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Joint use of hyperspectral remote sensing and fluxes to understand ecosystems responses to nutrient manipulation

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Alexander von Humboldt
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Motivation

nature COMMUNICATIONS

ARTICLE

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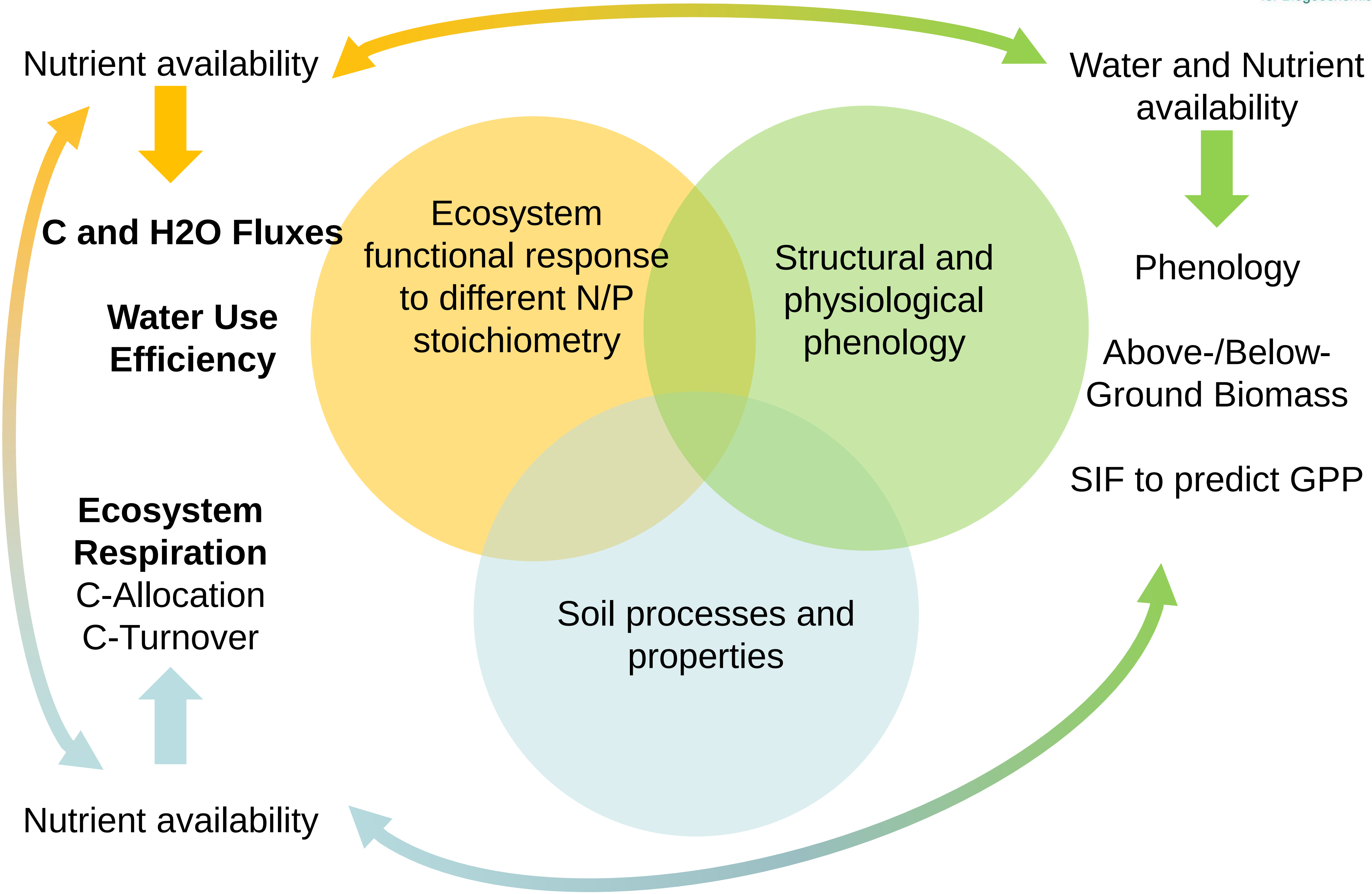
Human-induced nitrogen–phosphorus imbalances alter natural and managed ecosystems across the globe

