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Estimation of Carbon Cycle Parameters in JULES

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Abstract/Summary

- We are improving the terrestrial carbon cycle parameters in JULES by tuning them so we can simulate flux tower measurements.
- The tuning method is variational data assimilation.
- The usual formulation of Var is not applicable.
- A different weighting of prior and observation terms is needed.

Contents

This presentation covers the following areas

- Data assimilation: states or parameters?
- Data assimilation: sequential or variational?
- Var: the cost function.
- Var for parameter estimation.
- Weighting for the correlated problem.
- Results.
- What next?
- Q and A.

Data assimilation: states or parameters?

Data assimilation: states or parameters?

- The state of a system is the set of relevant or interesting evolving variables. E.g.:
  - the CO_2 concentration field in the atmosphere;
  - the salinity field in the ocean;
  - the velocity field in either;
  - the moisture content in soil layers.
- Parameters are the fixed numbers in a model, that control the state. E.g.:
  - k_{sat} in soil;
  - q_{10} in soil or leaves.

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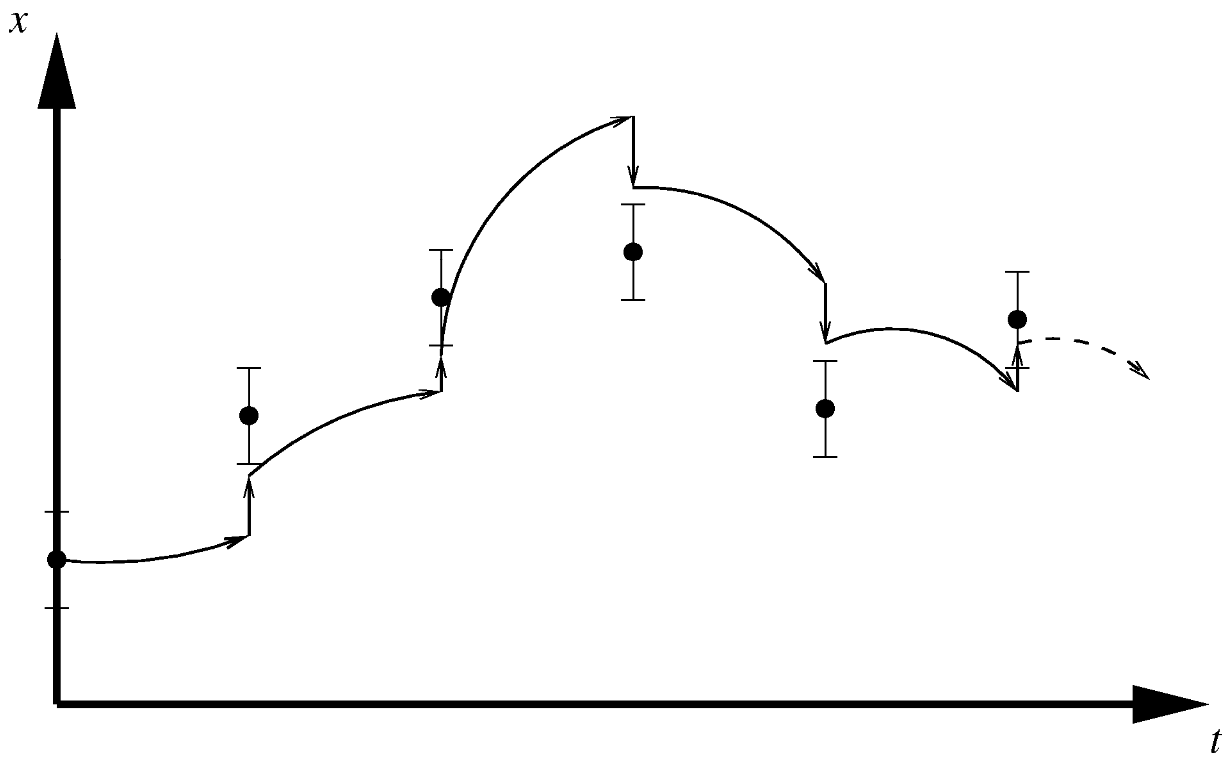
Data assimilation: sequential or variational?

