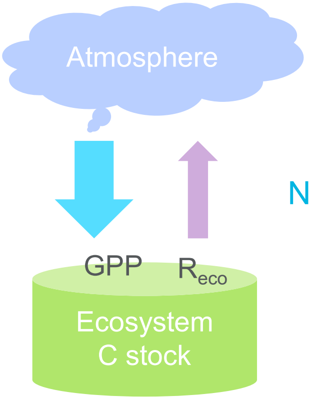
Compensatory mechanisms create an apparent CO2 fertilization effect of photosynthesis at a long-term boreal forest flux site

Samuli Launiainen et al.

Ecosystem carbon stock and carbon balance



NEE = - GPP + R_{eco}

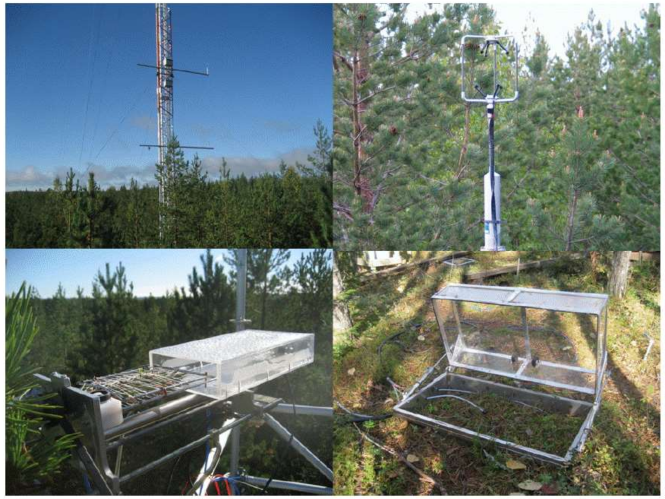


Figure 10: Measurement devices at SMEAR II. Top: Main mast where canopy scale fluxes and concentrations are measured; the 3D wind field is measured by sonic anemometer. Bottom: Chambers to monitor shoot gas exchange and soil CO_2 and H_2O fluxes.

NEE(t) is measured by eddy-covariance

R_{eco}(t) = f(Temperature) inferred based on night-time measurements.

GPP computed as residual GPP(t) = - NEE(t) + R_{eco}(t)

© Natural Resources Institute Finland

Eddy covariance

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

Horizontal homogeneity, stationarity

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

Integrate with depth z

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

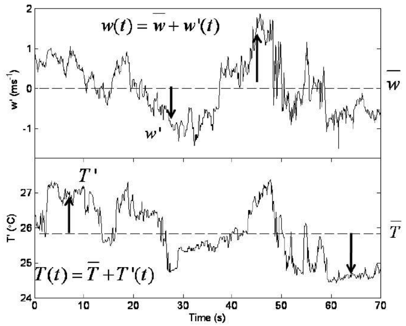


Figure 6: Turbulent time series of vertical wind (w) and temperature (T) measured on a clear sunny summer afternoon by a sonic anemometer at 23.3 m height, abound 8 m above a pine forest. The overbar represents time average and prime the instantaneous turbulent fluctuation around the mean (eq. 7). The 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'.

