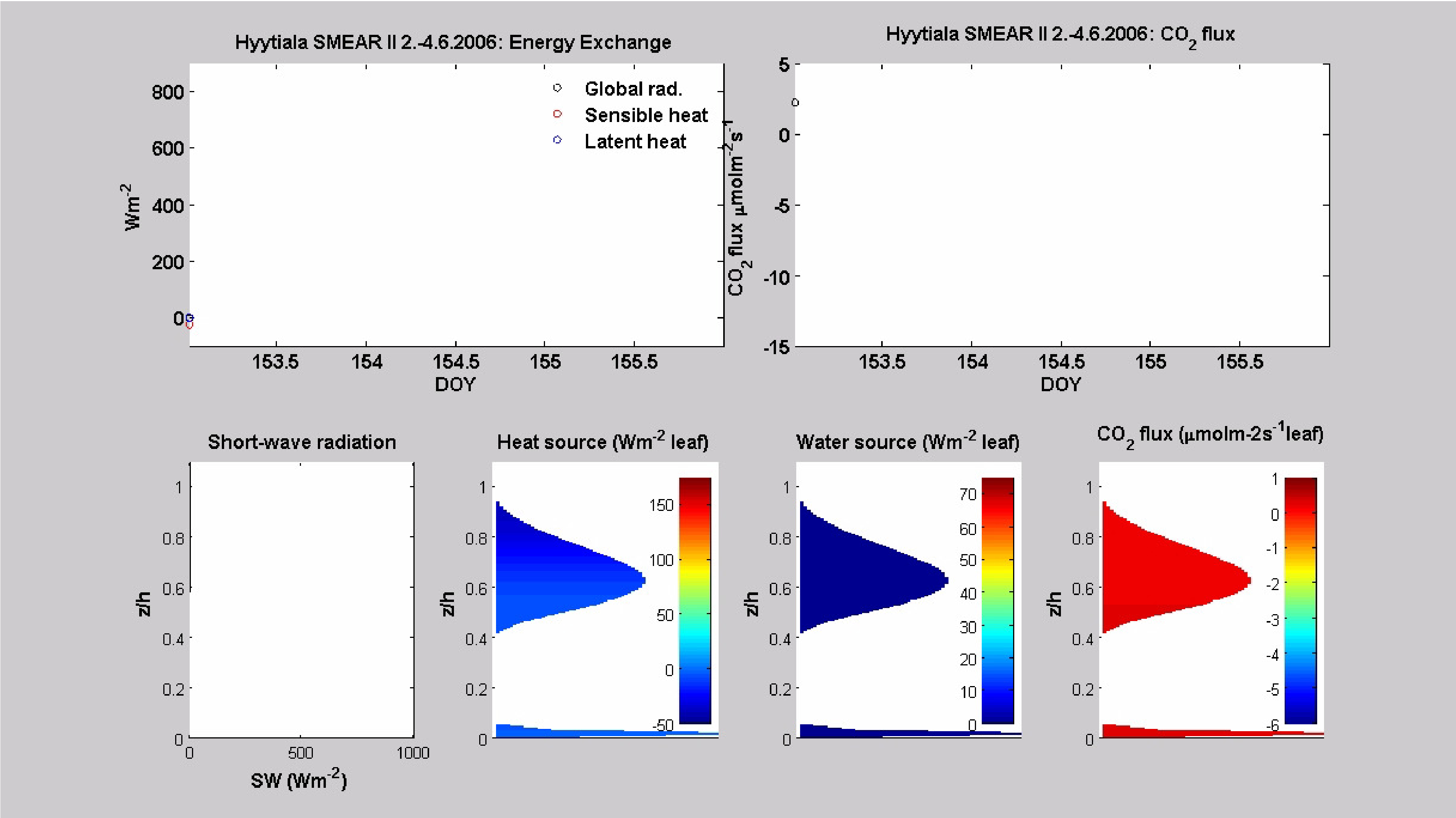
Heat, water and carbon fluxes



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CO2 flux from forest floor

Soil T

Flux

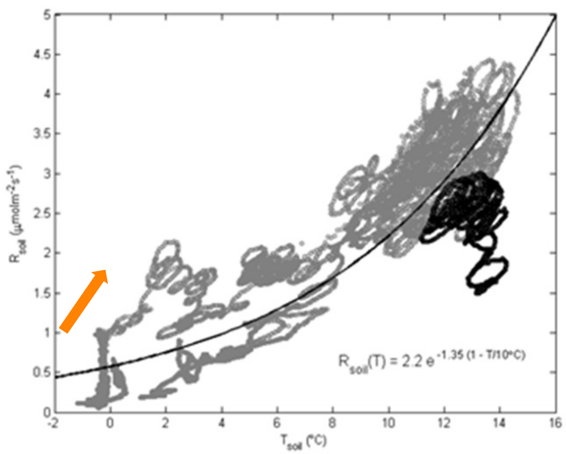

Figure 3: Temperature response of soil respiration (*R_{soil}*) in 2006 measured by soil chambers. The average base respiration rate at 10 °C is 2.2 μmolm^{-2}s^{-1} (eq. 4). The clear hysteresis-type behavior shows the importance of other factors such as photosynthetic production and soil moisture controlling *R_{soil}*. Because of this, both the base rate and temperature sensitivity vary across the season. Intense drought decreased soil respiration during the first three weeks of August (black circles).

- Temperature response modified e.g. by
  - Activity of decomposers
  - Litter availability
  - Input of sugars from photosynthesis (with delay)
- Hysteresis
- 'base rate' and temperature sensitivity vary in time

Detto et al. 2012. "Causality and persistence in ecological systems: A nonparametric spectral Granger causality approach". American Naturalist

Detto et al. 2013. "Multivariate Conditional Granger Causality Analysis for Lagged Response of Soil Respiration in a Temperate Forest." Entropy 15 (2013): 4266-4284.