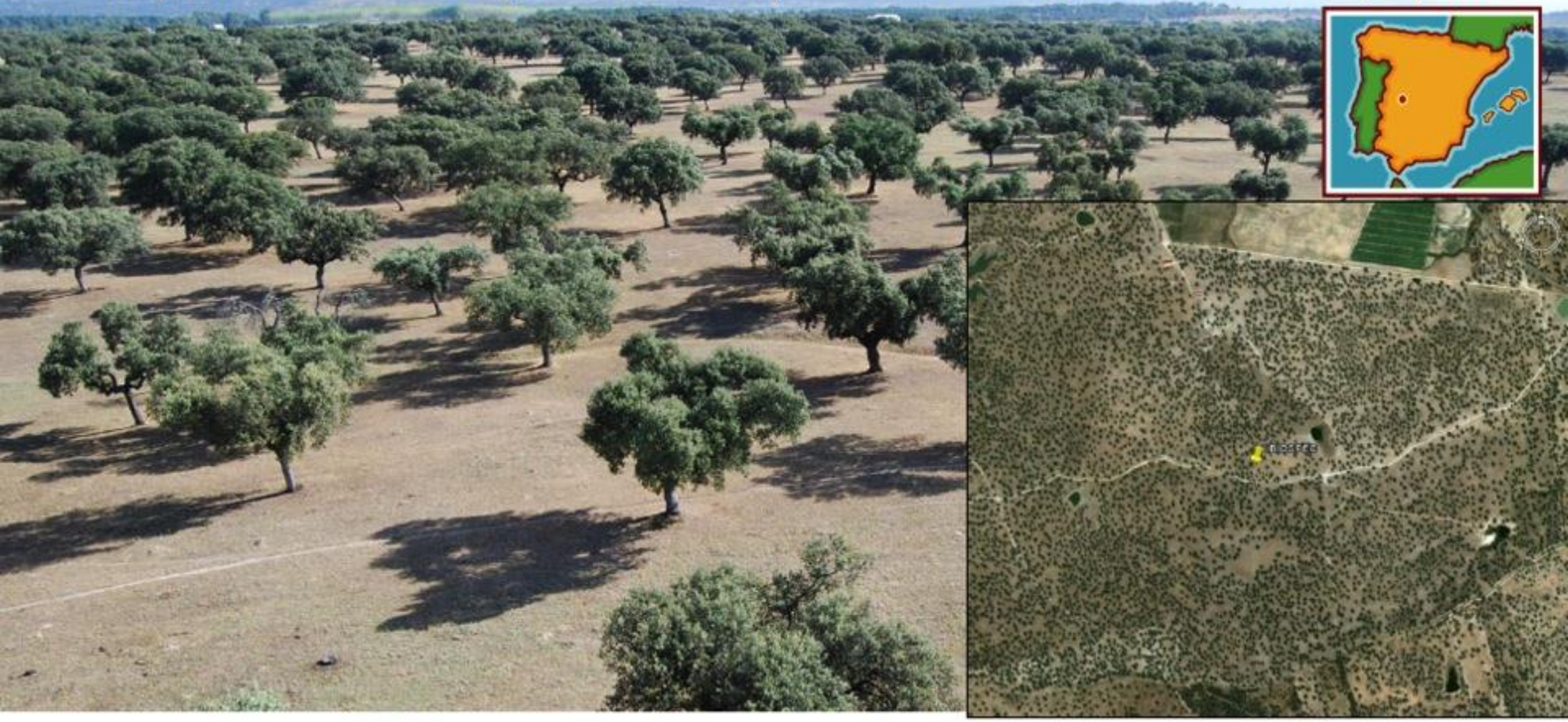
Josep Peñuelas[1,2], Benjamin Poulter[3], Jordi Sardans[1,2], Philippe Ciais[3], Marijn van der Velde[4], Laurent Bopp[3], Olivier Boucher[5], Yves Godderis[6], Philippe Hinsinger[7], Joan Llusia[1,2], Elise Nardin[6], Sara Vicca[8], Michael Obersteiner[4] & Ivan A. Janssens[8]

The availability of carbon from rising atmospheric carbon dioxide levels and of nitrogen from various human-induced inputs to ecosystems is continuously increasing; however, these increases are not paralleled by a similar increase in phosphorus inputs. The inexorable change in the stoichiometry of carbon and nitrogen relative to phosphorus has no equivalent in Earth's history. Here we report the profound and yet uncertain consequences of the human imprint on the phosphorus cycle and nitrogen:phosphorus stoichiometry for the structure, functioning and diversity of terrestrial and aquatic organisms and ecosystems. A mass balance approach is used to show that limited phosphorus and nitrogen availability are likely to jointly reduce future carbon storage by natural ecosystems during this century. Further, if phosphorus fertilizers cannot be made increasingly accessible, the crop yields projections of the Millennium Ecosystem Assessment imply an increase of the nutrient deficit in developing regions.

Motivation


Nutrient availability
C and H2O Fluxes
Water Use Efficiency
Ecosystem Respiration
C-Allocation
C-Turnover
Nutrient availability
Ecosystem functional response to different N/P stoichiometry
Structural and physiological phenology
Soil processes and properties
Water and Nutrient availability
Phenology
Above-/Below-Ground Biomass
SIF to predict GPP

Las Majadas del Tietar (39°56‘29'' N, 5°46'24'' W), Extremadura, Spain



Ecosystem: ***dehesa*** **Mediterranean Holm Oak open woodland (Savanna)**

Mediterranean Climate: annual T = 16.7 ºC, annual Prec = 550 mm LAI = 0.4 (trees) + 1-1.5 (grass)

Soil: Stagnic Alisols, depth > 2m. Texture: sandy loam. soil C is 8.5 g/kg and soil N is 0.82 g/kg (0-20cm layer).