Launiainen, 2011 Lectio Praecursoria

Measures vertical flux of CO2, water, energy from footprint (source area) upwind

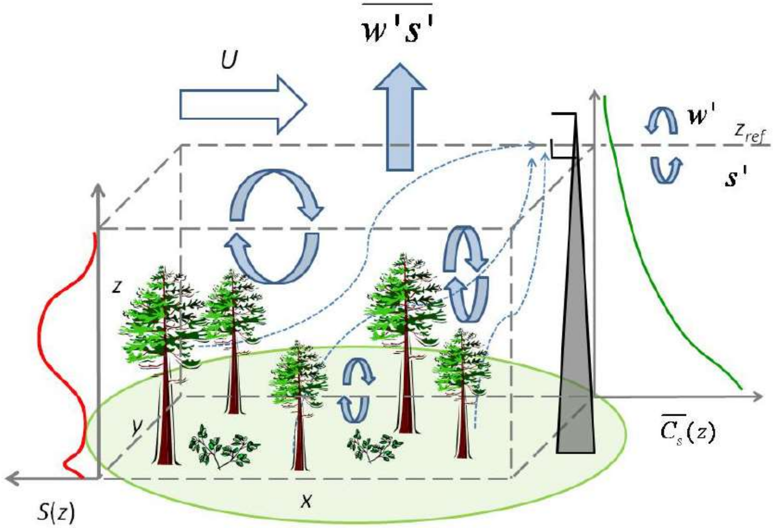
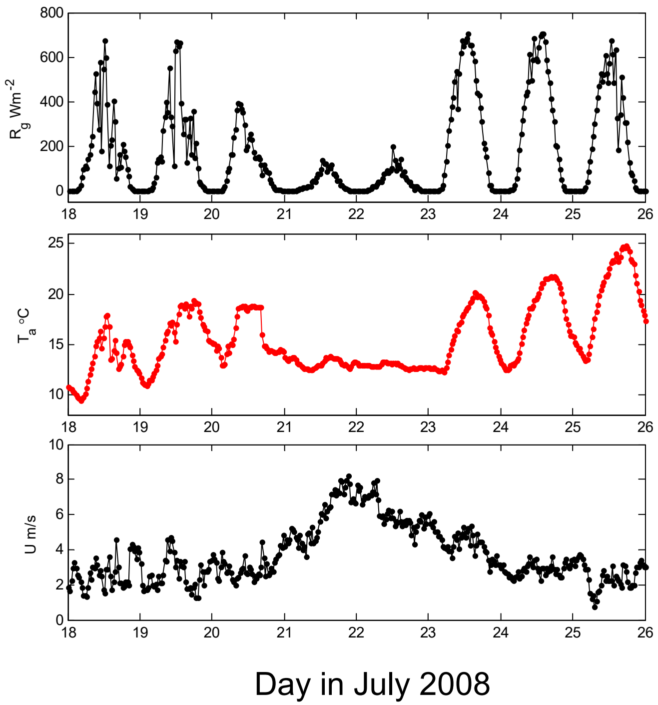
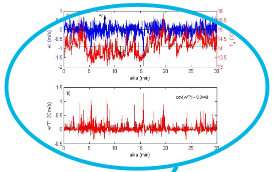


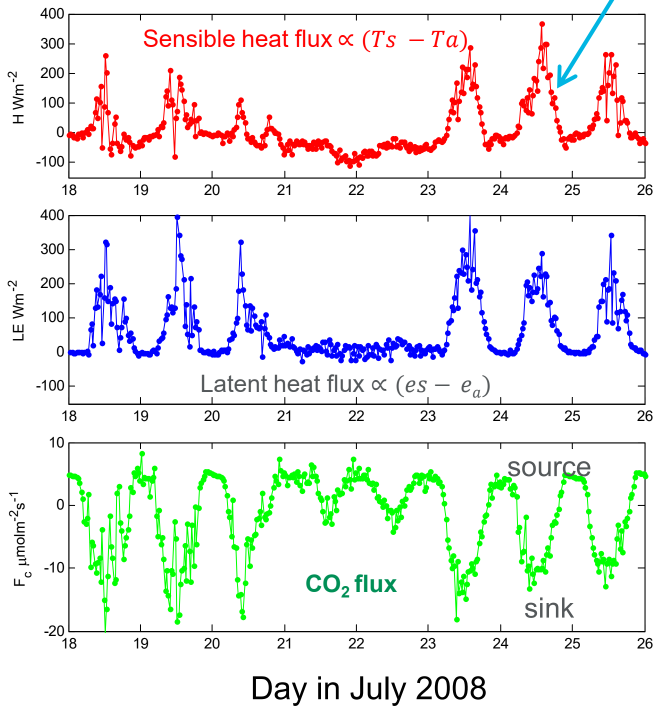
Figure 9: The principle of eddy-covariance is based on mass balance approach. In horizontally homogenous and stationary conditions the turbulent vertical flux at upper edge of the box (z_{ref}) should equal the integral over all sources and sinks, $S(z)$, within the studied volume (eq. 10). Eddies create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

Environmental variables



Ecosystem – atmosphere fluxes

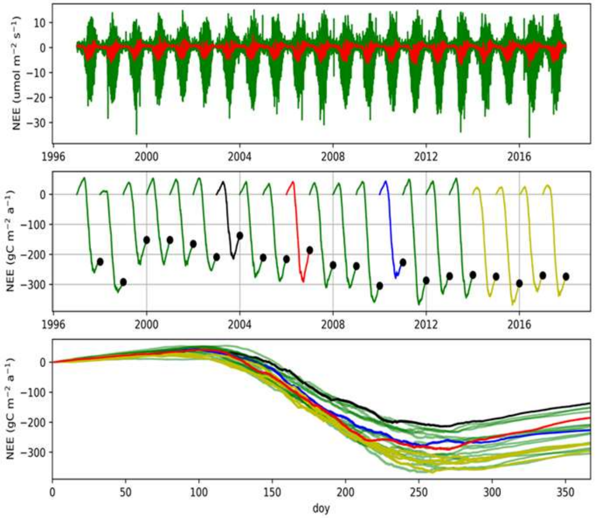




Sign convention:+ net flux to atmosphere

Annual carbon balance = time-integrated NEE

- Numerous pathways to same annual balance
- Processes non-linear; average environmental variables are not relevant to explain inter-annual variability