Shoot CO2 flux and transpiration

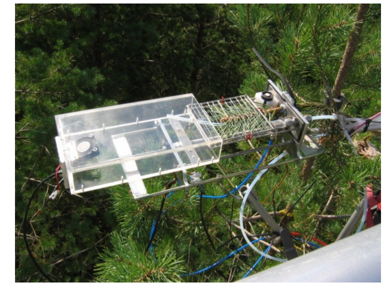

Photo: Pasi Kolari

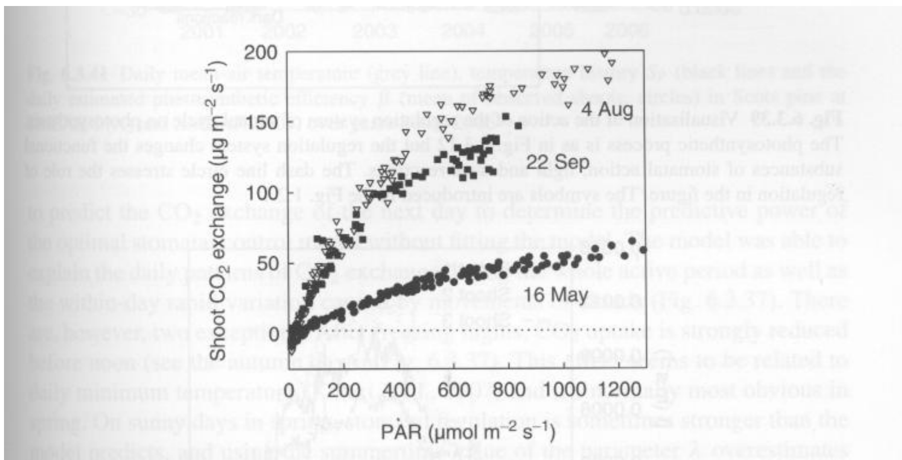

Fig. 6.3.38 Relationship between light (photosynthetically active radiation) and shoot CO_2 exchange at SMEAR I on three days in spring, summer and autumn (Redrawn from Kolari et al., 2007)

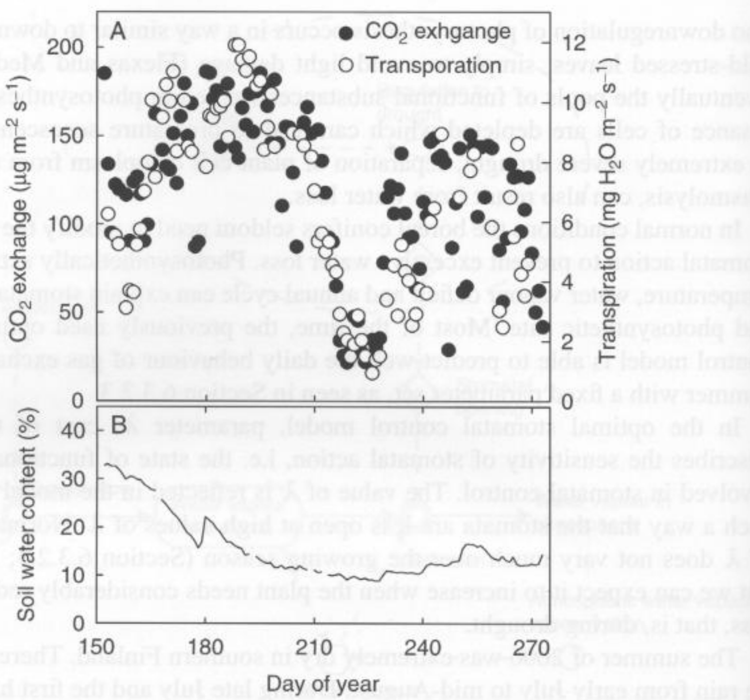

Fig. 6.3.55 CO_2 exchange (dots) and transpiration (circles) of Scots pine shoots (A) and soil water content (B) at SMEAR II in the summer of 2006. The fluxes are means of three shoots, averaged daily between 11:00 and 13:00 solar time

Hari P. and Kulmala L., 2008

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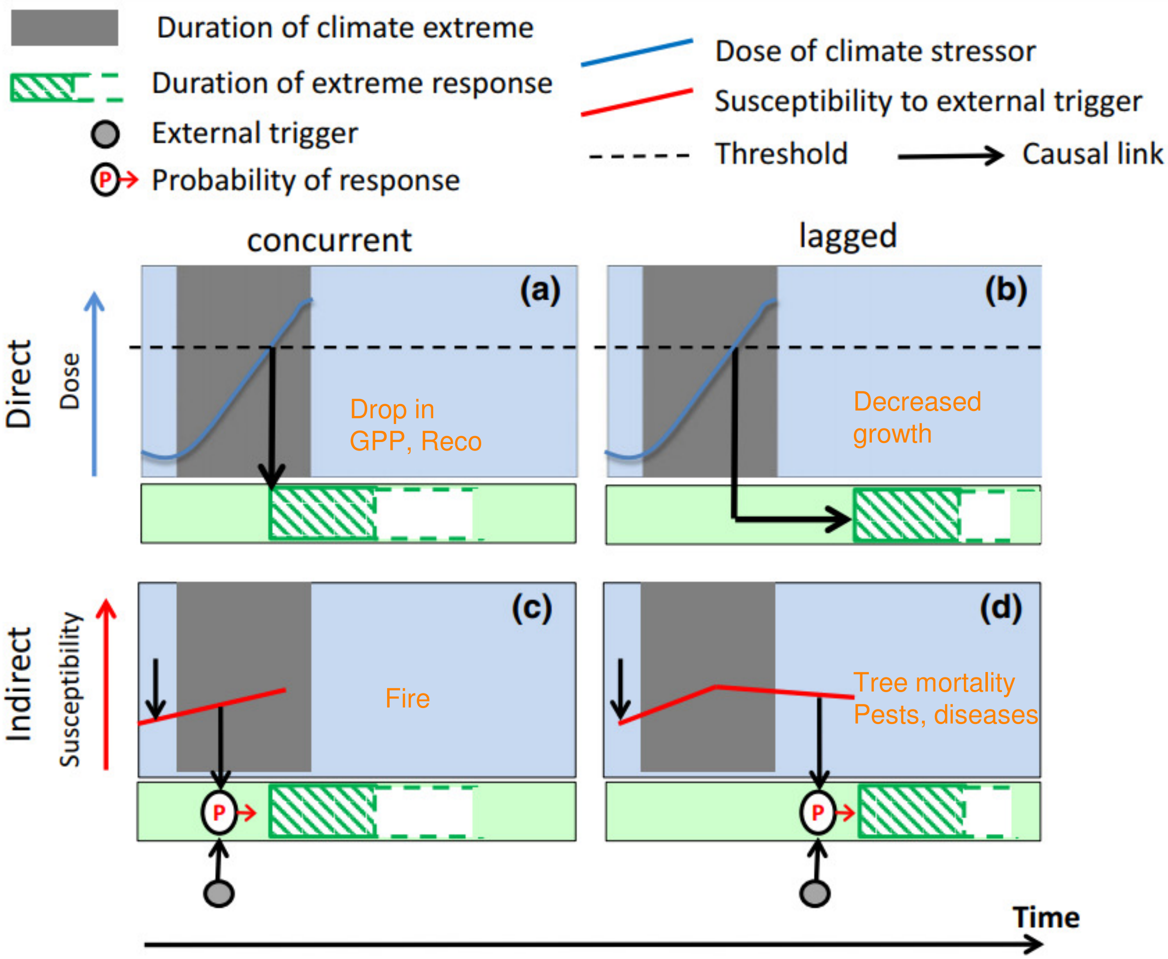
Concurrent and lagged responses: Drought stress



