ETH
Eidgenössische Technische Hochschule Zürich
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Quantifying Direct and Indirect Effects of Elevated CO_2 on Ecosystem Response

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TERENO
TERRESTRIAL ENVIRONMENTAL OBSERVATORIES

MOTIVATION

CO_2 INCREASE IS EXPECTED TO HAVE IMPORTANT CONSEQUENCES!

- **HYDROLOGY**
- **ENERGY FLUXES**
- **CARBON UPTAKE and STORAGE**
- **NUTRIENT DYNAMICS**

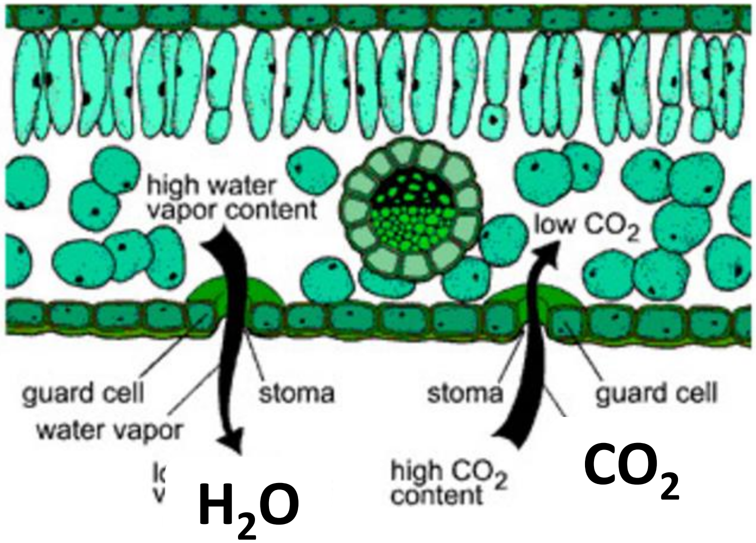
Projected increase in continental runoff due to plant responses to increasing carbon dioxide

Betts et al. 2007 *Nature*

Effect of increasing CO_2 on the terrestrial carbon cycle

Schimel et al. 2015 *PNAS*

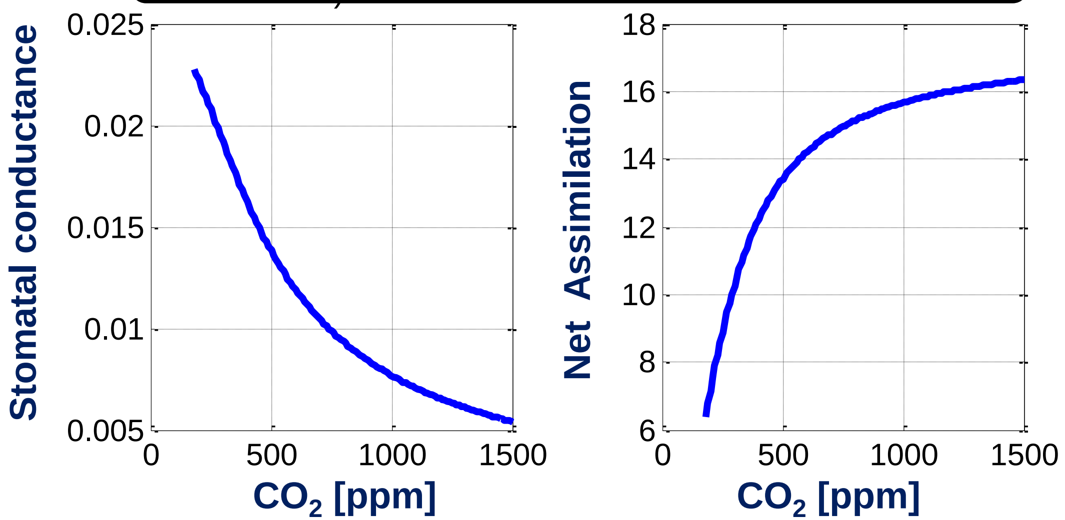
MOTIVATION



Water Use Efficiency

$$WUE = \frac{A_n}{T} = \frac{\text{Photosynthesis}}{\text{Transpiration}}$$

Leaf Level Physiological Response



C_3 plants

LITERATURE CONTEXT (Indirect effects)

Seasonal not annual rainfall determines grassland biomass response to carbon dioxide

Mark J. Hovenden[1], Paul C. D. Newton[2] & Karen E. Wills[1]

Hovenden et al. 2014 *Nature*

C_4 grasses prosper as carbon dioxide eliminates desiccation in warmed semi-arid grassland

Morgan et al. 2011 *Nature*

Elevated [CO_2] and forest vegetation: more a water issue than a carbon issue?

Holtum and Winter 2010 *Funct. Plant Biol.*

RESEARCH QUESTIONS

Which is the proportion of direct and indirect effects of elevated CO_2?

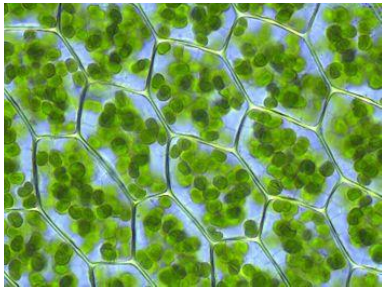
Where should we expect the strongest response?

PARTITIONING EFFECTS OF CO_2 FERTILIZATION

- E1: DIRECT PHYSIOLOGICAL EFFECT ON PHOTOSYNTHESIS **+**
- E2: INDIRECT EFFECT THROUGH SOIL MOISTURE SAVINGS **+**
- E3: INDIRECT EFFECT THROUGH INCREASED LAI **+ −**
- E4: INDIRECT EFFECT THROUGH INCREASED LAI AFFECTING SOIL MOISTURE **−**

TOTAL CO_2 EFFECT = E1 + E2 + E3 + E4

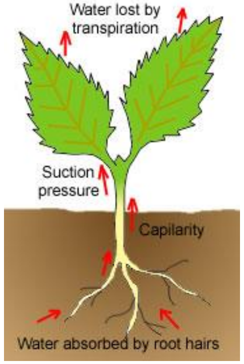
E1



E2

E3

E4



PARTITIONING EFFECTS OF CO_2 FERTILIZATION

Numerical Simulations

0. CO_2 ambient, SM ambient and LAI ambient

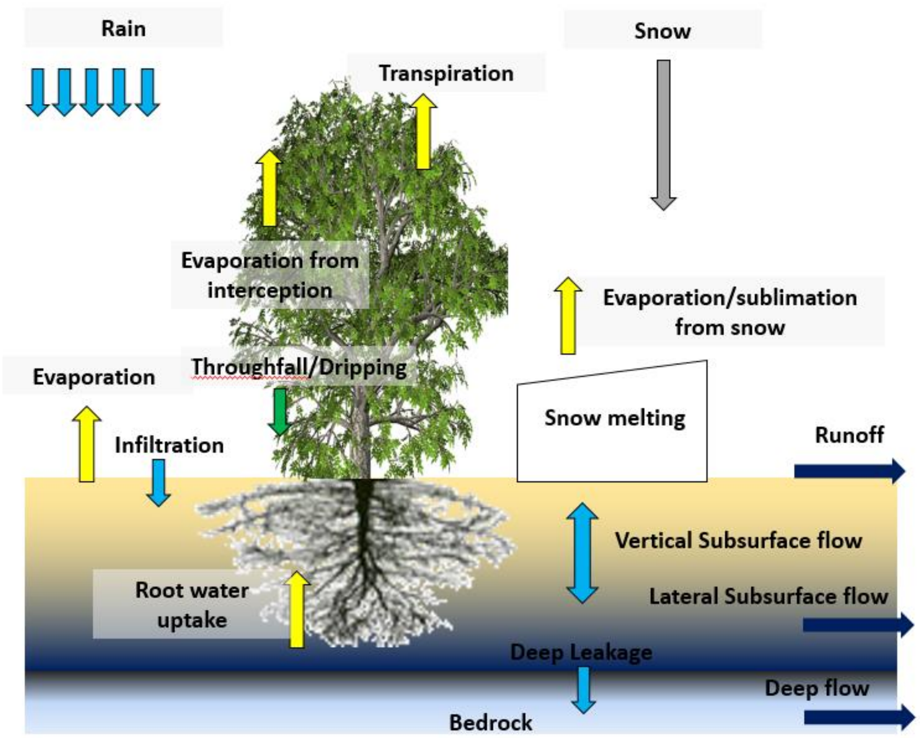
1. CO_2 elevated, SM elevated and LAI elevated = E1+E2+E3+E4
2. CO_2 elevated, SM ambient and LAI ambient = E1
3. CO_2 elevated and LAI ambient = E1+E2
4. CO_2 elevated, SM ambient and LAI elevated = E1+E3
5. CO_2 elevated, SM elevated and LAI ambient = E1+E2+E4

Ambient: 375 ppm
Elevated : 550 ppm

Simulations (2 to 5) carried out imposing a given LAI or soil moisture (SM)

METHOD: MECHANISTIC ECOHYDROLOGICAL MODEL

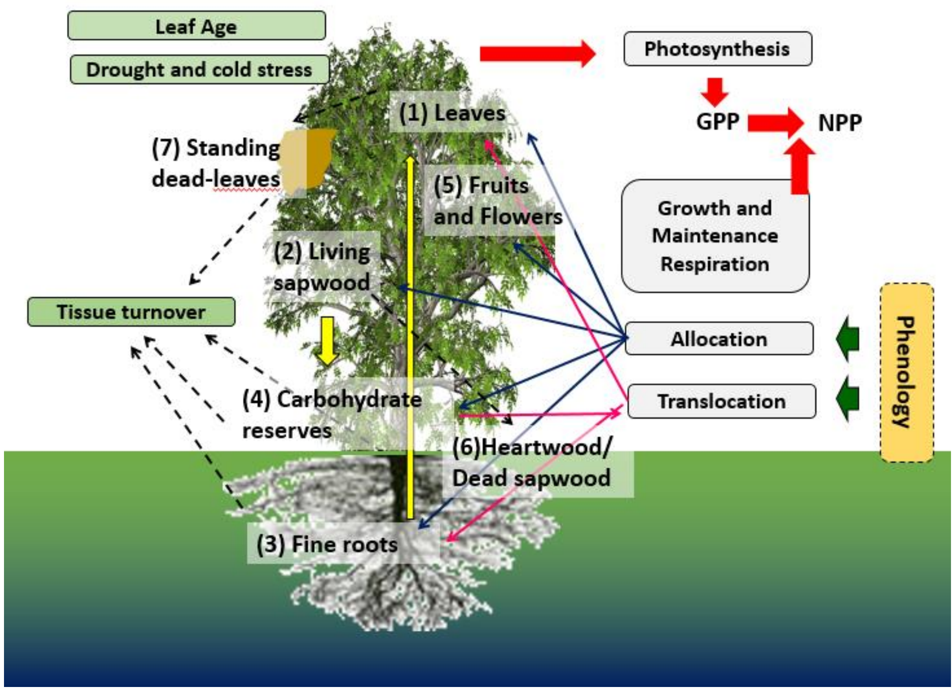
Hydrological Part



Fatichi et al., 2012a,b, *J. Advances in Modeling Earth Systems*
Fatichi and Leuzinger 2013, *Agr. For. Met.*
Fatichi et al., 2014, *WRR;* Fatichi and Ivanov 2014, *WRR;* Fatichi et al 2016, *PNAS*
Pappas et al. 2016 *NP;* Paschalis et al. 2015 *JGR*
Fatichi and Pappas, 2017, *GRL*