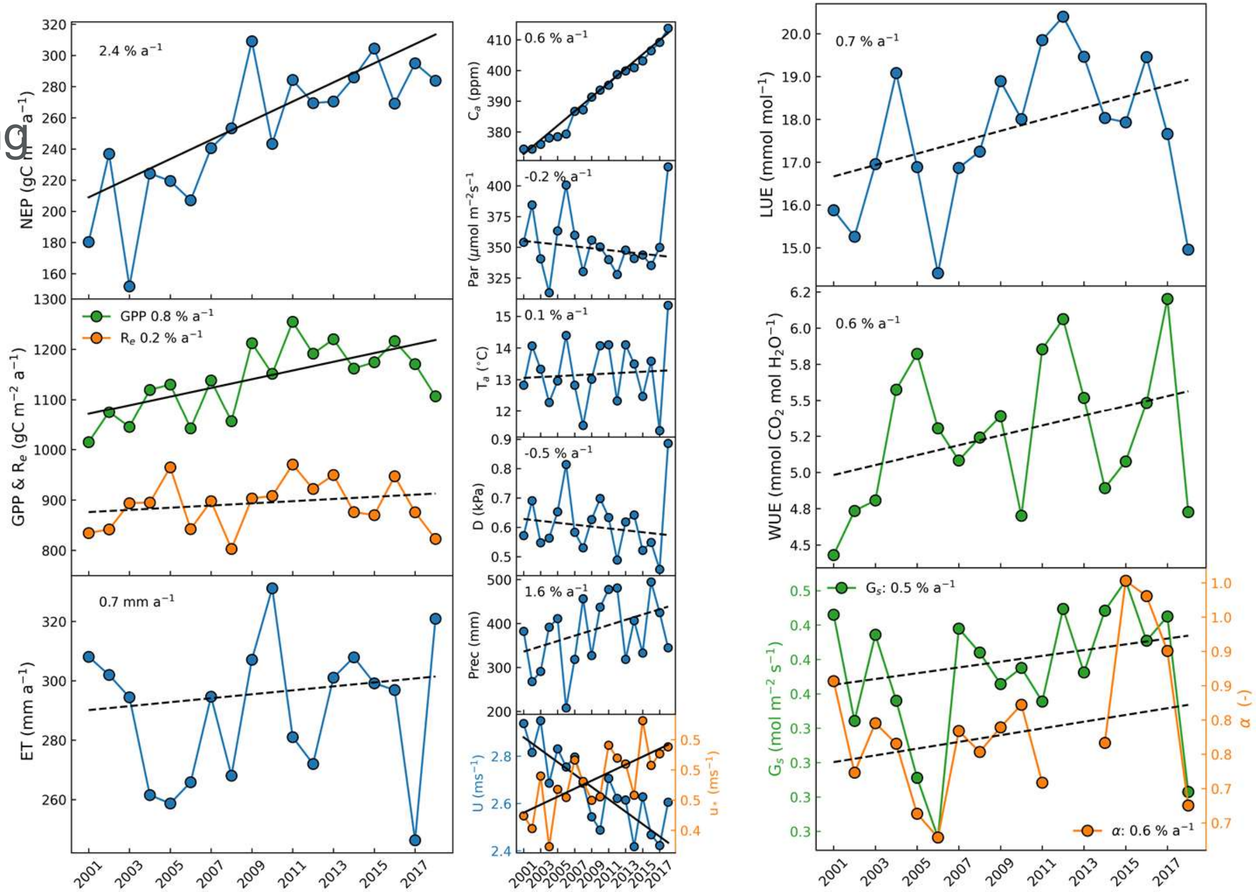


NATURAL RESOURCES INSTITUTE FINLAND

Hyytiälä SMEAR II: long-term trends

Long-term trends

- NEP = - NEE is increasing
- Due to increasing GPP
- No change in ET



Multiple factors can explain increasing GPP

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

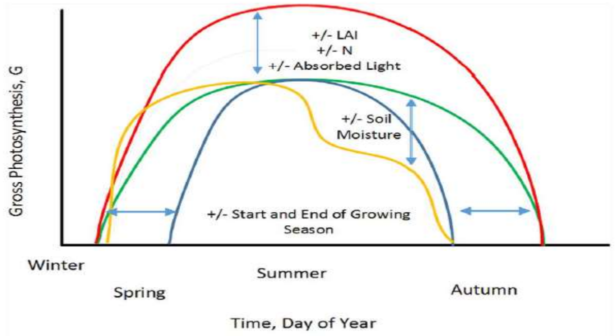
Atmospheric CO2 increase
- More food available