Dose = severity x duration

Ecosystem models bad in representing lagged and indirect responses

parameters and system state = f(history)

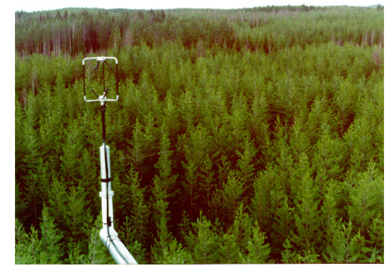
Q1: How to detect lagged and indirect impacts from time series?

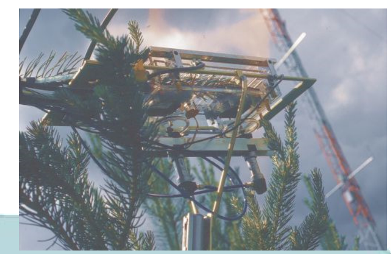
Frank et al. 2015 Global Change Biology

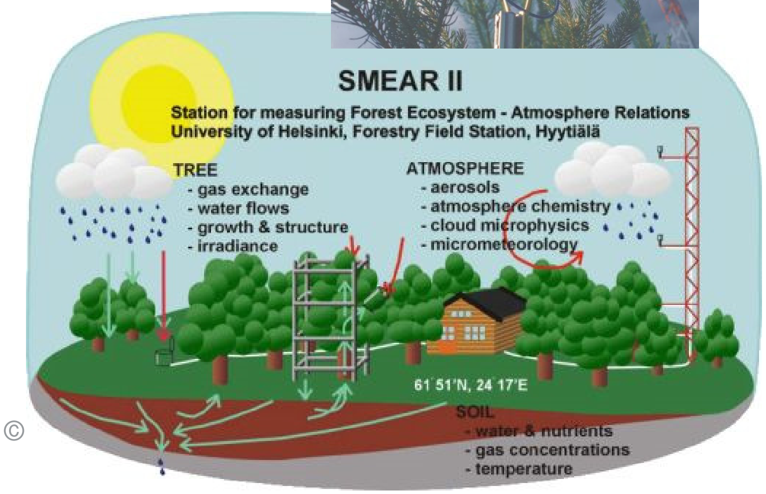
Hyytiälä SMEAR II - site

- In Boreal forest
  - At Juupajoki, North-East from Tampere
  - Scots pine, norway spruce, deciduous
  - Clear-cut + sown in late 1960's
  - Thinning in 2002
- Continuous eddy-covariance flux measurements 1996 →
- Fluxes: NEE, latent heat flux, sensible heat flux, momentum, aerosol deposition, O_3, COS, …
- Environmental variables