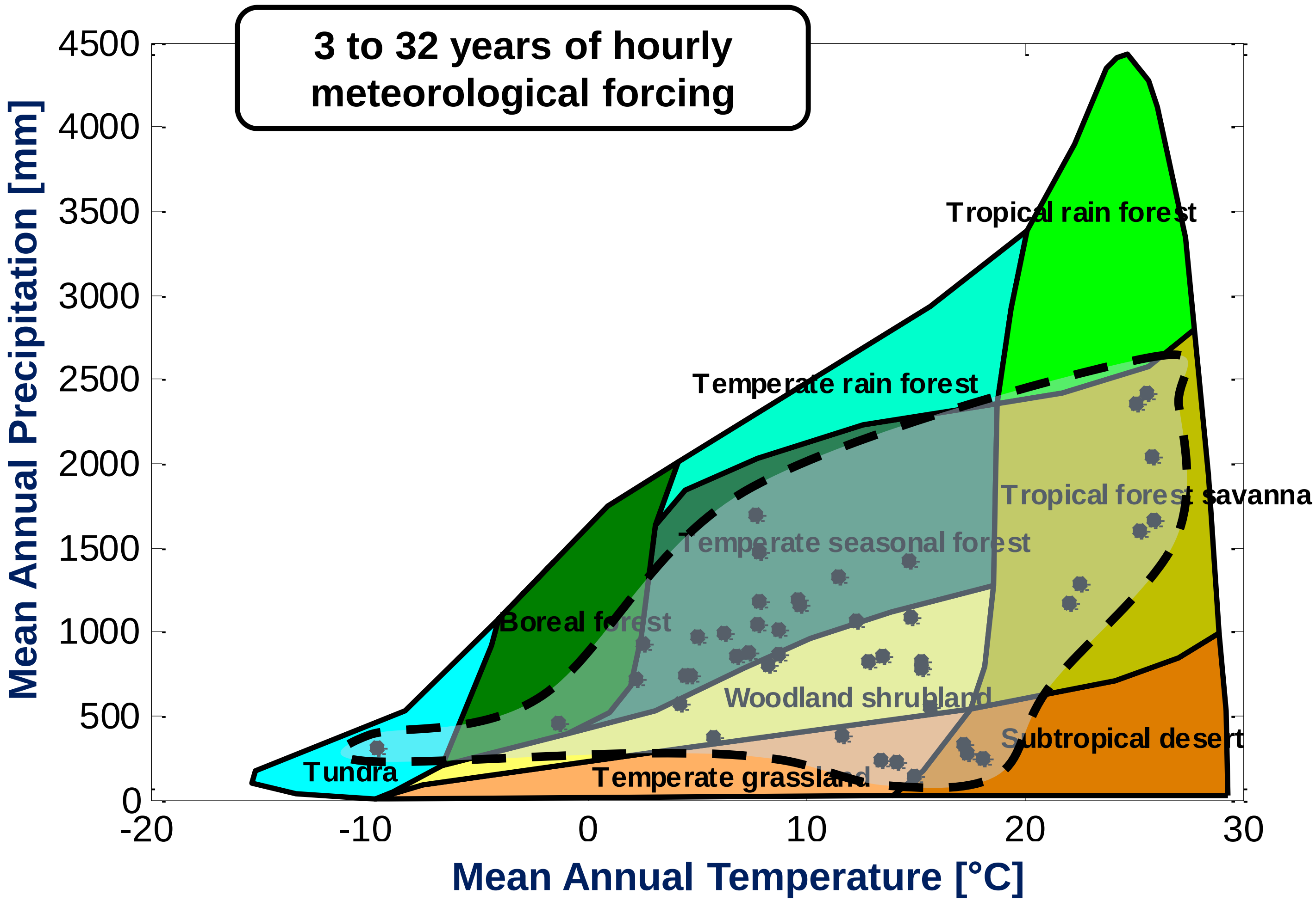
Tethys-Chloris (T&C)

Vegetation Part



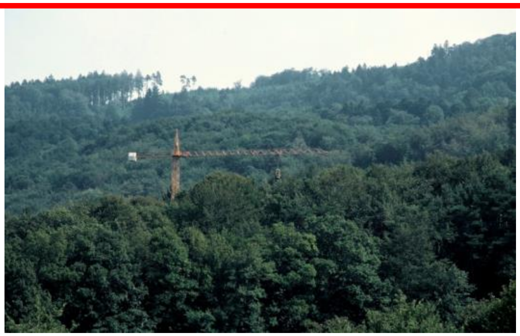
NO NUTRIENT LIMITATIONS!

44 CASE STUDIES COVERING DIFFERENT CLIMATES
(Flux towers and manipulation experiments)



FACE CASE STUDIES

SWISS CANOPY CRANE (CH)
Mixed Deciduous Forest



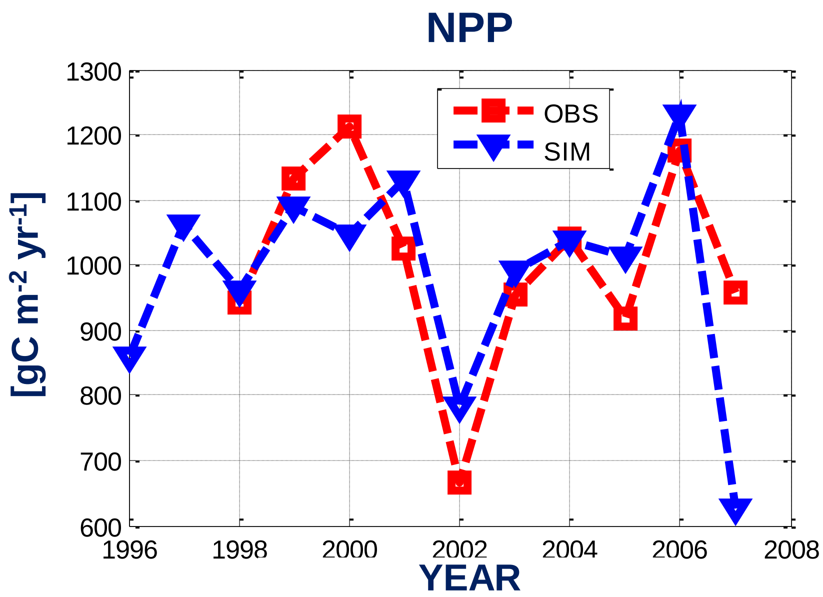
TasFACE (AUS)
C3/C4 Grassland

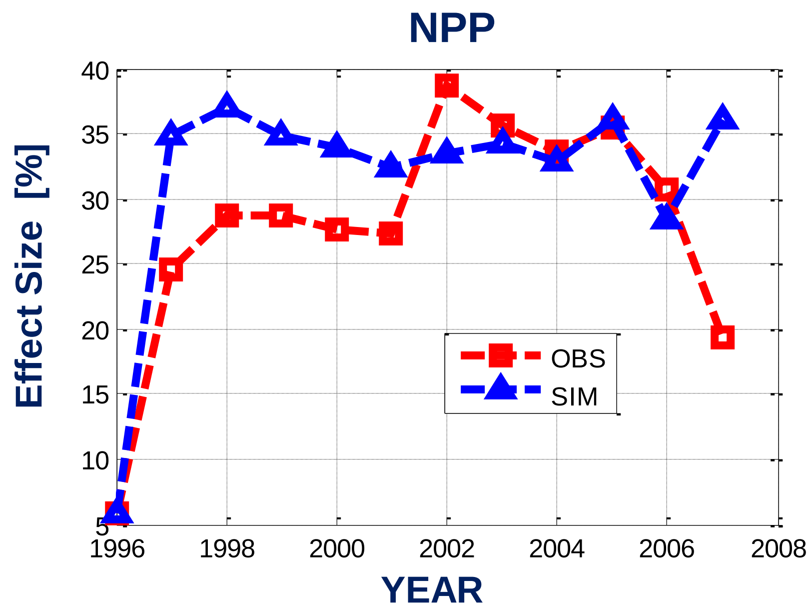
DUKE FACE (USA)
Loblolly Pine and Mixed Deciduous