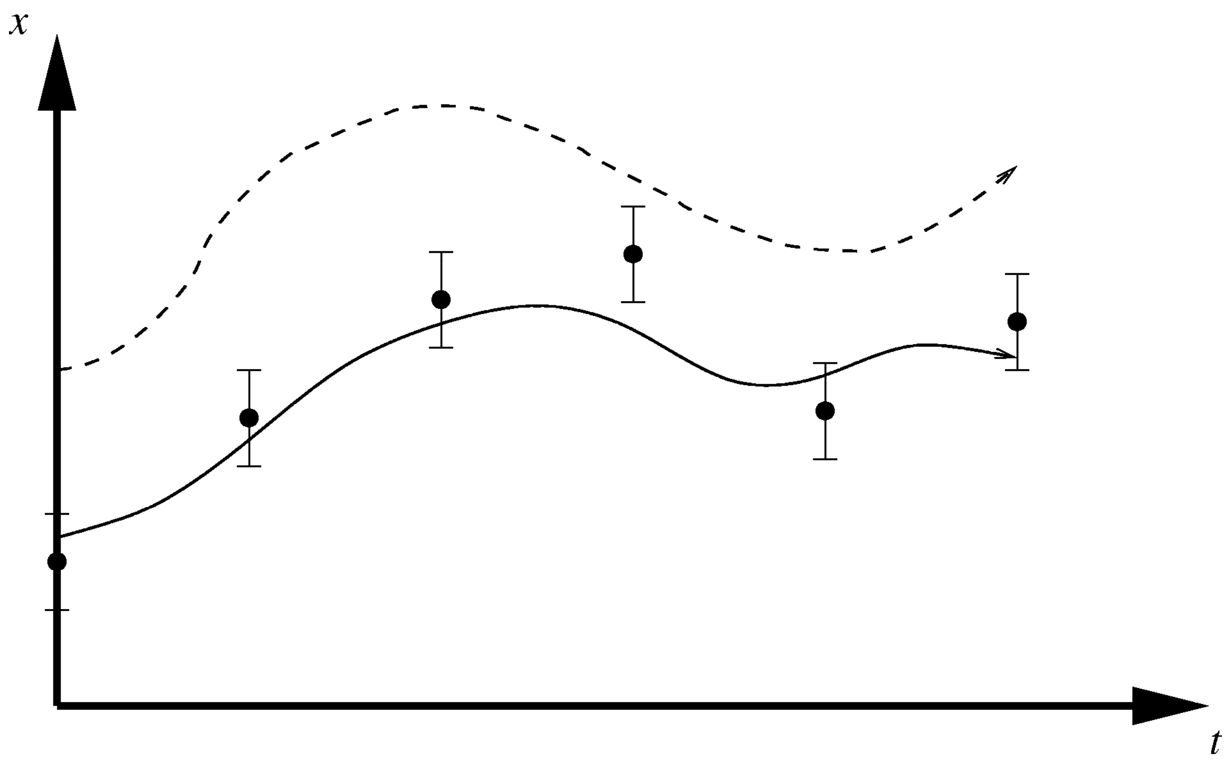
Data assimilation: sequential or variational?

- Sequential, e.g. the Kalman filter.



Data assimilation: sequential or variational?

- Variational, e.g. 4D-Var.



Data assimilation: sequential or variational?

- State vectors:
  - Sequential DA naturally accommodates model error;
  - Sequential DA does not naturally accommodate nonlinearity.
  - Var does not naturally accommodate model error;
  - Var naturally accommodates nonlinearity.
- Parameters:
  - Parameters are fixed, but sequential DA allows them to change;
  - Parameter-Var has fixed parameters;
  - JULES is more suited to variational parameter estimation than sequential estimation.

Data assimilation: sequential or variational?

For parameter estimation in JULES, Var beats sequential

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Var: the cost function.

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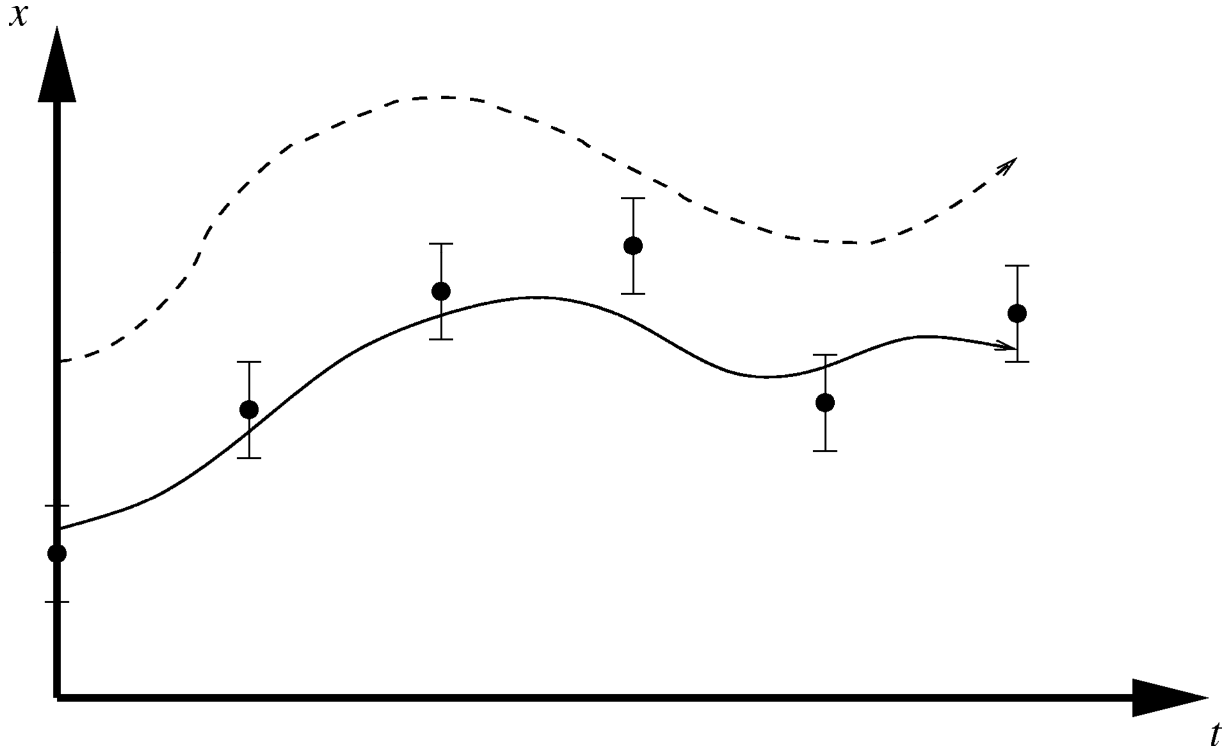

$$J(\mathbf{x}_0) = \frac{1}{2}(\mathbf{x}_0 - \mathbf{x}_b)^T \mathbf{B}^{-1} (\mathbf{x}_0 - \mathbf{x}_b) + \frac{1}{2} \sum_i [\mathbf{y}_i - H(\mathbf{x}_i)]^T \mathbf{R}^{-1} [\mathbf{y}_i - H(\mathbf{x}_i)]$$

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Var for parameter estimation.