- Near-continuous timeseries
  - Gap-filling







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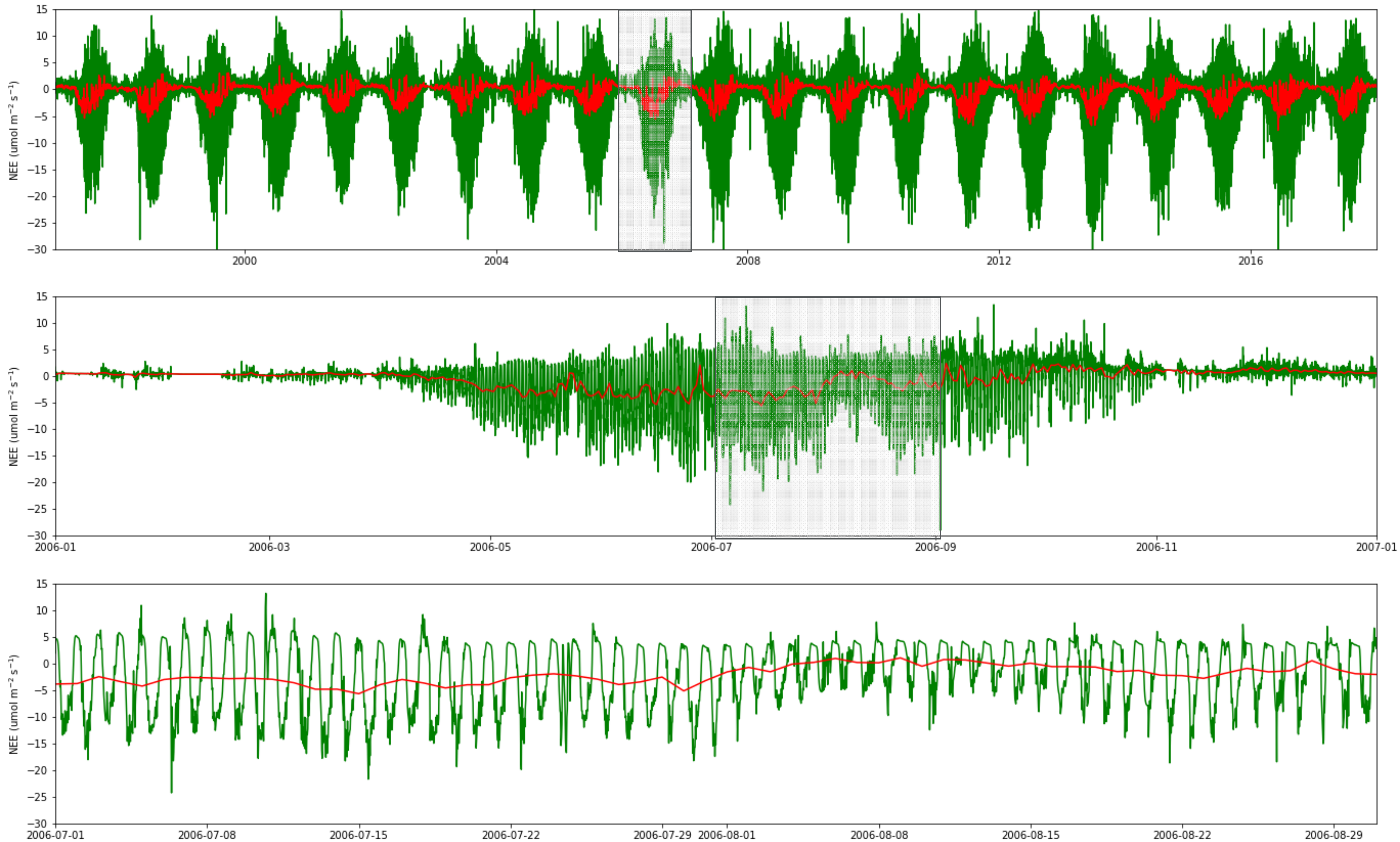
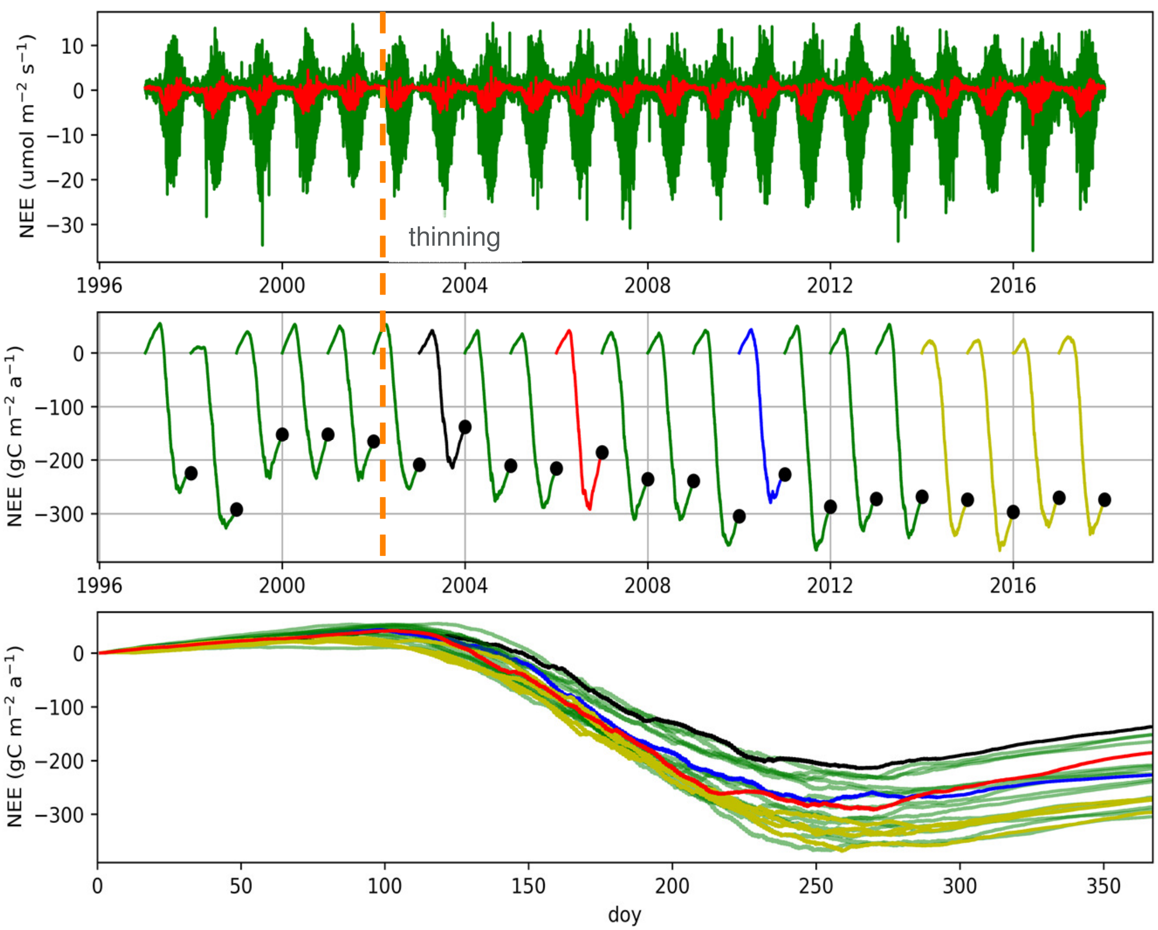


Green = 1/2h
Red = daily mean

Signs:
- net uptake of CO2: photosynthesis > respiration
+ net release of CO2: photosynthesis < respiration

Annual C balance



Q2: How to identify temporal anomalies and concurrent & delayed mechanisms causing them?

C sink increases

~7g C m^{-2} a^{-1}

Q3: How to explain variability and trend in annual C balance?

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Compensatory mechanisms: alternative paths to similar annual C balance?