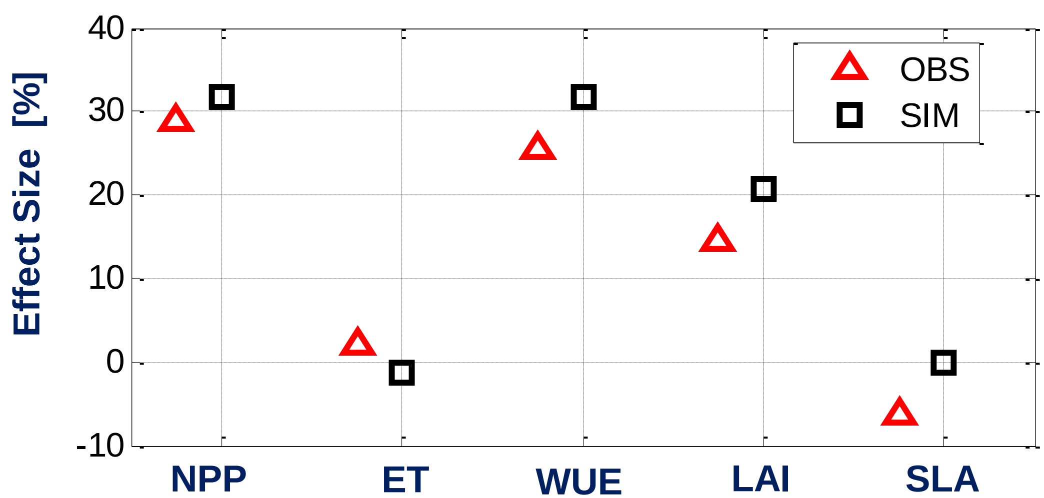
SERC (USA)
Florida Scrub Oak

ORNL FACE (USA)
Sweetgum plantation

DUKE FACE



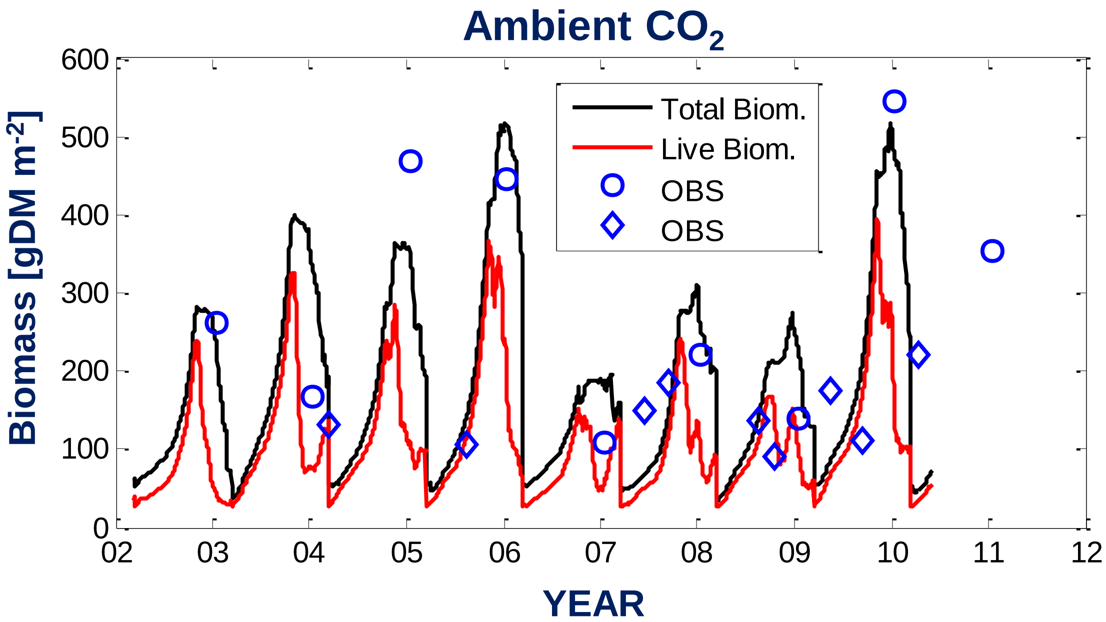


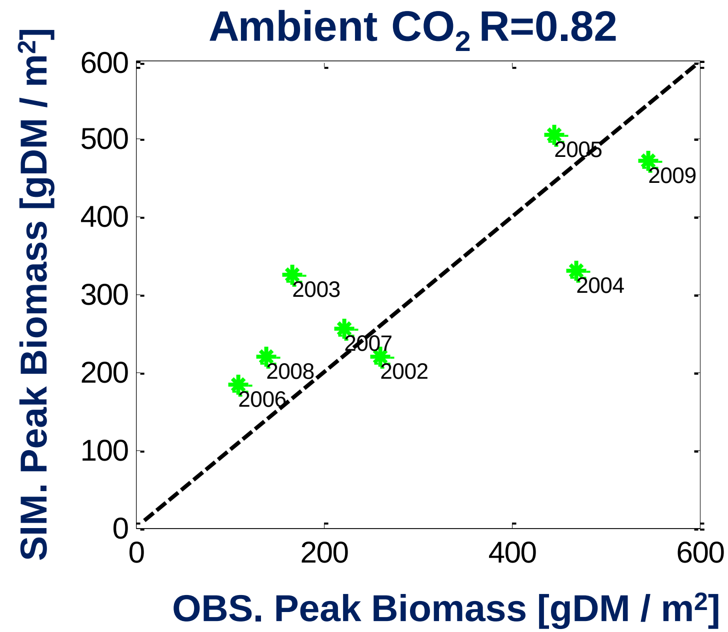


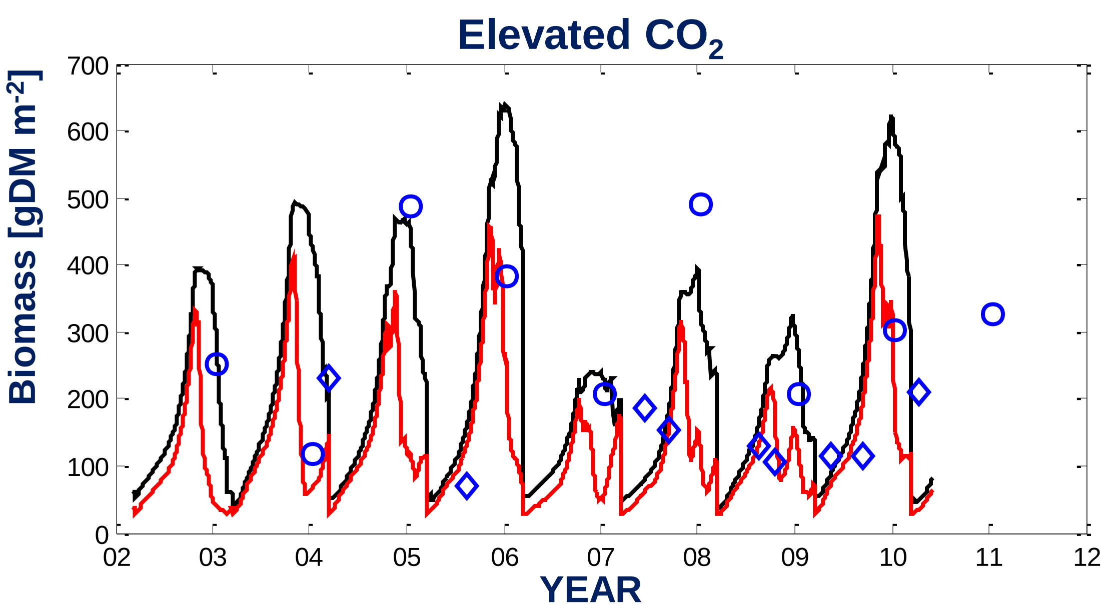
Very consistent predictions across a range of metrics