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$$J(\mathbf{x}_0) = \frac{1}{2}(\mathbf{x}_0 - \mathbf{x}_b)^T \mathbf{B}^{-1}(\mathbf{x}_0 - \mathbf{x}_b) + \frac{1}{2}\sum_i [\mathbf{y}_i - H(\mathbf{x}_i)]^T \mathbf{R}^{-1}[\mathbf{y}_i - H(\mathbf{x}_i)]$$

$$J(p) = \frac{1}{2}(p - p_b)^T \mathbf{B}^{-1}(p - p_b) + \frac{1}{2}\sum_i [\mathbf{y}_i - H(\mathbf{x}_i)]^T \mathbf{R}^{-1}[\mathbf{y}_i - H(\mathbf{x}_i)]$$

Var for parameter estimation.

- Q. Can we really do this?
- A1. State estimation theory [Jazwinski (1970)] can be manipulated to give a (nearly) identical parameter estimation theory.
- A2. "It just works", i.e. it is rational even if it is not optimal.
- A3. Equivalent least-squares problem.

$$J(p) = \frac{1}{2}(p - p_b)^T \mathbf{B}^{-1}(p - p_b) + \frac{1}{2}\sum_i [\mathbf{y}_i - H(\mathbf{x}_i)]^T \mathbf{R}^{-1}[\mathbf{y}_i - H(\mathbf{x}_i)]$$

A. Jazwinski, "Stochastic Processes and Filtering Theory" Chapter 5 (1970)

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Parameter estimation for JULES.

Parameter estimation for JULES

- We want to optimise the terrestrial carbon cycle.
- Q. Which set of parameters do we work with?
- A1. Start with a set already studied [Booth (2009)];
- A2. Choose a few more;
- A3. Sensitivity analysis to find which subset had a strong effect on annual carbon pools and the timing and amplitude of seasonality.

[B. Booth et al., *Increased importance of terrestrial carbon cycle feedbacks under global warming.* Submitted to Nature (2009).]

Parameter estimation for JULES

T_{low} and T_{upp}	Maximum and minimum temperature constraints on photosynthesis. These were covaried. [°C]
dQ_{crit}	Critical humidity deficit for photosynthesis. [kg water / kg air]
f_0	Controller of stomatal carbon dioxide concentration. [unitless]
LAI_{min}	Minimum leaf area for vegetation areal expansion. [unitless]
n_{l0}	Top leaf nitrogen concentration . [kg N / kg C]
$q_{10,leaf}$	Base for leaves in q_{10} model of respiration. [unitless]
$q_{10,soil}$	Base for soil in q_{10} model of respiration. [unitless]
α	Soil albedo. [unitless]
g_{grow}	Rate of leaf growth. [/360 days]
g_{root}	Turnover rate for root biomass. [/360 days]
g_{wood}	Turnover rate for woody biomass. [/360 days]

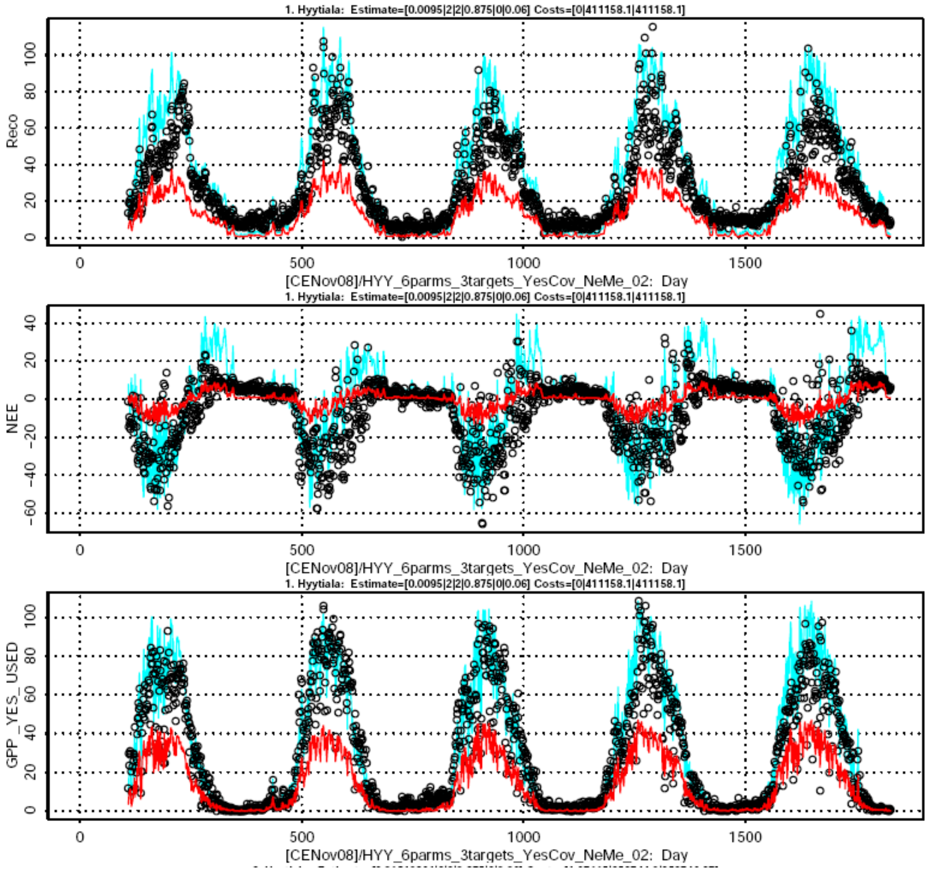
Parameter estimation for JULES

$$J(p) = \frac{1}{2}(p - p_b)^T \mathbf{B}^{-1}(p - p_b) + \frac{1}{2}\sum_i [\mathbf{y}_i - H(\mathbf{x}_i)]^T \mathbf{R}^{-1}[\mathbf{y}_i - H(\mathbf{x}_i)]$$