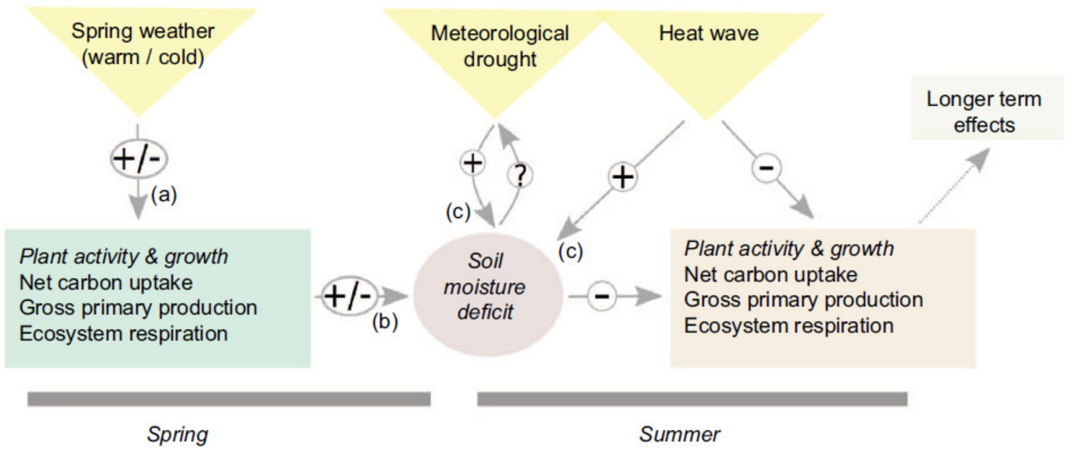


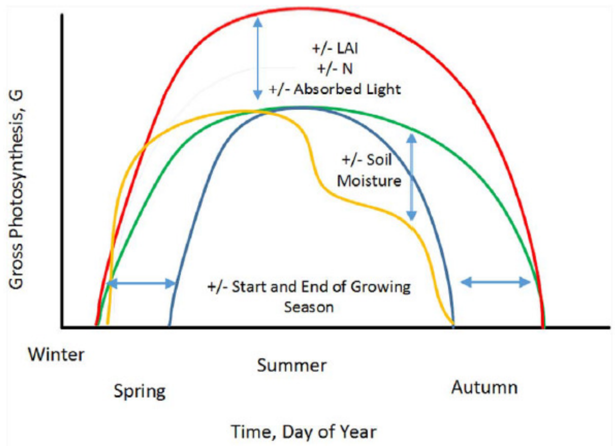
Figure 1. Conceptual illustration of spring-summer interacting carbon cycle effects due to climate extremes. In years affected by summer heat and drought (arrows (*c*)), warm spring conditions could potentially partly compensate for carbon losses in summer due to higher carbon uptake in spring (arrow (*a*), associated with (+)). Conversely, however, warm spring conditions might lead to earlier soil moisture depletion (arrow (*b*), associated with (+)) and thus a carry-over effect from spring to summer carbon cycling. Diagram modified from Sippel *et al* (2016b), CC BY 4.0.

Sippel et al. 2017 Environ. Res. Letters

Multiple factors can explain increasing photosynthesis

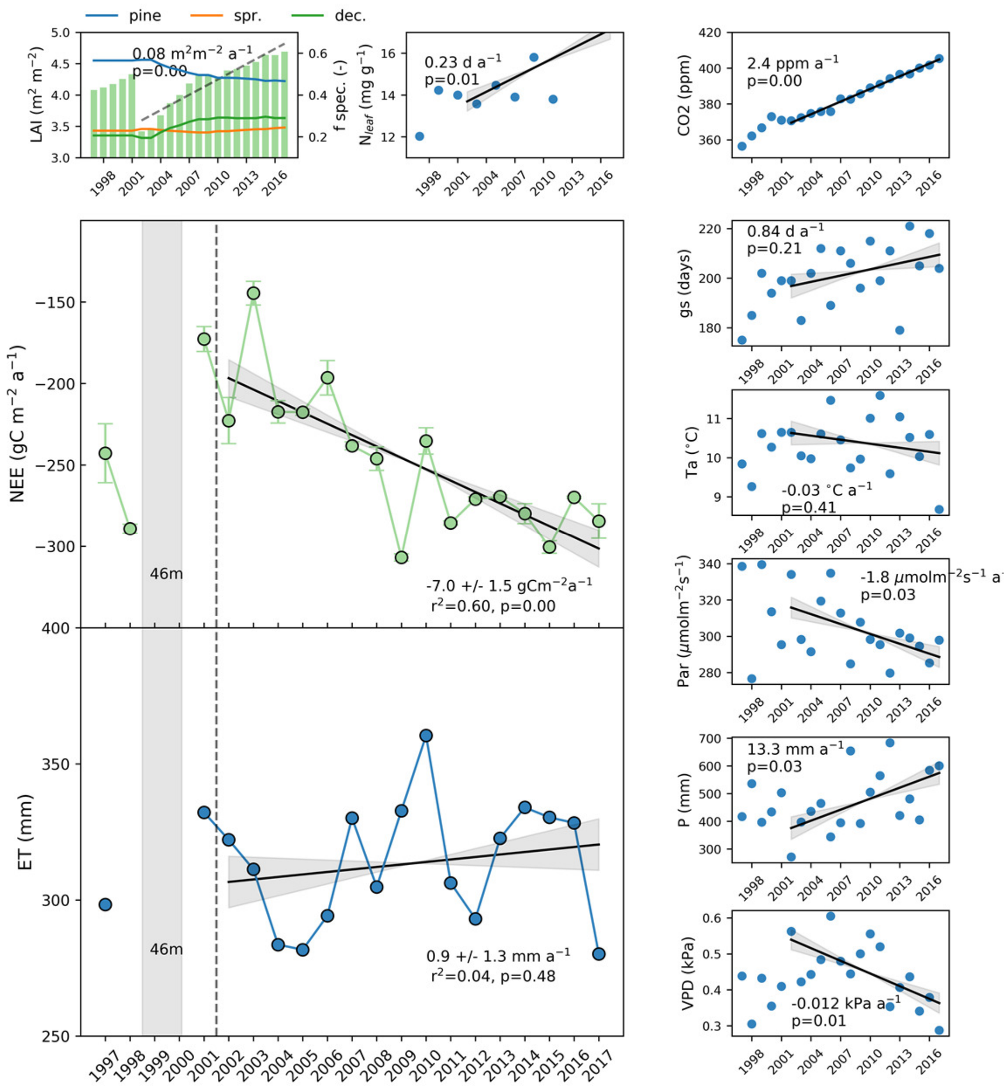
GPP = f(light, CO_2, T, water availability, amount of biomass, …)

- Atmospheric CO_2 increase
  - More food available!
- Increasing leaf nitrogen content
  - Hungrier leaves
- Increasing biomass and LAI
  - More leaves that eat the food
- Increasing diffuse radiation
  - Leaves deeper in forest see food better
- Longer growing seasons (increasing spring temperature)
  - More time to eat breakfast



Baldocchi et al. 2018. Agr. For. Met

All previous are plausible for Hyytiälä!