Data from: De Kauwe et al., 2013 *GCB*; Zaehle et al 2014 *NP*

TasFACE



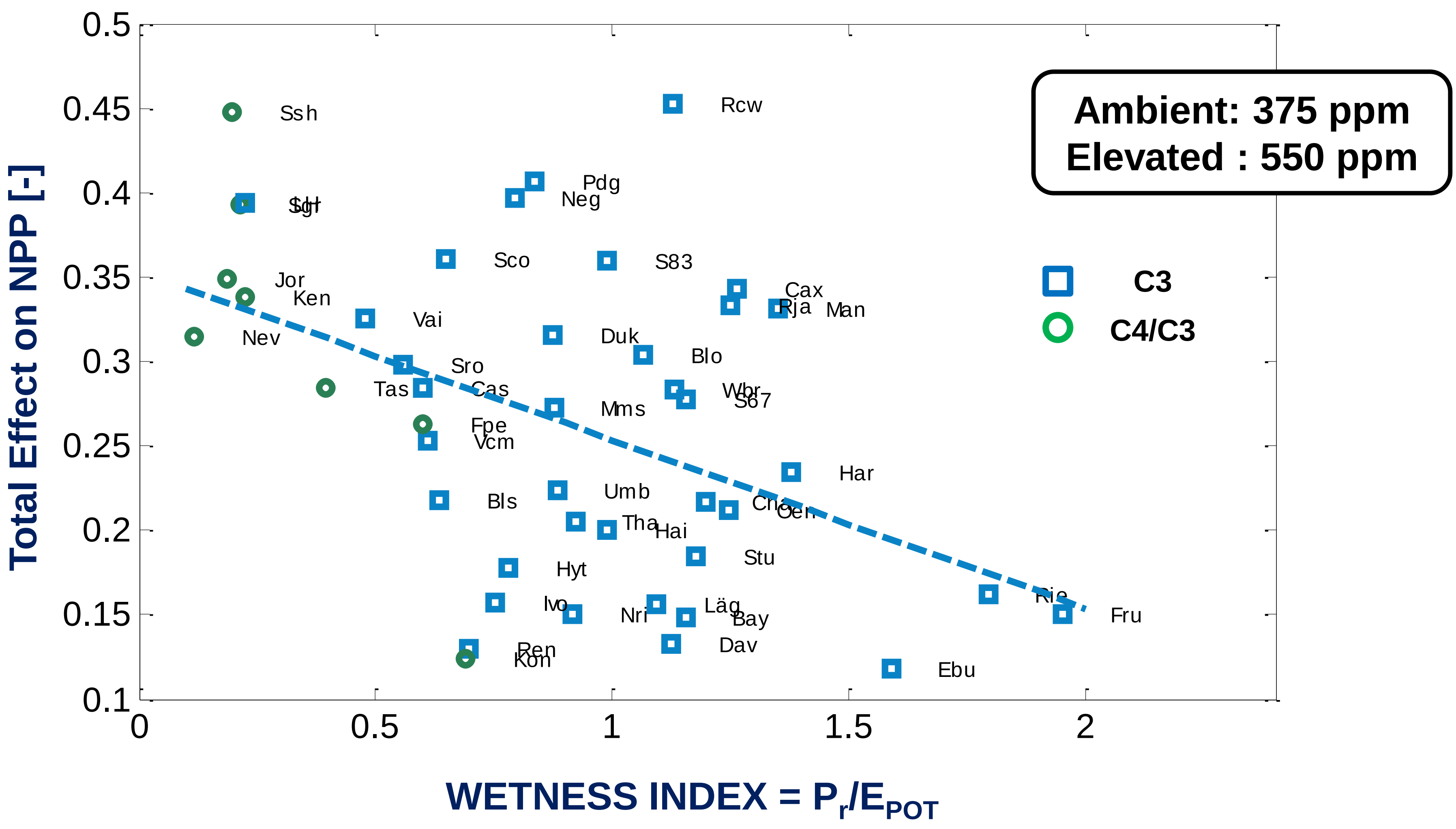




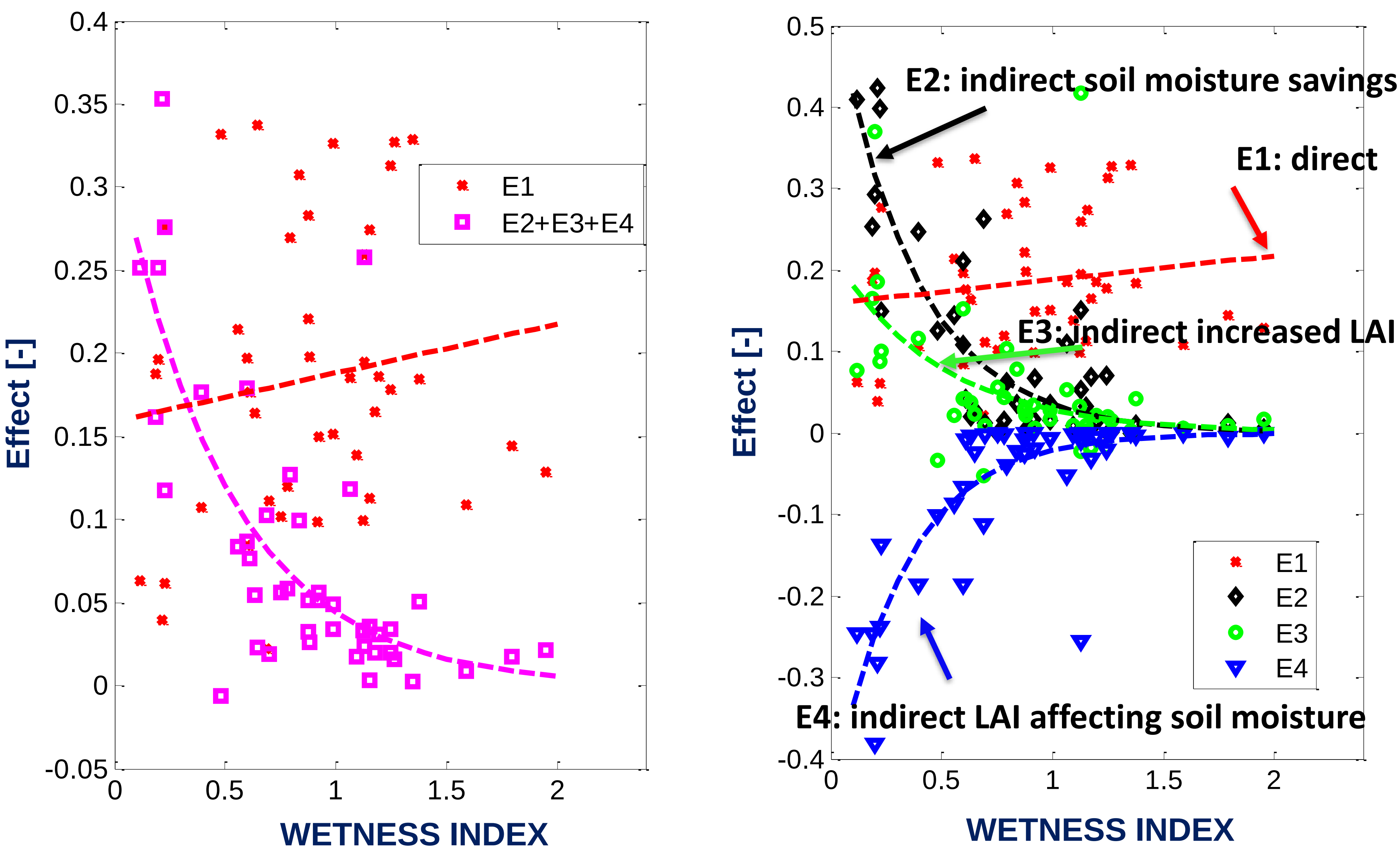
Total CO_2 Effect Average across years
SIM. 23%
OBS. 18%