- **p**=(T_{low}, dQ_{crit}, f_0, n_{l0}, $q_{10.leaf}$, $q_{10.soil}$)
- Find **p** that minimises J(**p**) by the Nelder-Mead method over the 6-dimensional parameter space.
- Target functions: daily R_{eco}, GPP and NEE over as many years as are available.
- (Note: NEE = -NEP)

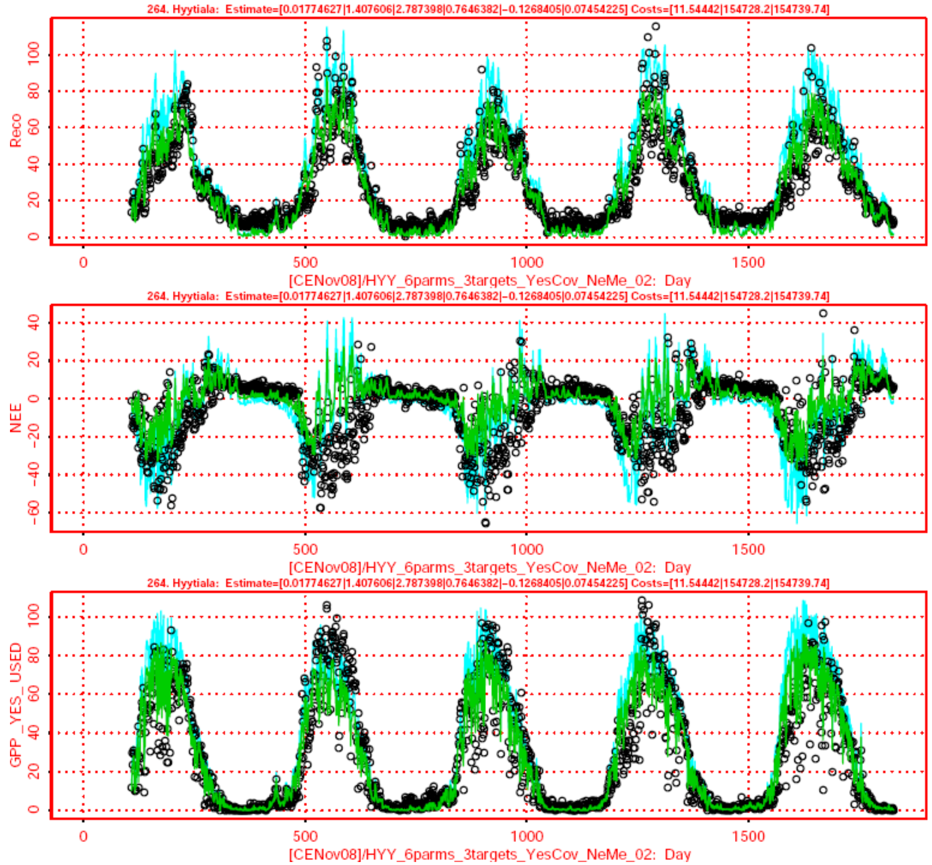
Parameter estimation for JULES

- Hyytiala: “standard” parameters



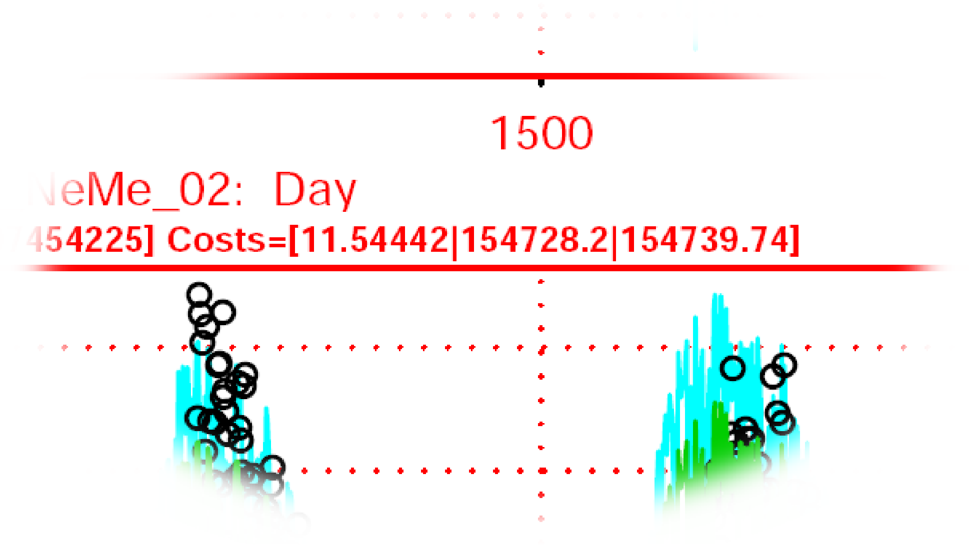
Parameter estimation for JULES

- Hyytiala: “best” parameters



Parameter estimation for JULES

- Hyytiala: "best" parameters …but …



- … the cost is completely dominated by the observations.