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Model -scenarios

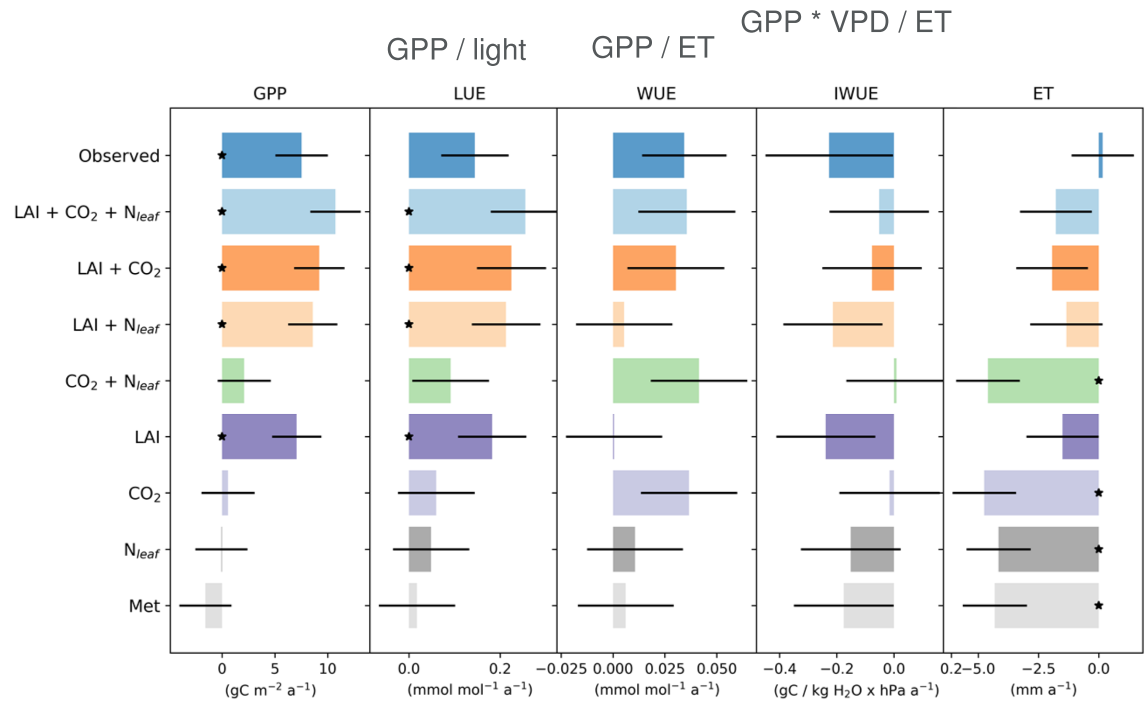
affect model parameters

External inputs X_n change

- ”Factorial design”

- LAI + CO2 + Nleaf + Met
- LAI + CO2 + Met
- LAI + Nleaf + Met
- CO2 + Nleaf + Met
- LAI + Met
- CO2 + Met
- Nleaf + Met
- Met

- Run model for 21 years
- Analyze 2002 – 2017 trend in selected outputs Y_m



Model suggests:
- Effect of changing Met. negligible
- Role of CO_2 and N_{leaf} increase minor
- LAI major factor
- CO_2 necessary to capture increasing WUE

Q4: how to do same ’data-driven’?

FLUXNET

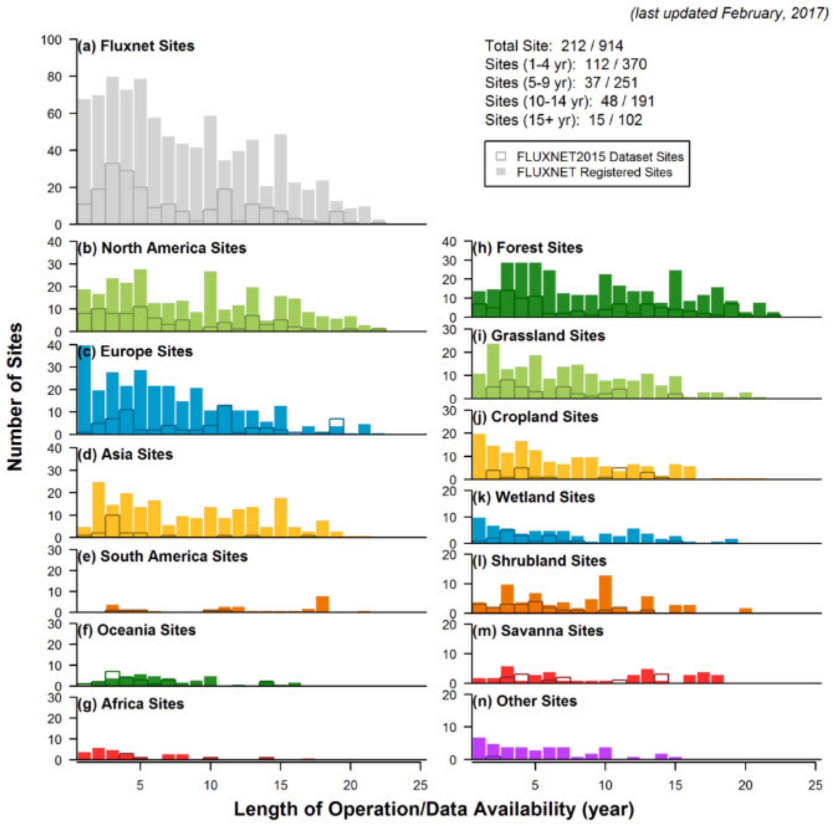
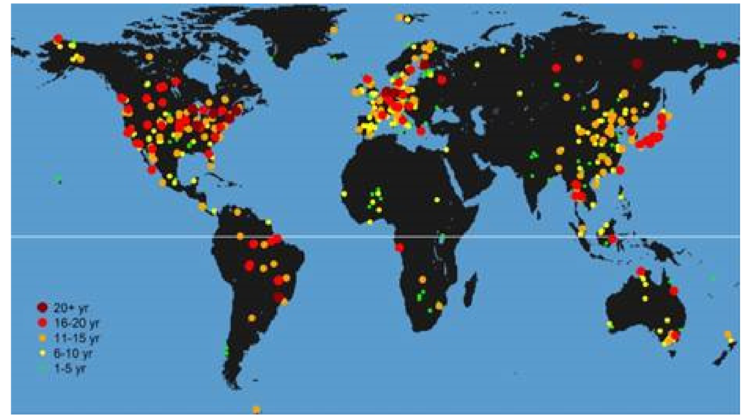