Data from: Hovenden et al., 2014 *Nature*

NPP – Total Effect

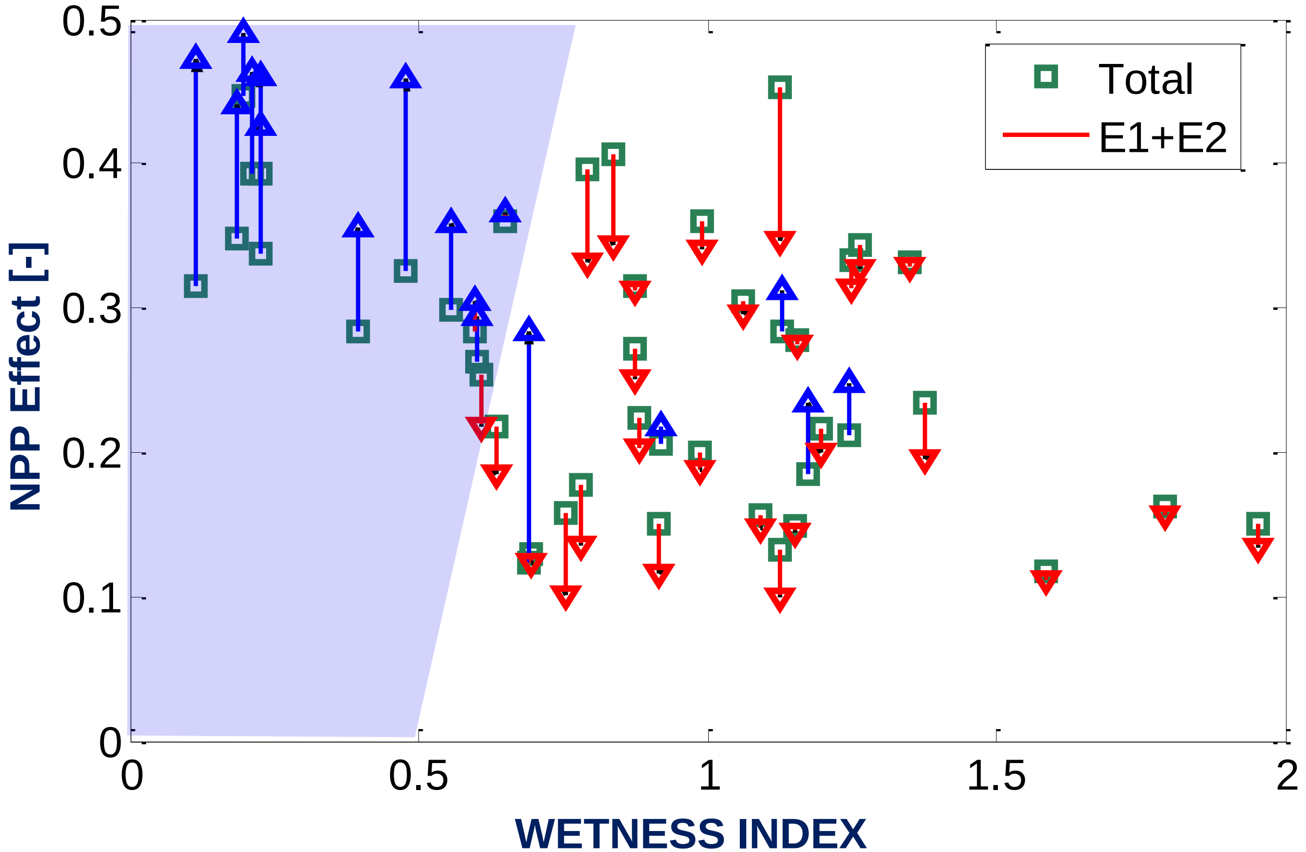


NPP: PARTITIONING EFFECTS



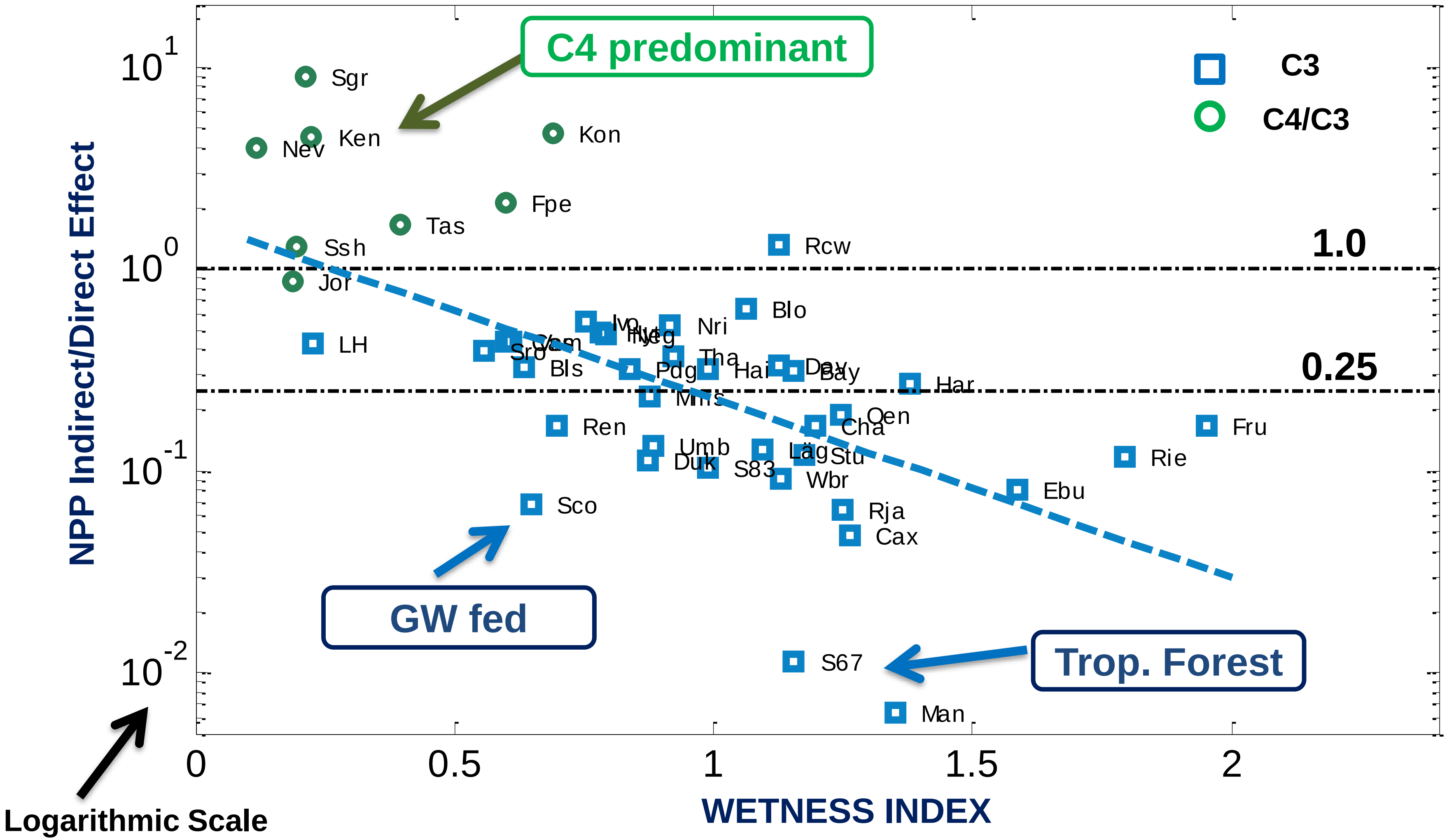
NPP: PARTITIONING EFFECTS

Removing the changes in LAI has contrasting effects

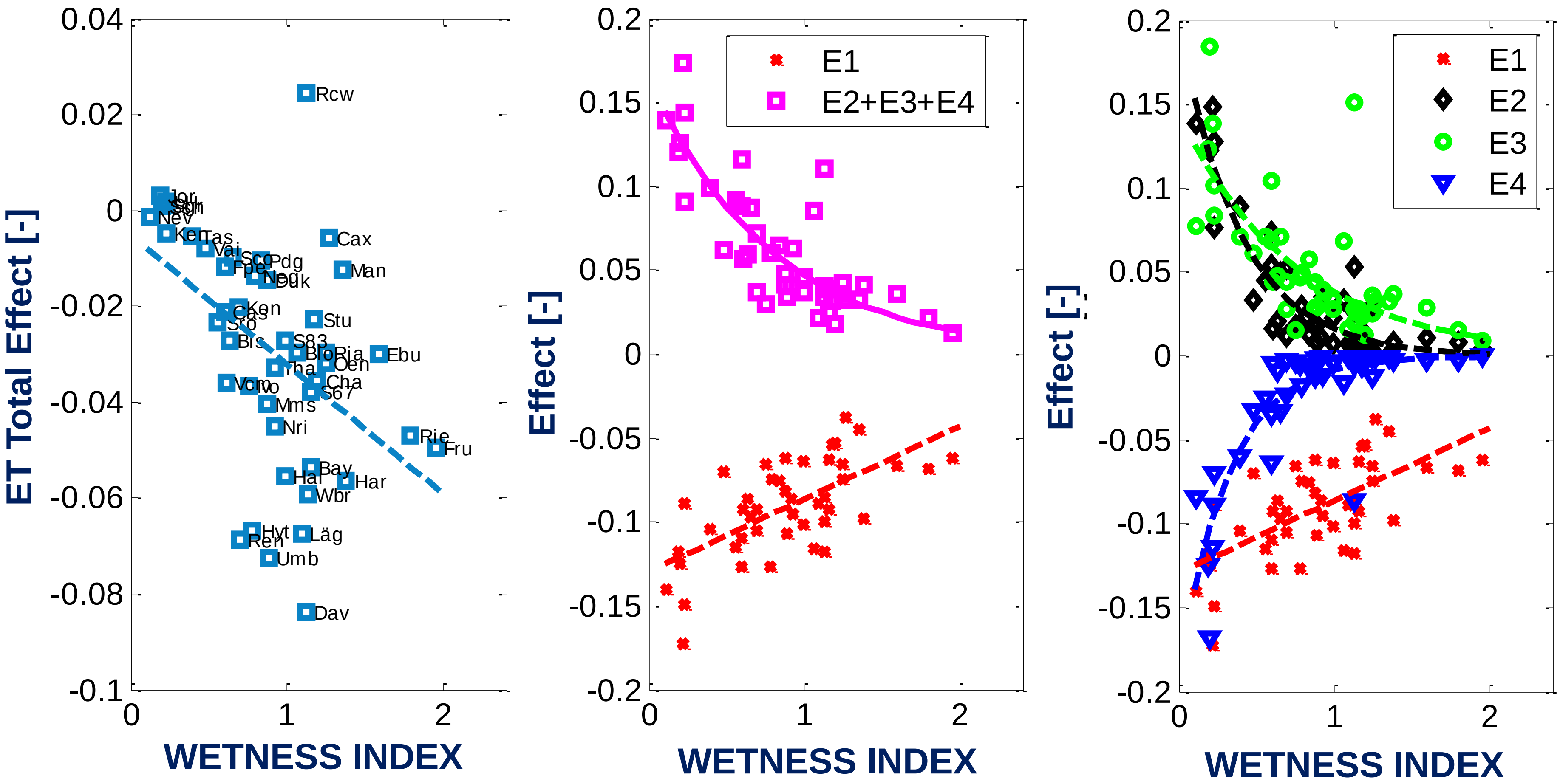


Total vs. Direct + SM Indirect

NPP – Direct vs Indirect



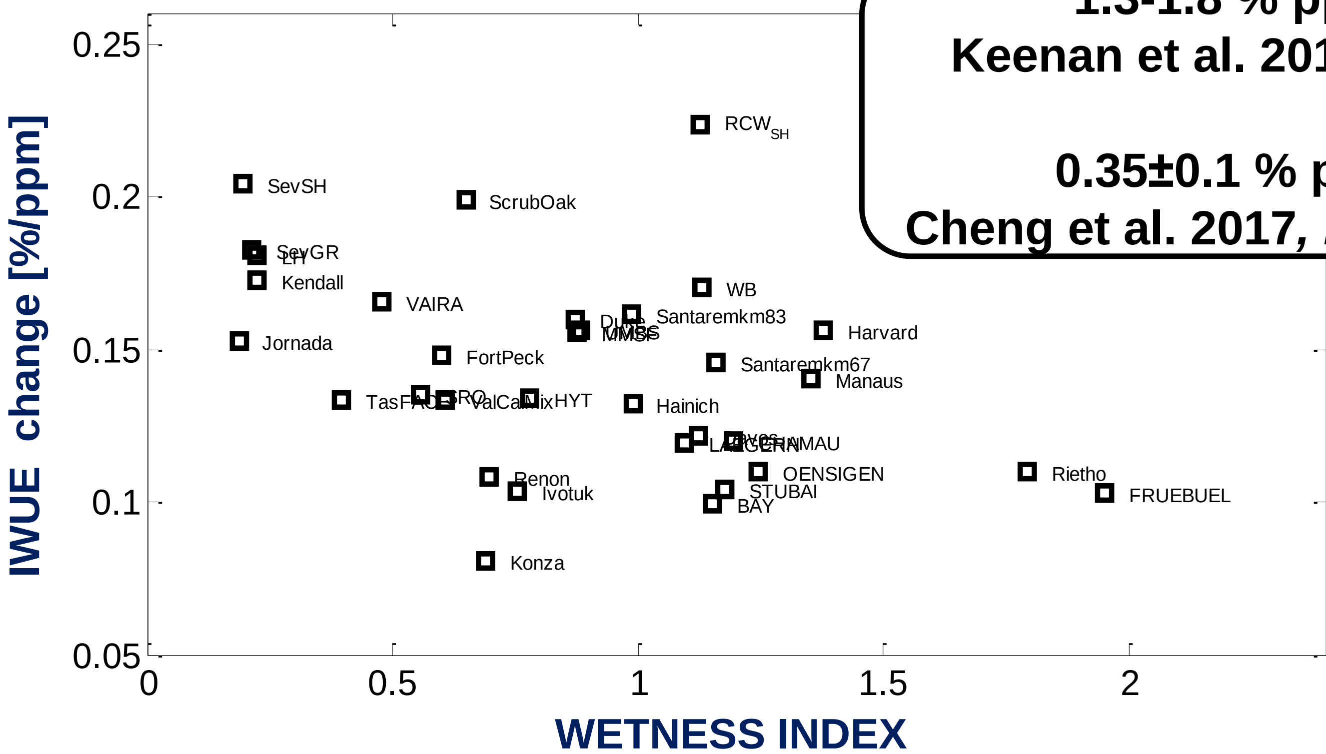
EVAPOTRANSPIRATION: PARTITIONING EFFECTS



Inherent Water Use Efficiency (Ecosystem scale)
IWUE = GPP*VPD/ET

1.3-1.8 % ppm^{-1}
Keenan et al. 2013 *Nature*

0.35±0.1 % ppm^{-1}
Cheng et al. 2017, *Nat. Comm.*



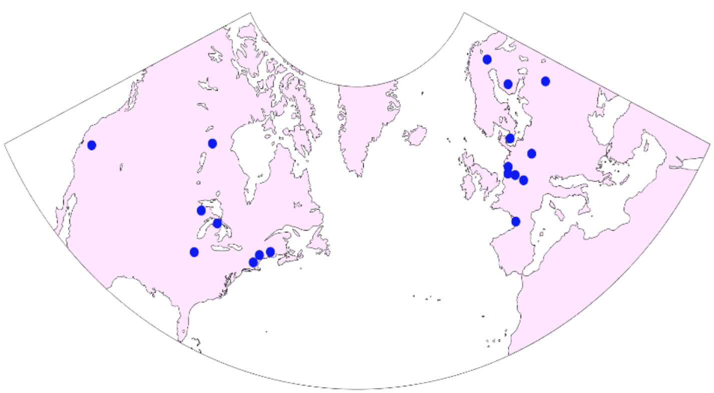
RESEARCH QUESTIONS

Can plant-trait plasticity explain the "unexpected" increase in WUE?

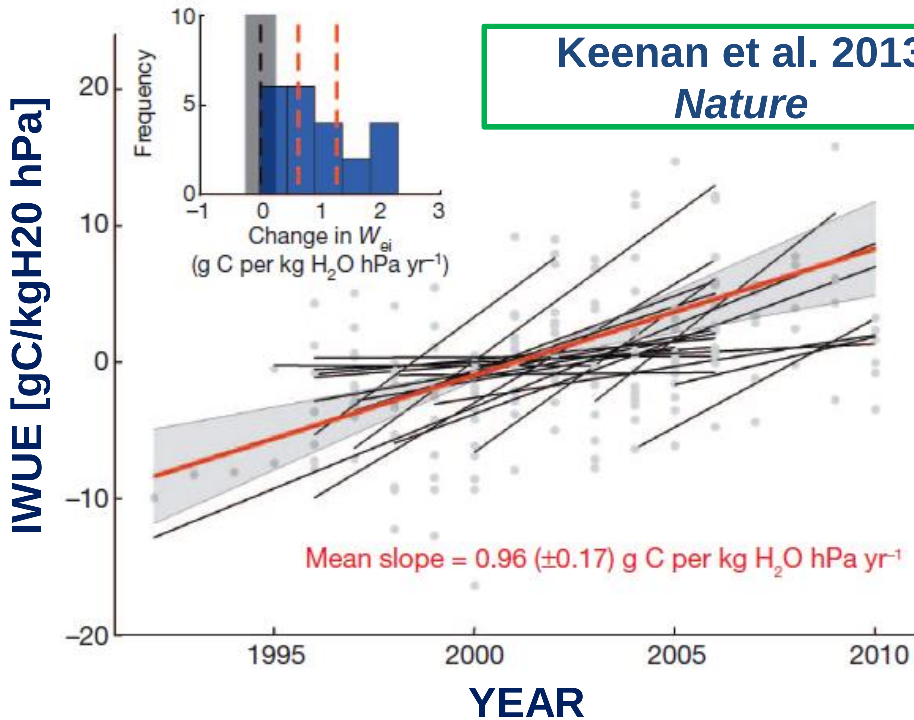
INHERENT WATER USE EFFICIENCY

$$IWUE = \frac{GPP}{ET} VPD$$ ➡ if $\frac{C_i}{C_a}$ is roughly constant ➡ $$IWUE \propto C_a$$

Flux-tower observations from 21 forested ecosystem in northern hemisphere (≈1995-2010)