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Weighting for the correlated problem.

Weighting for the correlated problem.

- Var derivation assumes the system is 1st-order Markov: $\mathbf{x}_{k+1} = f(\mathbf{x}_k) + \mathbf{e}_k$.
- OK for NWP and other autonomous systems.
- Not correct for systems driven by serially-correlated phenomena (e.g. the land surface is driven by weather and radiation).
- Correlated inputs → correlated outputs, containing less information.
- Therefore we should give less weight to observation terms.
- But how much?

Weighting for the correlated problem.

- Numerical experiment: weight prior and obs terms by chosen factors:

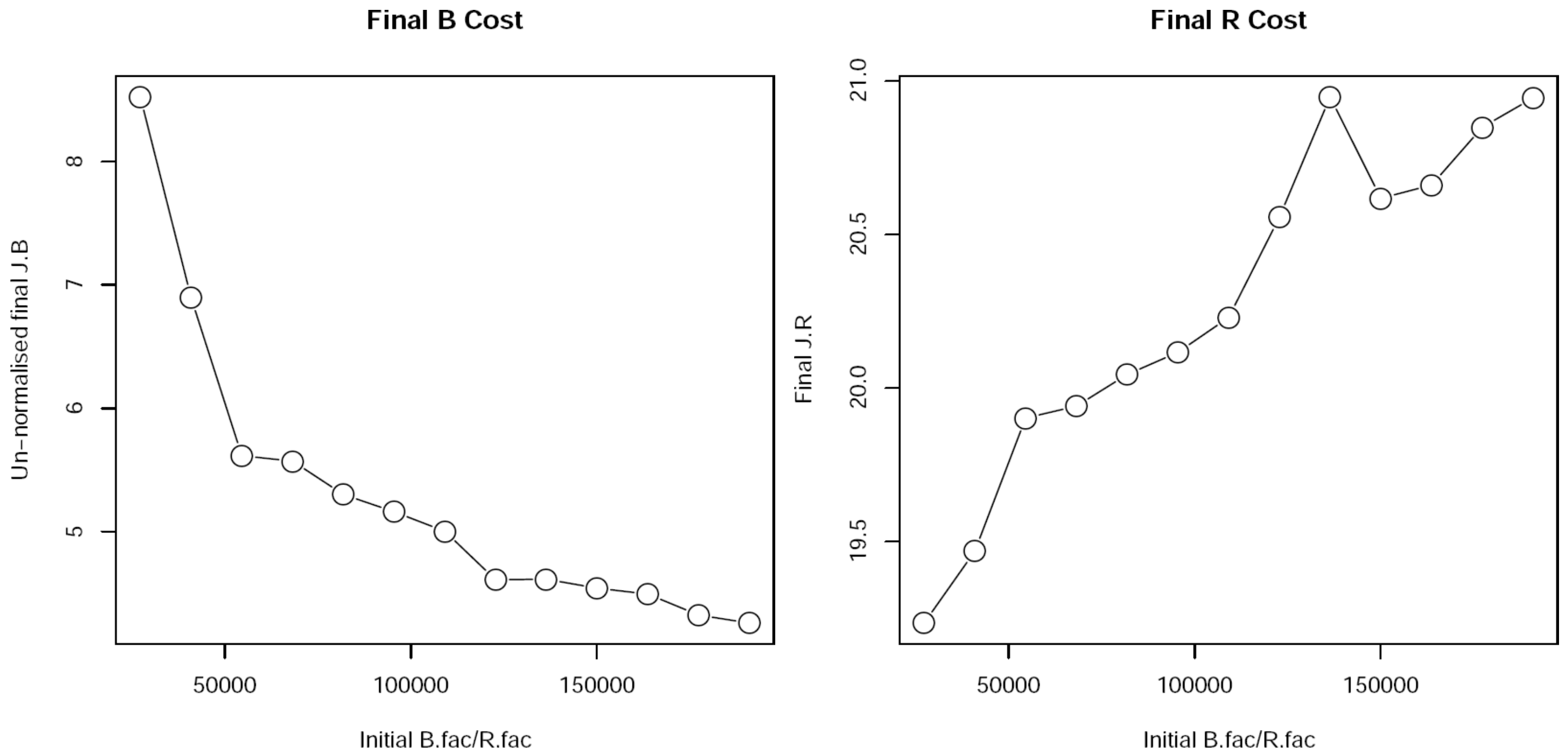
Multiply by B.fac — Multiply by R.fac

$$J(p) = \boxed{\frac{1}{2}(p - p_b)^T \mathbf{B}^{-1}(p - p_b)} + \boxed{\frac{1}{2}\sum_i [\mathbf{y}_i - H(\mathbf{x}_i)]^T \mathbf{R}^{-1}[\mathbf{y}_i - H(\mathbf{x}_i)]}$$

- R.fac is small.
- Only the ratio is important.