Longer growing seasons
- More time to eat breakfast and supper
- Increasing diffuse radiation
- Leaves deeper in forest see food better

Increasing leaf nitrogen content
- Hungrier leaves ←→ higher photosynthetic capacity

Increasing biomass and LAI
- More leaves that eat the food

Changing footprint
- Stand growth, spatial heterogeneity → measured system changes



Baldocchi et al. 2018. Agr. For. Met

All can occur simultaneously and are correlated

Simple theoretical approach: a big-leaf model

$$\mathrm{GPP} = \mathrm{LAI}\left[\mathrm{c_a}\,\mathrm{g_s}\left(1-\frac{\mathrm{c_i}}{\mathrm{c_a}}\right)\right]. \tag{1}$$

Using a first-order Taylor series expansion, the relative changes in GPP can be expressed and interpreted as

$$\frac{\delta\mathrm{GPP}}{\mathrm{GPP}} = \underbrace{\left[\frac{\delta c_a}{c_a}\right]}_{\text{fertilization}} + \underbrace{\left[\frac{\delta\mathrm{LAI}}{\mathrm{LAI}}\right]}_{\text{structural}} + \underbrace{\left[\frac{\delta g_s}{g_s} + \frac{\delta\,(1-c_i/c_a)}{1-c_i/c_a}\right]}_{\text{physiological}}, \tag{2}$$

$$\frac{\delta\mathrm{NEP}}{\mathrm{NEP}} = (1-\mathrm{cue})\frac{\delta\mathrm{GPP}}{\mathrm{GPP}} + \frac{\delta\mathrm{R_h}}{R_h}. \tag{4}$$

$$ET = 1.6\,g_s\,LAI\,D + E, \tag{5}$$

$$\frac{\delta\mathrm{ET}}{\mathrm{ET}} = \left[\frac{\delta\mathrm{LAI}}{\mathrm{LAI}} + \frac{\delta D}{D} + \frac{\delta g_s}{g_s}\right] + \frac{\delta\mathrm{E}}{\mathrm{E}}$$
$$= \left[\frac{\delta\mathrm{GPP}}{\mathrm{GPP}} + \frac{\delta D}{D} - \frac{\delta c_a}{c_a} - \frac{\delta\,(1-c_i/c_a)}{1-c_i/c_a}\right] + \frac{\delta\mathrm{E}}{\mathrm{E}}, \tag{6}$$

Role of changing Ca, LAI, leaf N., environmental drivers can be explored by model simulations

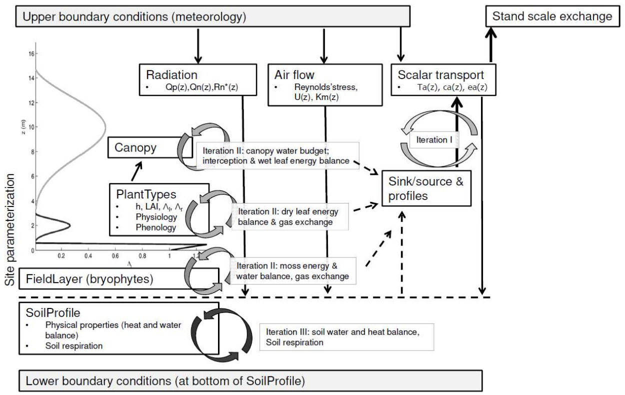
Luke NATURAL RESOURCES INSTITUTE FINLAND

External forcings

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

pyAPES

Processes ~ functions
System components = sub-models
Parameters ~ properties; depend on current conditions and/or history
States ~ model state variables; depend on history



Fluxes between system and the environment

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

GPP, ET,
LUE = GPP/Par
WUE = GPP/ET
IWUE = GPP / Gc

Launiainen et al. 2015. Ecol. Mod; 2016 Global Change Biol.
Leppä et al., 2020. Agric. For. Met