Expectation of 0.5%/yr increase in IWUE

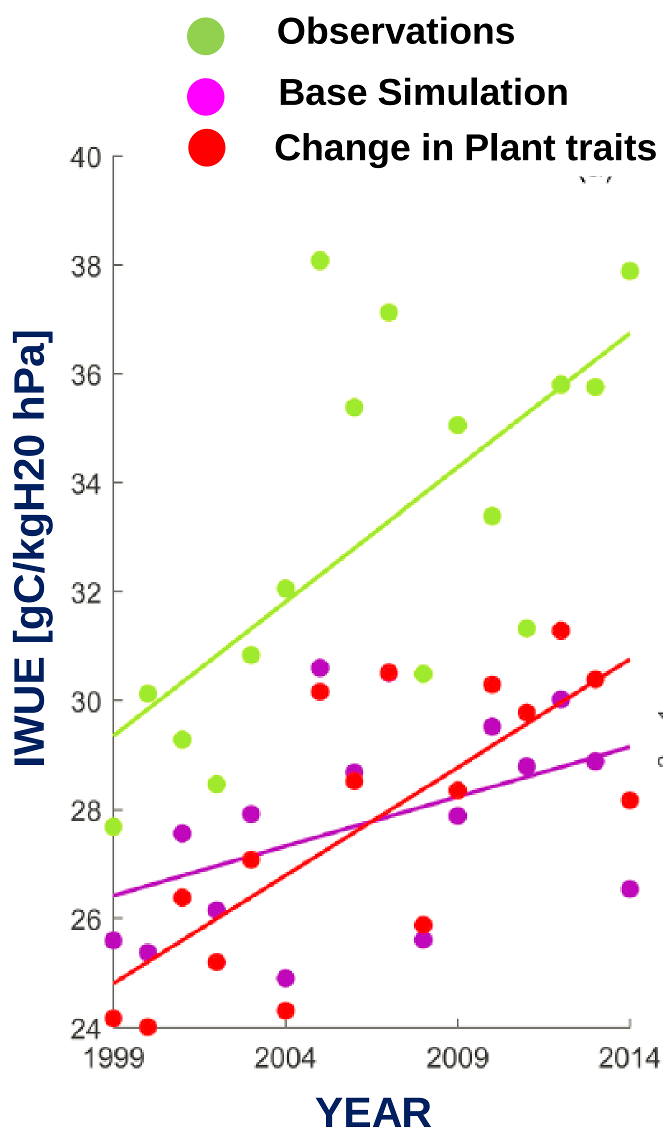


Keenan et al. 2013 *Nature*

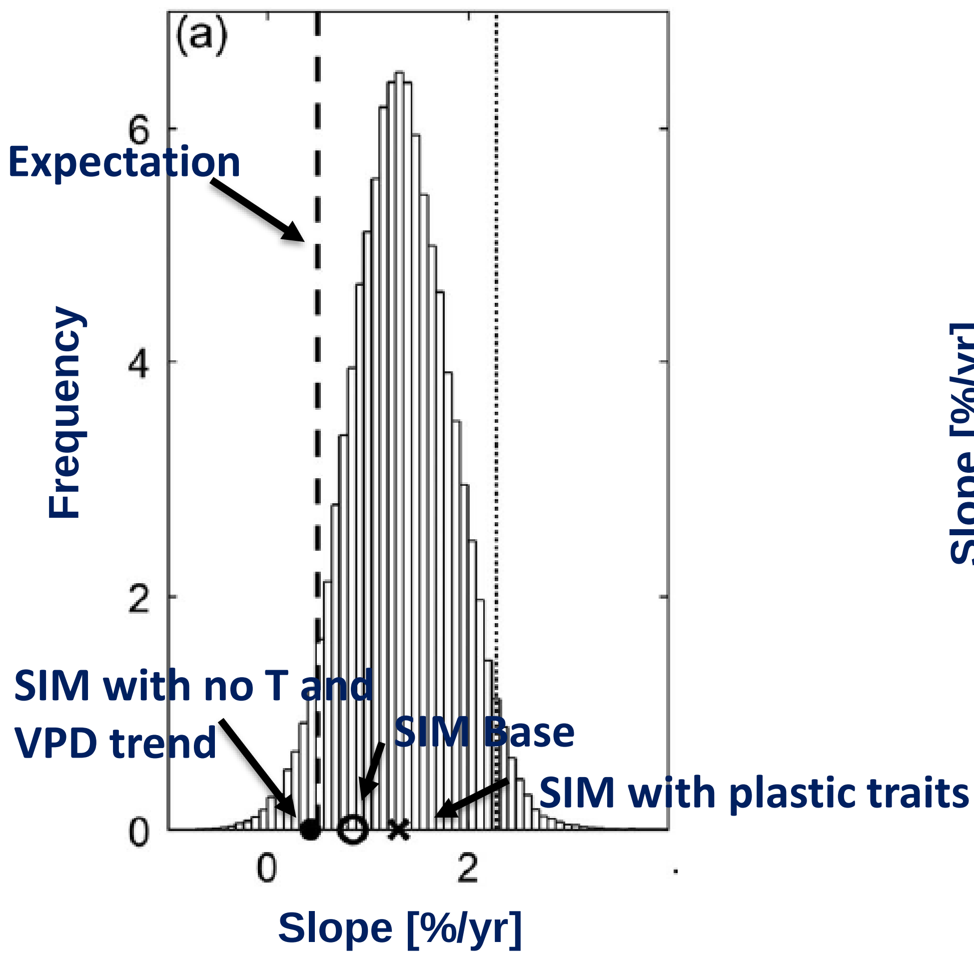
Increase in IWUE of 2.3%/yr
vs.
Model ensemble simulates 0.04 %/yr

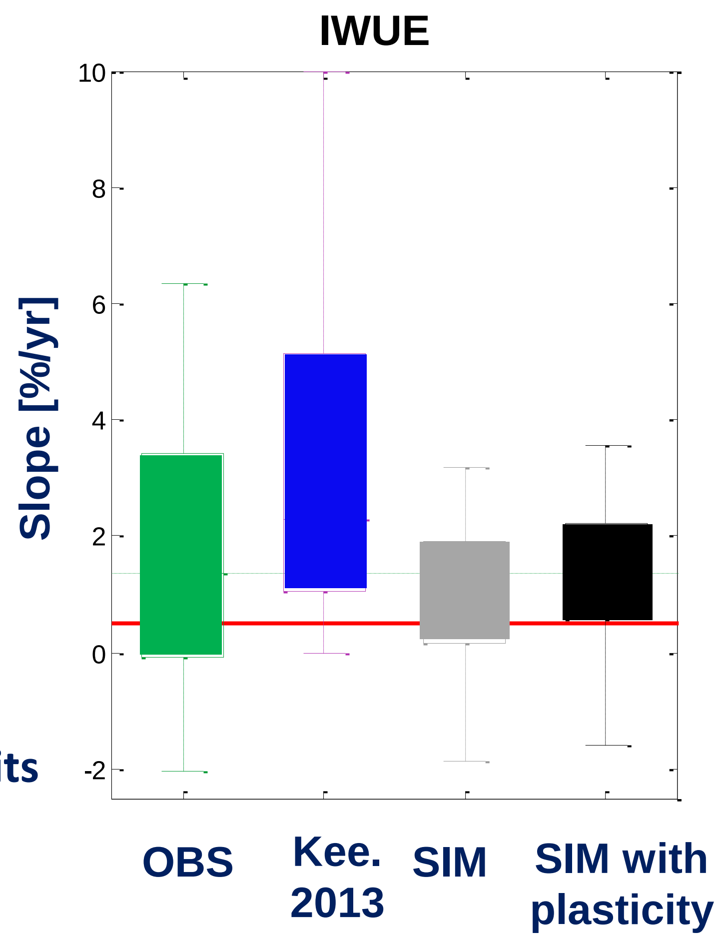
DESIGN OF THE EXPERIMENT

- Re-computing IWUE with longer time series and a proper estimate of uncertainty.
- Simulations with “static” parameters.
- Simulations with trends [1% yr^{-1}] in a number of selected plant traits (model parameters).



CHANGES IN IWUE





Median IWUE change (1.3%/yr). It is 2.6 times above expectations

CONCLUSIONS (1)

- Mechanistic models do provide insights on ecosystem response to elevated CO_2.
- Differences between CO_2 scenarios (375 vs 550 ppm) in terms of water fluxes are typically < 8%, while they are in the order of 20-40% for NPP.
- Indirect effects can be comparable or larger than direct effects.
- Additional analyses are required to better understand the effect of sink limitations (nutrients, turgor, temperature) on plant growth.
- Regardless, ecosystems experiencing water stress are expected to be the most responsive in terms of carbon fluxes.

e.g.,

Impact of CO_2 fertilization on m
warm, arid environments

Ahlström et al. 2015 *Science*

The dominant role of semi-arid ecosystems in the trend and variability of the land CO_2 sink

CONCLUSIONS (2)

- We computed a median increase in IWUE of 1.3%/yr across 20 north hemisphere forests in the last two decades.
- T&C predicts an increase of 0.9%/yr in IWUE larger than expected but less than observed.
- Plasticity in ecosystem traits can potentially explain the “unexpectedly” large IWUE increase.
- A new challenge for the parametrization of ecosystem models, where key physiological parameters may not be necessary temporally constant, is suggested.

Thanks for your attention !

Partitioning direct and indirect effects reveals the response of water-limited ecosystems to elevated CO_2

Simone Fatichi[a,1], Sebastian Leuzinger[b], Athanasios Paschalis[c,d], J. Adam Langley[e], Alicia Donnellan Barraclough[b], and Mark J. Hovenden[f]

Fatichi et al. 2016 *PNAS*

Linking plant functional trait plasticity and the large increase in forest water use efficiency

Mastrotheodoros et al. 2017 *JGR*

Theodoros Mastrotheodoros[1], Christoforos Pappas[2], Peter Molnar[1], Paolo Burlando[1], Trevor F. Keenan[3], Pierre Gentine[4], Christopher M. Gough[5], and Simone Fatichi[1]

MOTIVATION

PROJECTIONS OF FUTURE TERRESTRIAL CARBON AND WATER CYCLE RELY ON NUMERICAL TOOLS

DGVMs
Terrestrial Biosphere Models
Terrestrial Ecosystem Models
Ecohydrological Models