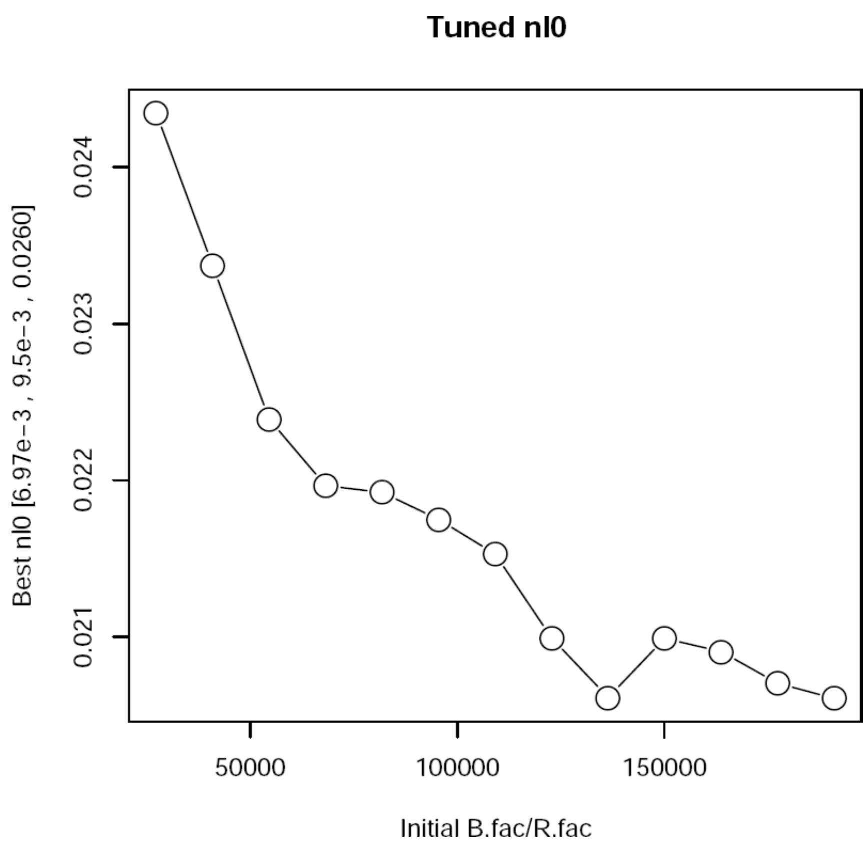
Weighting for the correlated problem.

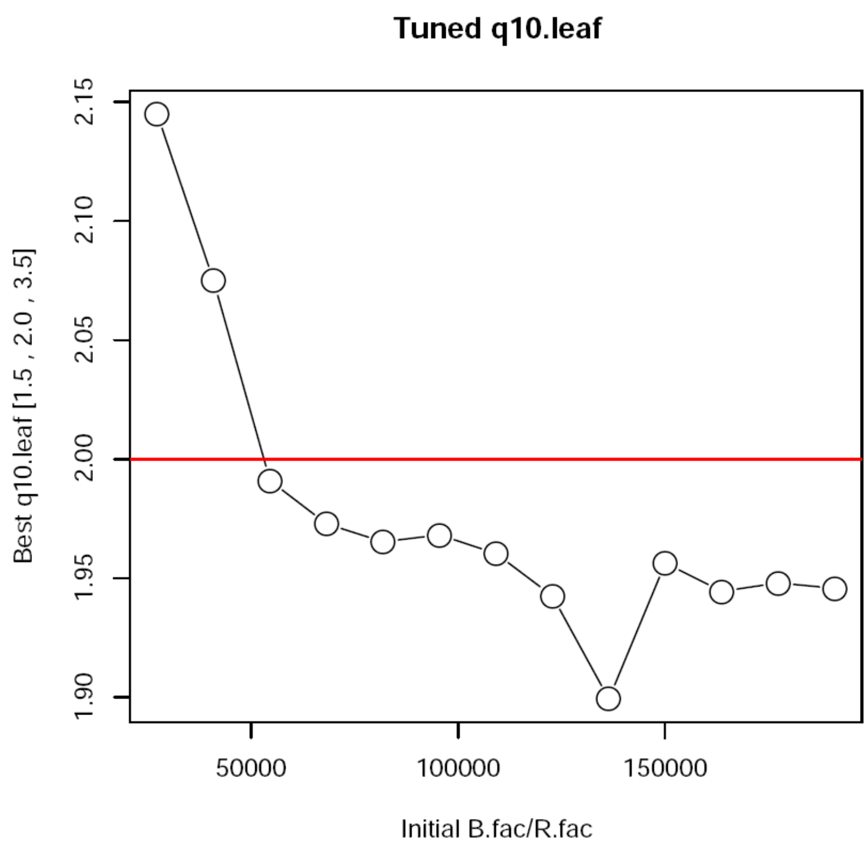
- What happens when we vary the weights?



Weighting for the correlated problem.

- What happens when we vary the weights?





Weighting for the correlated problem.

- Changes in the relative weights cause changes in the results (of course!).
- The changes are systematic (good!)
- What are the best weights? (Difficult problem!)