Figure 1. Summary of tower sites that are registered in FLUXNET (closed bars) and included in the FLUXNET2015 Dataset (open bars). "Registered sites" represent sites that have been registered in fluxdata.org, FLUXNET-ORNL, AmeriFlux, ICOS, AsiaFlux, OzFlux, or ChinaFlux. Sites are grouped by regions (b-g) and vegetation classification (h-n) (IGBP: International Geosphere–Biosphere Programme). Forest: ENF+DBF+EBF+MF, Grassland: GRA, Cropland: CRO+CVM, Wetland: WET, Shrubland: OSH+CSH, Savanna: SAV+WSA, Other: BSV+URB+WAT+SNO (last updated in February, 2017)

http://fluxnet.fluxdata.org



- Global network > 1000 sites
- 15+ yr records ~100 sites

- Fluxes at ½ h time resolution
- Environmental variables

- Standardized methods & data format

- Biogeochemistry, micrometeorology, ecology, hydrology, …
- Mechanistic modeling, GCM surface schemes, ground-truth for remote-sensing schemes

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Carbon balance of terrestrial ecosystems

Source

Sink

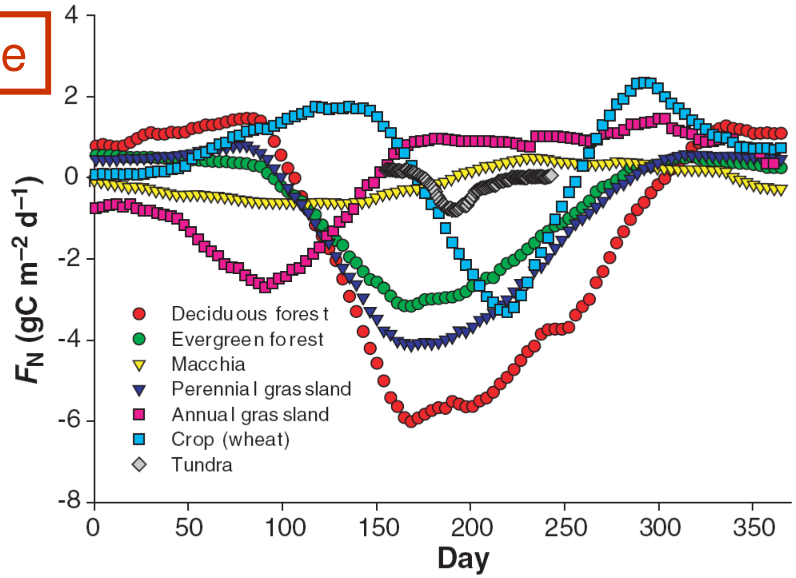

Fig. 2. Seasonal patterns in net ecosystem CO_2 exchange. Adapted from Baldocchi and Valentini (2004).

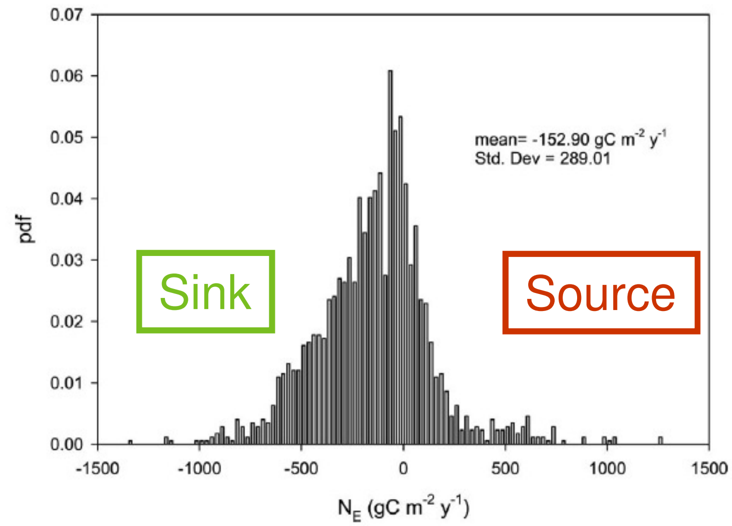

Fig. 1. Histogram of published values of net ecosystem carbon exchange, N_E, derived from annual long studies using the eddy covariance method. The histogram is based on 1781 site years of data. The y axis represents the probability density function, pdf.

Units: 1 g of C m^{-1} d^{-1}
= 10 kg C ha^{-1} d^{-1}

Baldocchi et al. (2018)

Baldocchi (2008)

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Common challenges

1) Environmental variables highly correlated
2) Ecosystem processes non-linear and coupled
   - Concurrent responses
   - Delayed effects (history)
3) Uncertainty
   - random and systematic; noise and calibration drift, change of instruments, gaps
   - nighttime problem; weak turbulence & advection
4) Footprint heterogeneity
   - source area ’seen’ by eddy-covariance changes with wind direction, boundary layer conditions, forest growth, …