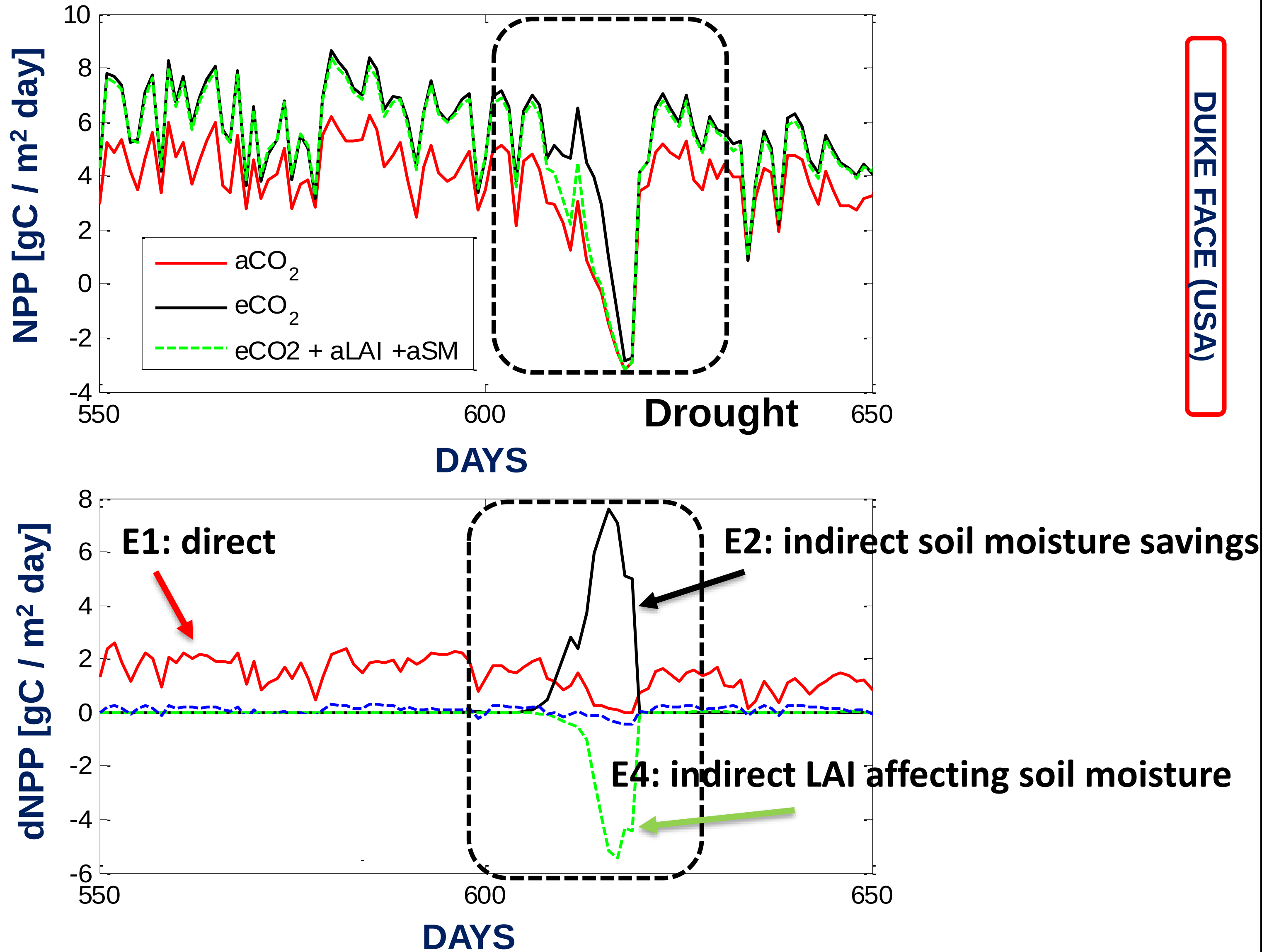
RESULTS FROM MANY MANIPULATION EXPERIMENTS ARE AVAILABLE

Warming

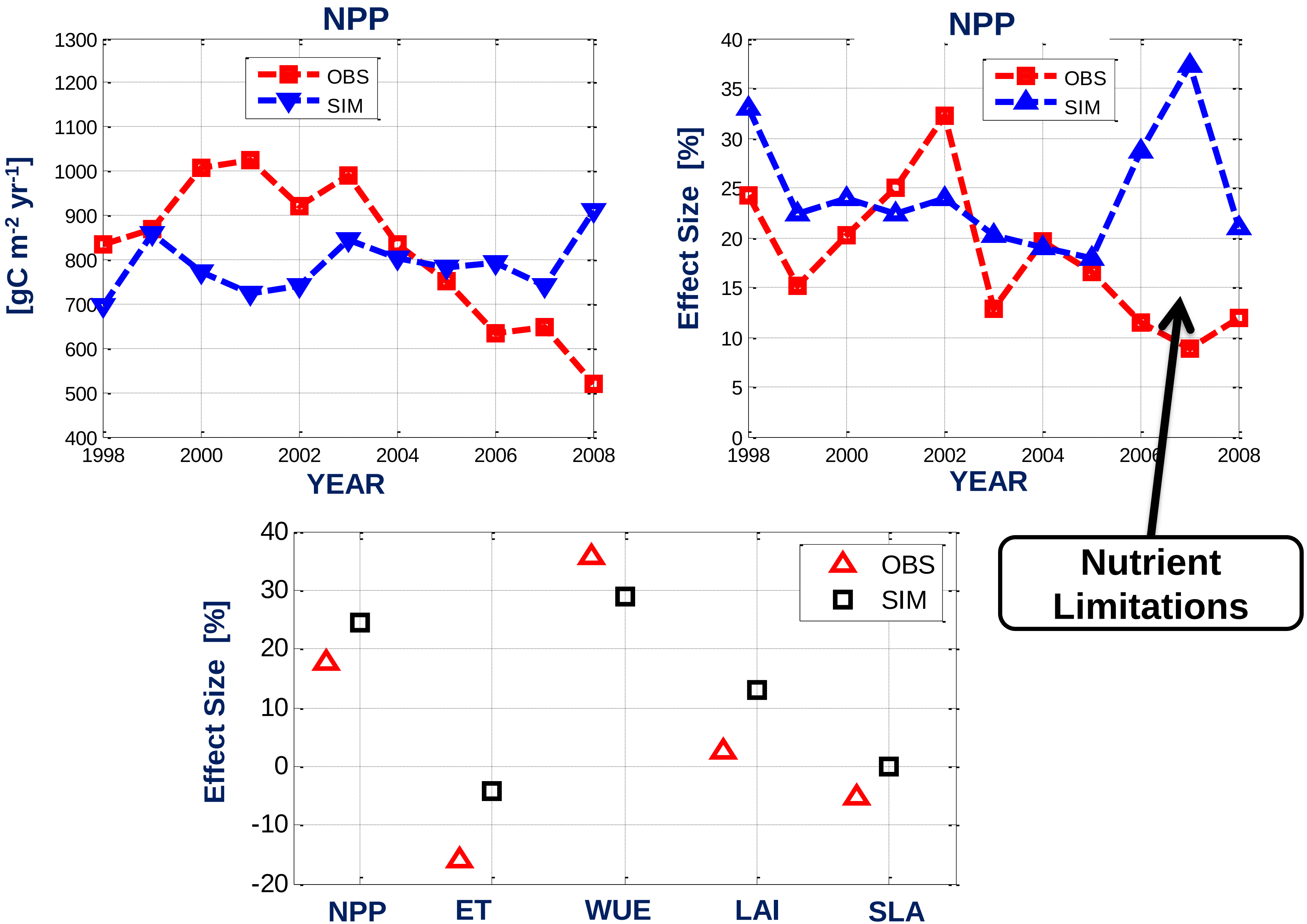
Rainfall Exclusion

Girdling

PARTITIONING EFFECTS OF CO_2 FERTILIZATION

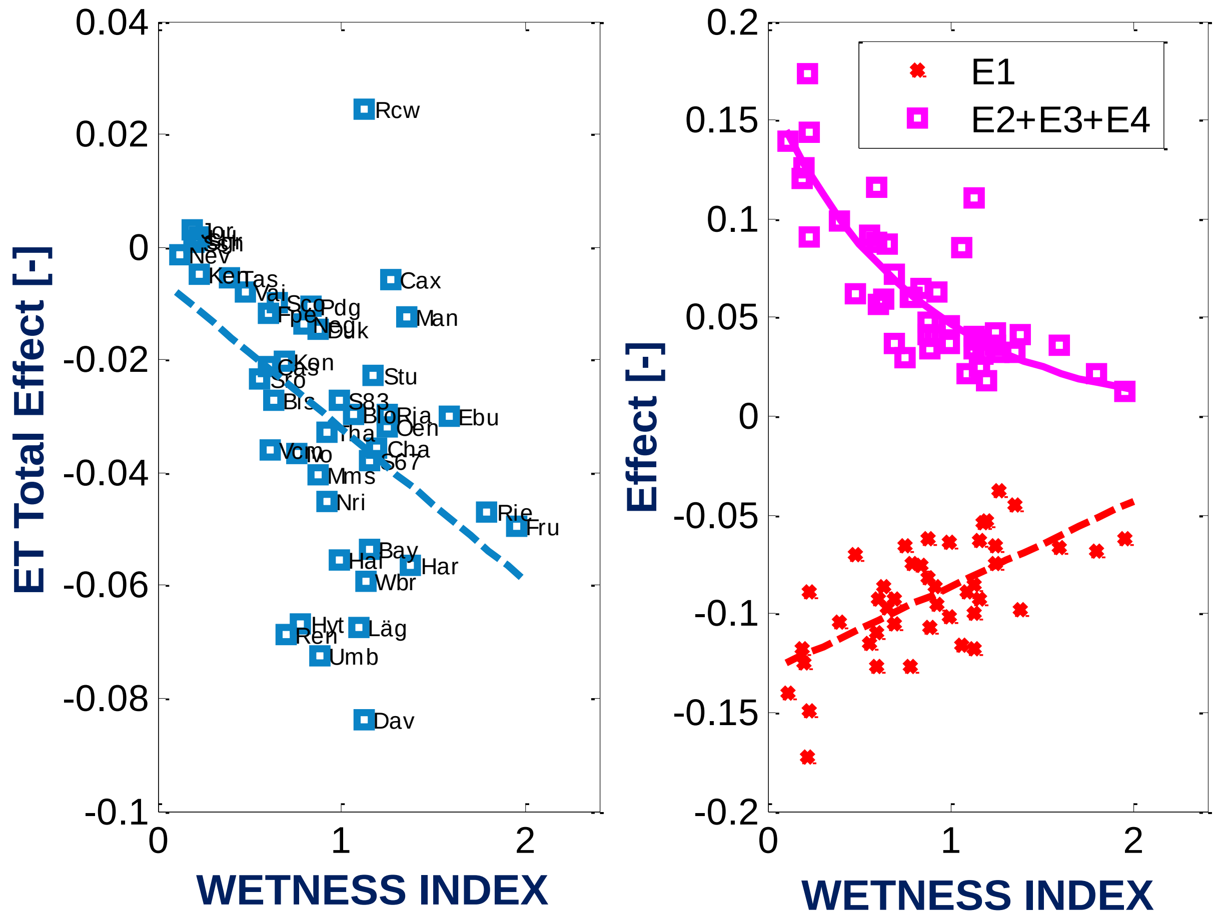


ORNL FACE

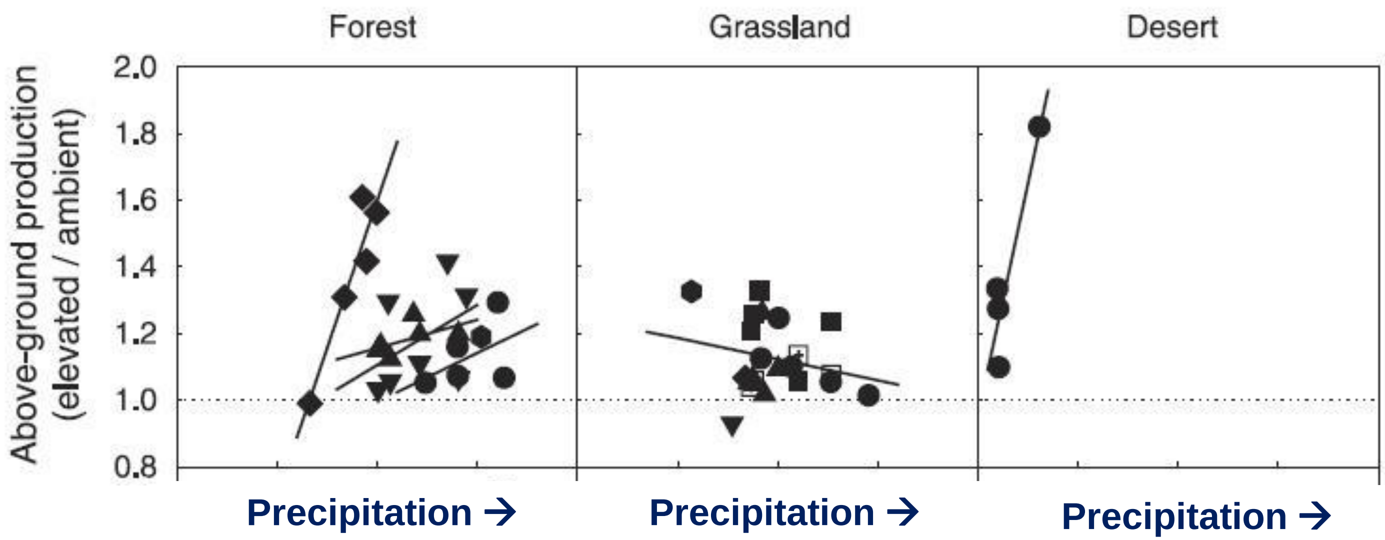


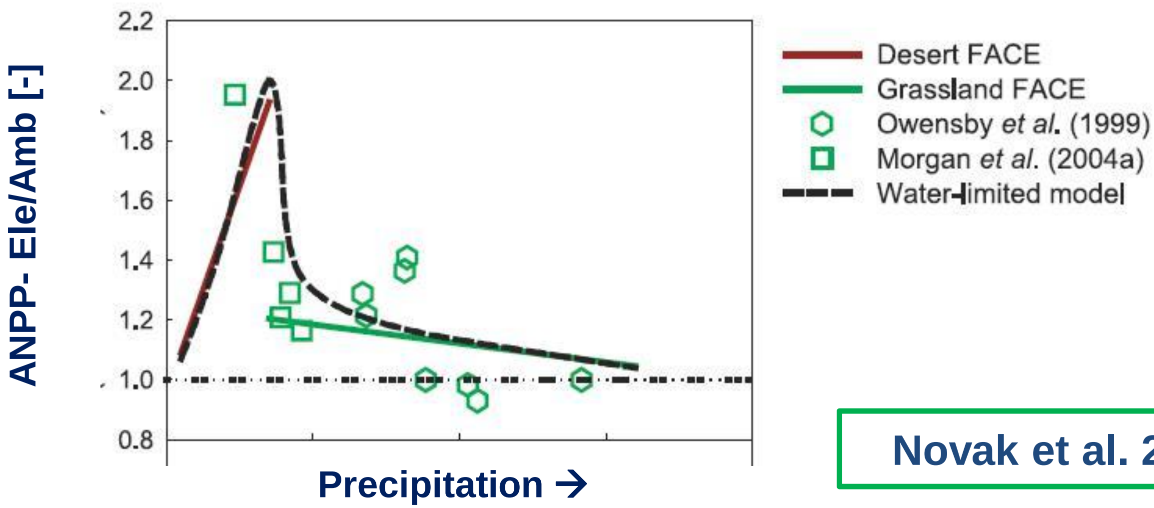
Data from: De Kauwe et al., 2013 *GCB*; Zaehle et al 2014 *NP*

EVAPOTRANSPIRATION: PARTITIONING EFFECTS