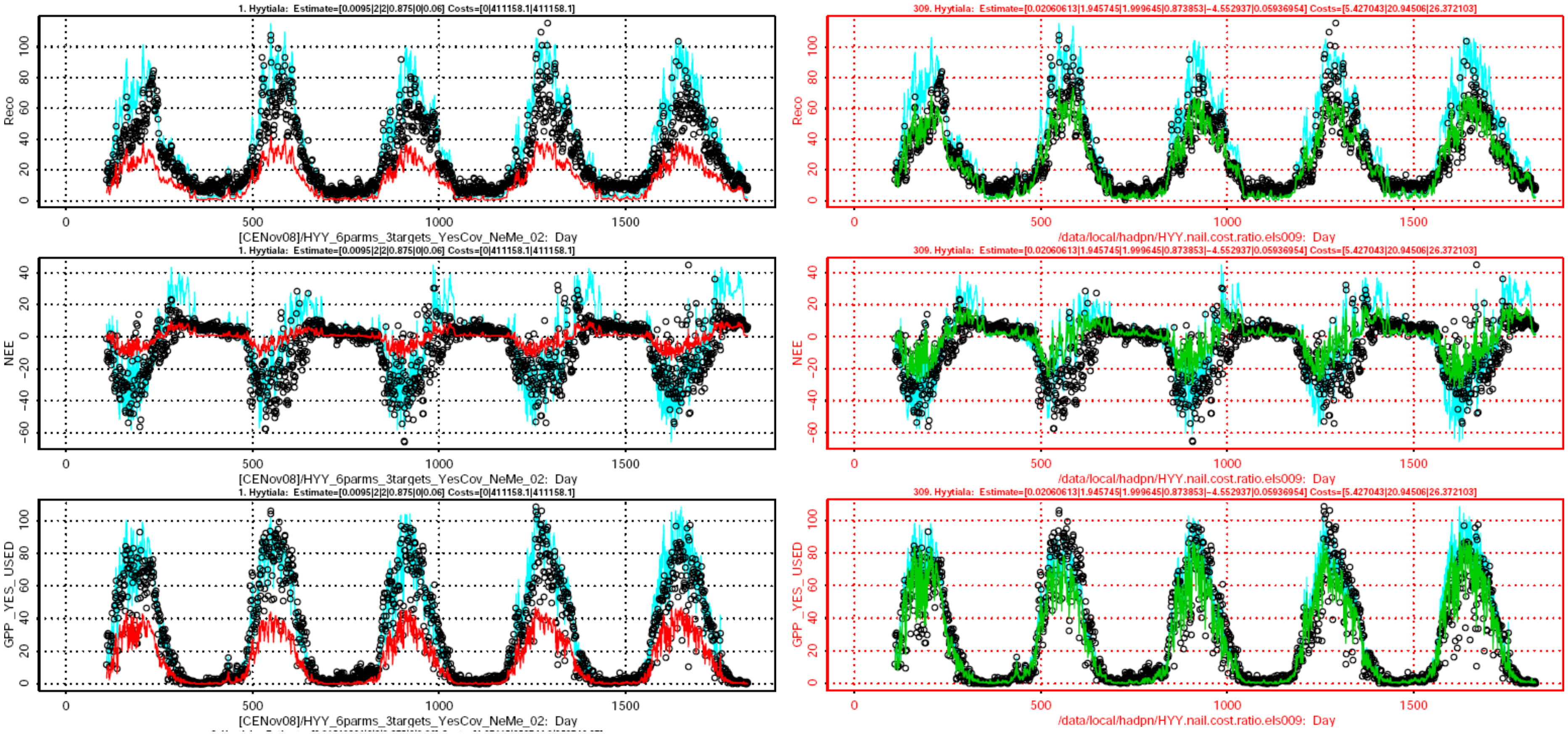
Weighting for the correlated problem.

- Michalak et al., *Maximum likelihood estimation of covariance parameters for Bayesian atmospheric trace gas surface flux inversions*. JGR **110**, D24107 (2005).
- NWP experience of correlated obs errors.
- Least-squares parameter estimation for time series.

Results.