NATURAL RESOURCES INSTITUTE FINLAND

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

GPP / light

GPP / ET

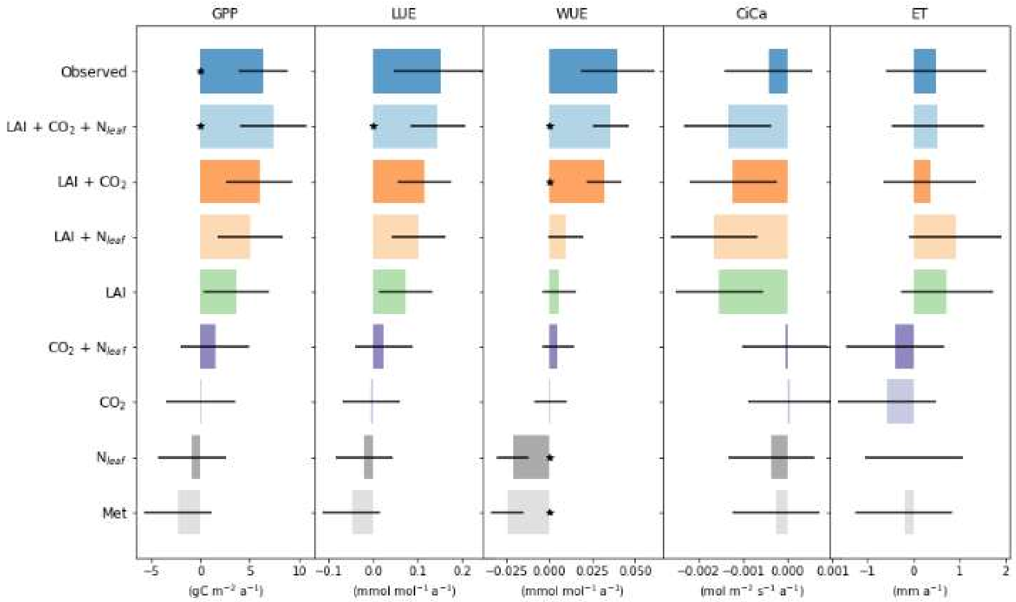


Figure 5: Observed and modeled trends (2001 - 2018, period of consistent measurement and data-processing) for the May-Sept period. Trends are evaluated as slope of linear least square fit and asterix marks significance at $p<0.05$.

Interpreting the results:

$$\mathrm{GPP} = \mathrm{LAI}\left[c_a\, g_s \left(1 - \frac{c_i}{c_a}\right)\right]. \tag{1}$$

Using a first-order Taylor series expansion, the relative changes in GPP can be expressed and interpreted as

$$\overset{+}{\frac{\delta \mathrm{GPP}}{\mathrm{GPP}}} = \underbrace{\overset{+}{\left[\frac{\delta c_a}{c_a}\right]}}_{\text{fertilization}} + \underbrace{\overset{+}{\left[\frac{\delta \mathrm{LAI}}{\mathrm{LAI}}\right]}}_{\text{structural}} + \underbrace{\left[\overset{-}{\frac{\delta g_s}{g_s}} + \overset{+/-}{\frac{\delta\left(1 - c_i/c_a\right)}{1 - c_i/c_a}}\right]}_{\text{physiological}}, \tag{2}$$

$$\frac{\delta \mathrm{NEP}}{\mathrm{NEP}} = (1 - \mathrm{cue})\frac{\delta \mathrm{GPP}}{\mathrm{GPP}} + \frac{\delta R_h}{R_h}. \tag{4}$$

$$ET = 1.6\, g_s\, LAI\, D + E, \tag{5}$$

$$\begin{aligned} \overset{+/-}{\frac{\delta \mathrm{ET}}{\mathrm{ET}}} &= \left[\overset{+}{\frac{\delta \mathrm{LAI}}{\mathrm{LAI}}} + \overset{-}{\frac{\delta D}{D}} + \overset{-}{\frac{\delta g_s}{g_s}}\right] + \overset{-}{\frac{\delta \mathrm{E}}{\mathrm{E}}} \\ &= \left[\frac{\delta \mathrm{GPP}}{\mathrm{GPP}} + \frac{\delta D}{D} - \frac{\delta c_a}{c_a} - \frac{\delta\left(1 - c_i/c_a\right)}{1 - c_i/c_a}\right] + \frac{\delta \mathrm{E}}{\mathrm{E}}, \end{aligned} \tag{6}$$

Compensatory effect cancel this term and we get apparent dependency on CO2

NATURAL RESOURCES INSTITUTE FINLAND

To conclude:

- Increasing carbon sink mainly due to increasing LAI
- CO_2 can explain ~1/3 of total trend. But its rise is seen in water use characteristics (WUE)
- Respiration changes in line with GPP increase and litterfall (LAI) increase
- NEP trend and trend in annual biomass growth ~comparable

- Potential increase in leaf N has minor effect.
- No significant changes in growing season length

- Trends are weak compared to inter-annual variability
- Long-term flux data is prone to errors

- The conclusion is trivial but the analysis is not

NATURAL RESOURCES
INSTITUTE FINLAND