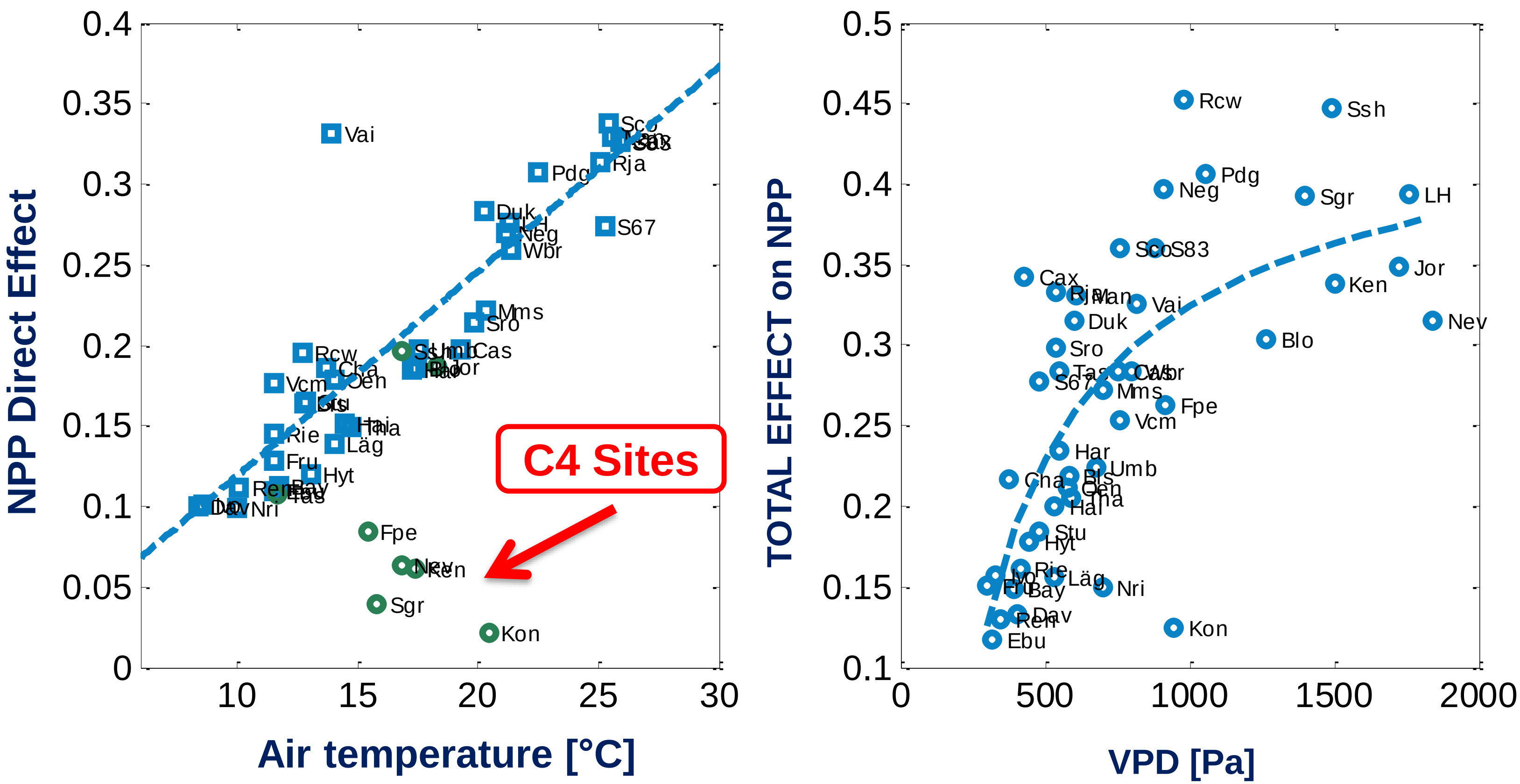
LITERATURE CONTEXT

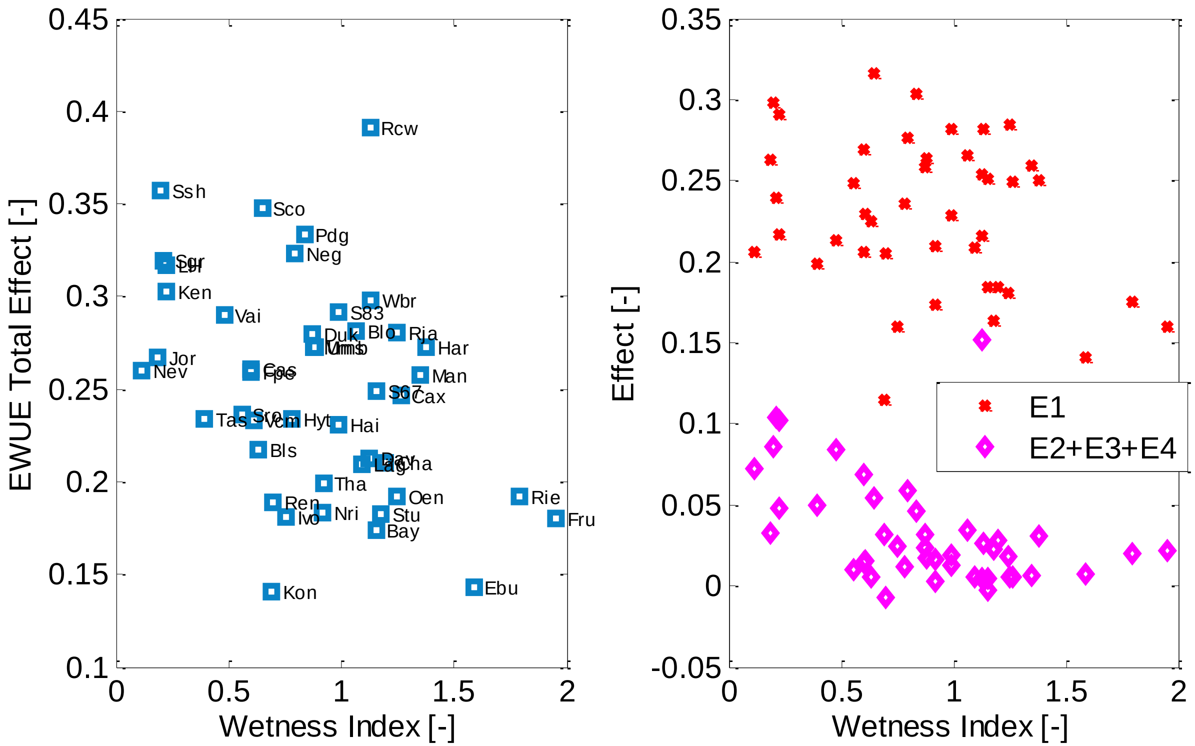




Novak et al. 2004 *New Phyt.*

NPP – Direct effect only




EWUE Total Effect [-]
Wetness Index [-]
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0
0.5
1
1.5
2
Rcw
Ssh
Sco
Pdg
Neg
Ken
Vai
Wbr
S83
Duk
Blo
Ria
Har
Jor
Nev
Man
Cax
Tas
Hyt
Hai
Bls
Tha
Oen
Rie
Ren
Nri
Ivo
Stu
Fru
Bay
Kon
Ebu
Effect [-]
Wetness Index [-]
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
0
0.5
1
1.5
2
E1
E2+E3+E4