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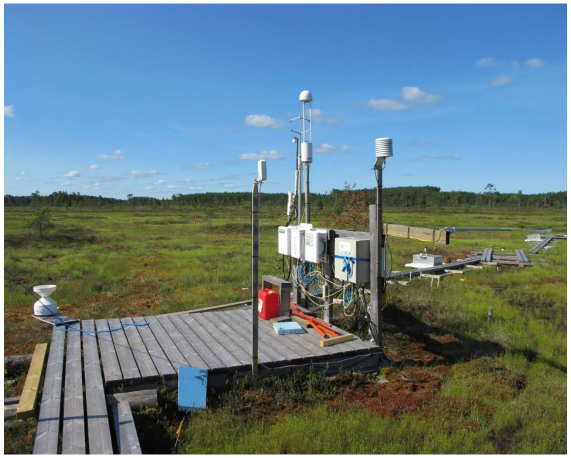
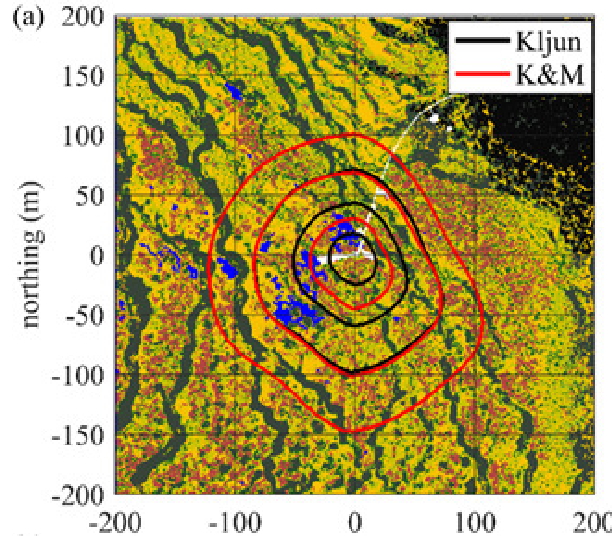
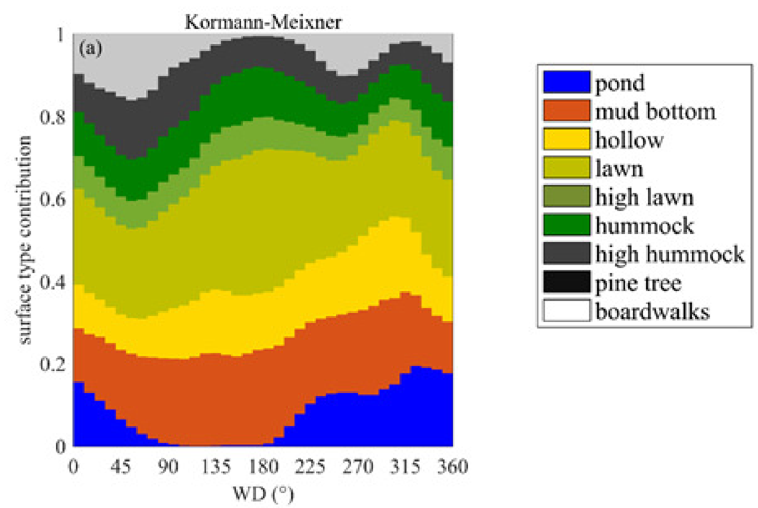
Footprint heterogeneity: Siikaneva-2 'bog'





- Does footprint heterogeneity explain residuals in measured – modeled flux?
- WD-dependency & role of surface layer stability
- High-frequency thermal imaging
- Hyperspectral imaging
- LES with surface-type dependent emission rates



Alekseychik et al. 2019. Six years of eddy-covariance measurements in a heterogeneous Finnish bog (in prep.)

Discussion !

Q1: How to detect lagged and indirect impacts?

Q2: How to identify temporal anomalies and concurrent & delayed mechanisms causing them?

Q3: How to analyze variability and trend in annual C balance?

Q4: Data-driven approach to explain increasing C sink at Hyytiälä?

Literature

Detto et al. 2012. Causality and persistence in ecological systems: A nonparametric spectral Granger causality approach. American Naturalist.

Detto et al. “Multivariate Conditional Granger Causality Analysis for Lagged Response of Soil Respiration in a Temperate Forest.” *Entropy* 15 (2013): 4266-4284.

Papangianopoulou et al., 2017. Non-linear Granger-causality framework to investigate climate-vegetation dynamics. Geosci. Model Dev. 10, 1945-1960.

Papangianopoulou et al., 2017. Vegetation anomalies caused by antecedent precipitation in most of the world. Environ. Res. Lett. 12074016

Krich et al. 2018. Revealing causal dependencies between land-surface fluxes and meteorological variables. Geophys. Res. Abstracts, https://meetingorganizer.copernicus.org/EGU2018/EGU2018-6304.pdf

Alekseychik et al. 2019. Six years of eddy-covariance measurements in a heterogeneous Finnish bog (in prep.)

Baldocchi et al. 2018. Inter-annual variability of net and gross ecosystem carbon fluxes: A review. *Agric. For. Meteorol.*, 249, 520-533.

Baldocchi D.2008. ‘Breathing’of the terrestrial biosphere: lessons learned from a global network of carbon dioxide flux measurement systems. *Australian Journal of Botany*, *56*(1), pp.1-26.

Frank et al. 2015. Effects of climate extremes on the terrestrial carbon cycle: concepts, processes and potential future impacts, *Global Change Biol.* 21, 2861-2880.

Hari P. and Kulmala L. (eds.): Boreal forest and climate change, *Advances in Global Change Research*, Vol. 34, Springer, Dordrecht, 2008.

Sippel et al. 2017. Contrasting and interacting changes in simulated spring and summer carbon cycle extremes in European ecosystems. *Environmental Research Letters*, *12*(7), p.075006.

Launiainen et al. 2016. Do the energy fluxes and surface conductance of boreal coniferous forests in Europe scale with leaf area? *Global Change Biology*, doi: 10.1111/gcb.13497

Launiainen et al. 2015. Coupling boreal forest CO_2, H_2O and energy flows by a vertically structured forest canopy – soil model with separate bryophyte layer, *Ecol. Mod.*, 312, 385–405, doi:10.1016/j.ecolmodel.2015.06.007.

Launiainen 2011. Canopy processes, fluxes and microclimate in a pine forest. *Report Series in Aerosol Science*, 117, 2011. http://urn.fi/URN:ISBN:978-952-5822-32-8

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Thank you!

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