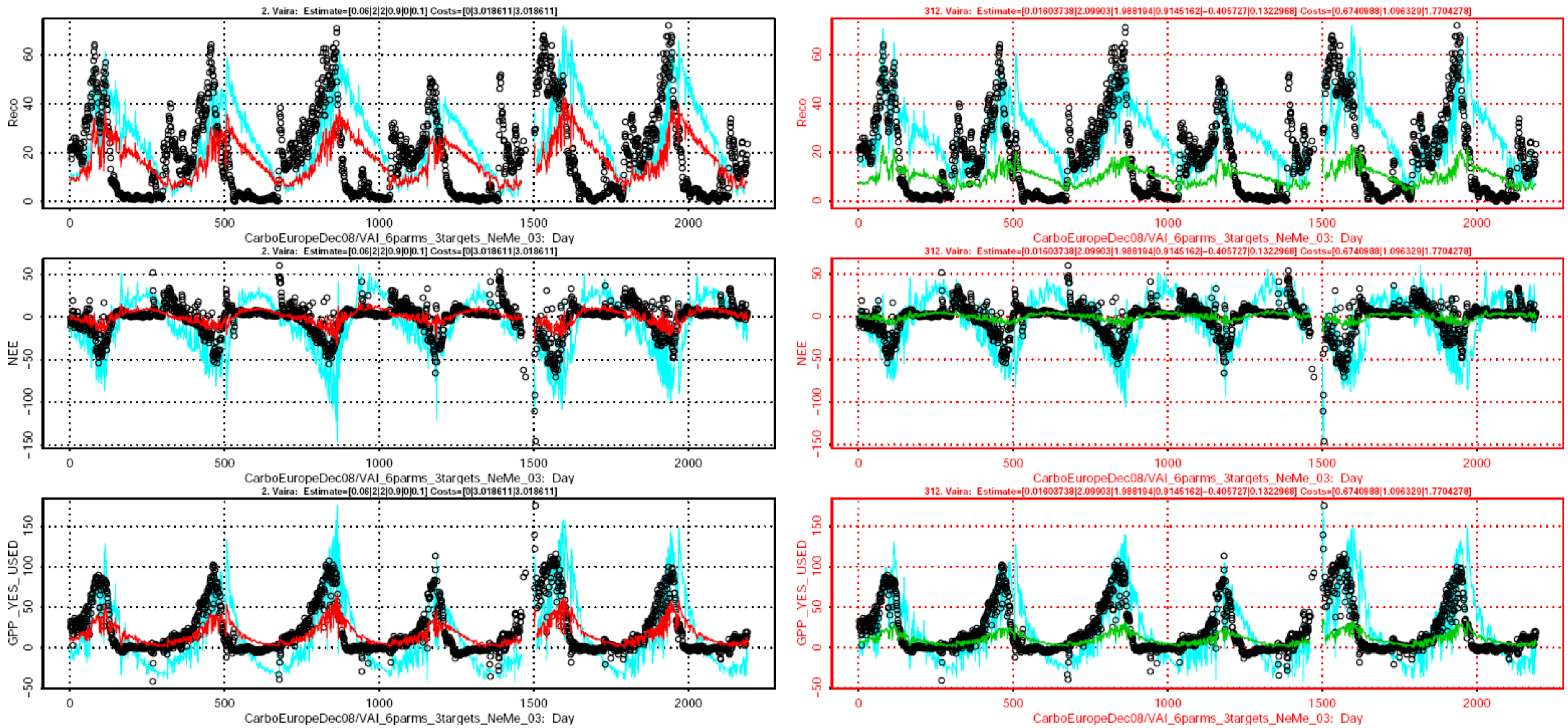
Results

- Hyytiala, Finland: NL forest



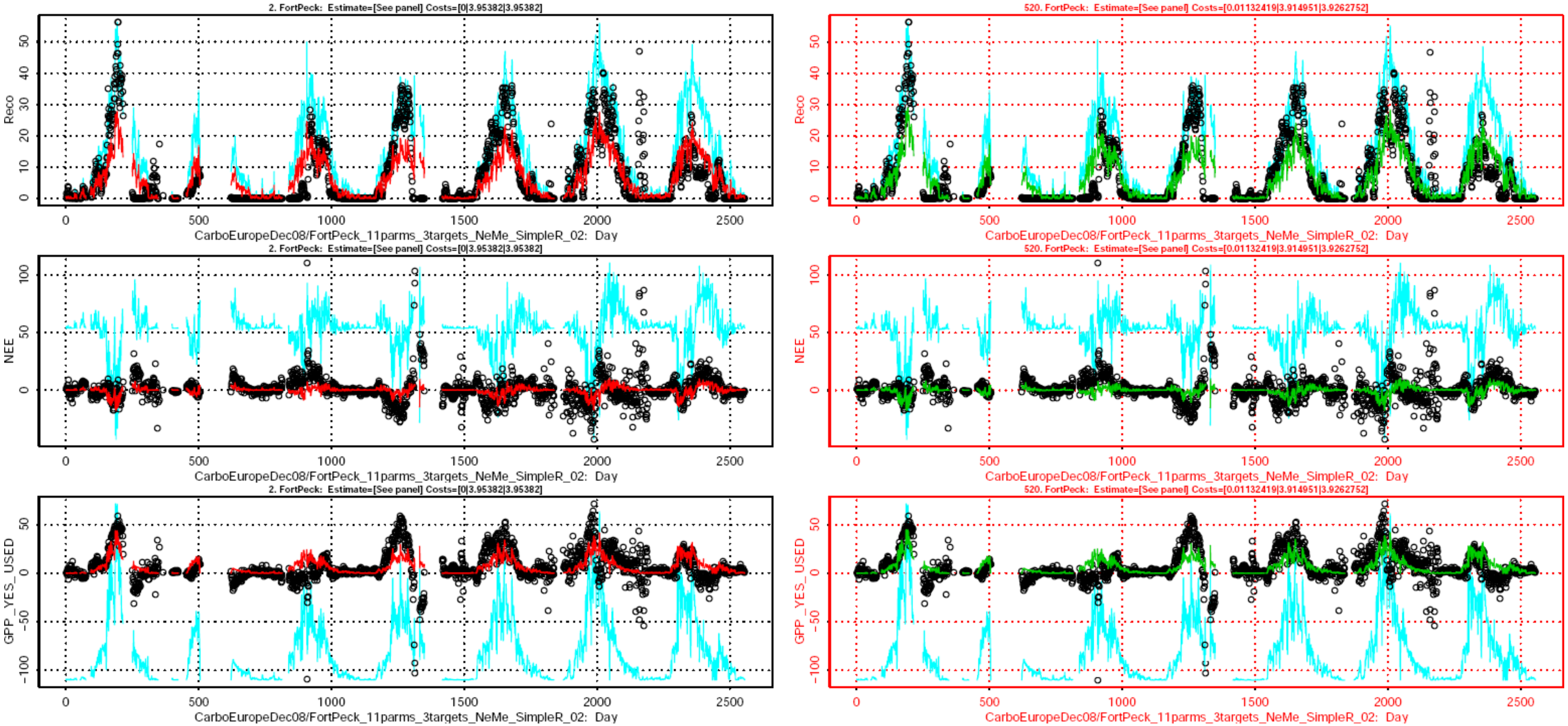
Results

- Vaira Ranch, CA: grazed C3 grass



Results

- Fort Peck, Montana: mixed C3/C4 grass



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What next?

What next?

- Resolve the weighting problem.
- Gather more flux tower data over different PFTs.
- Take advantage of “JULES-TAF” (discussed by Tim Jupp in this session) for faster convergence.
- Examine the response of large-area carbon cycles (e.g. Europe or World).

Questions and answers

Abstract/Summary

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Spare Slides

`f0` and `dqcrit`

$$\left\{\frac{c_i - \Gamma}{c_c - \Gamma}\right\} = F_0 \left\{1 - \frac{D_*}{D_c}\right\}$$

- c_i is the internal partial pressure of CO_2
- c_a is the external partial pressure of CO_2
- Γ is the photorespiration compensation point
- F_0 is a tuning parameter
- D_* is the humidity deficit at the leaf's surface
- D_c is a tuning parameter