Tree canopy: 98% *Quercus Ilex;* 25 tree/ha; mean DBH = 45cm; canopy height = 7-10 m; canopy fraction = 20%

Management: tree pruning every 25 years to optimize acorn production

Herbaceous layer: high biodiversity (easy to find > 20 species within 4 m^2); ≠ composition below tree / open;

Management: continuous grazing (cows)

Courtesy A. Carrara

Experimental Site

MaNiP

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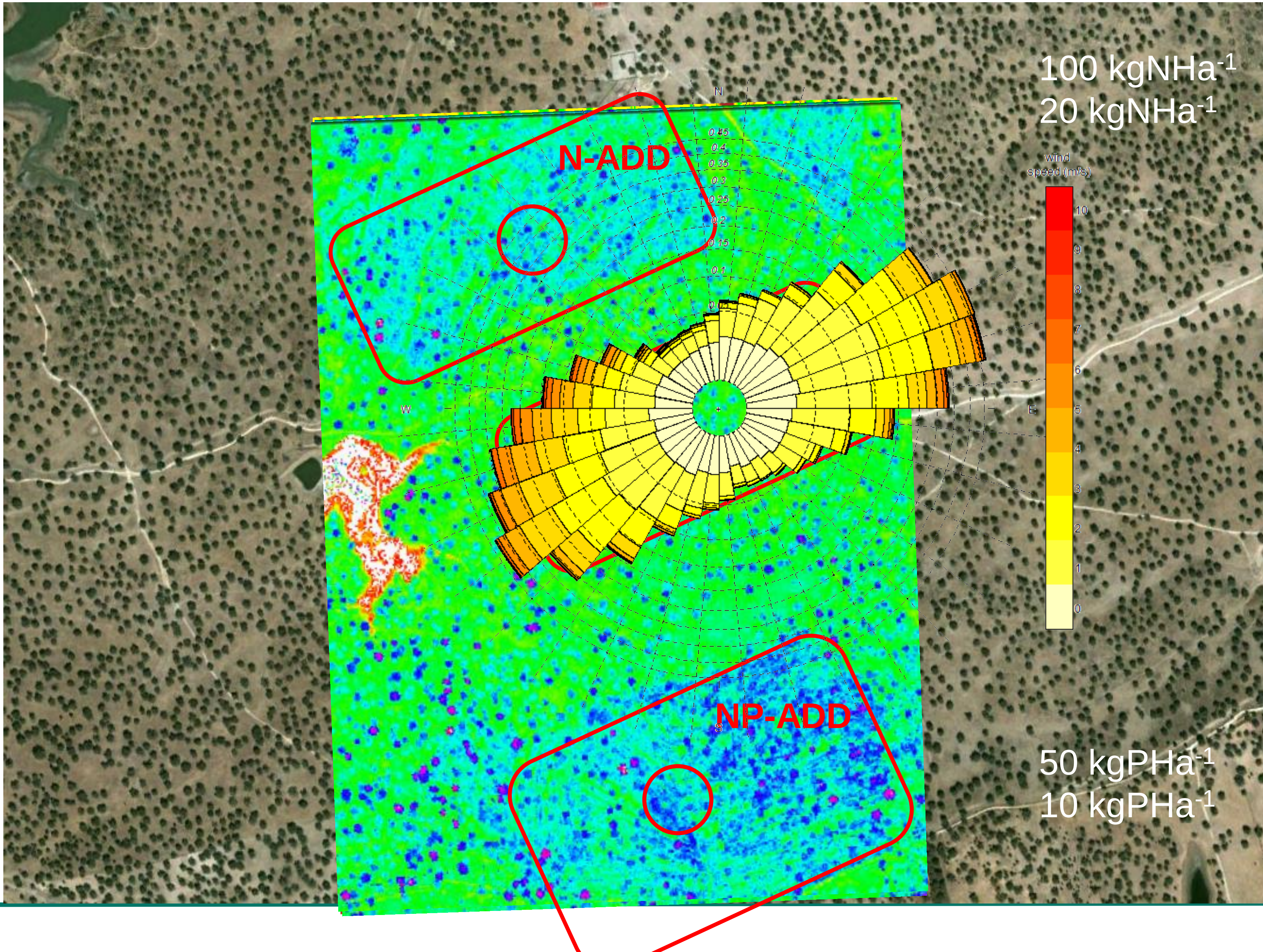

Experimental Site

MaNiP

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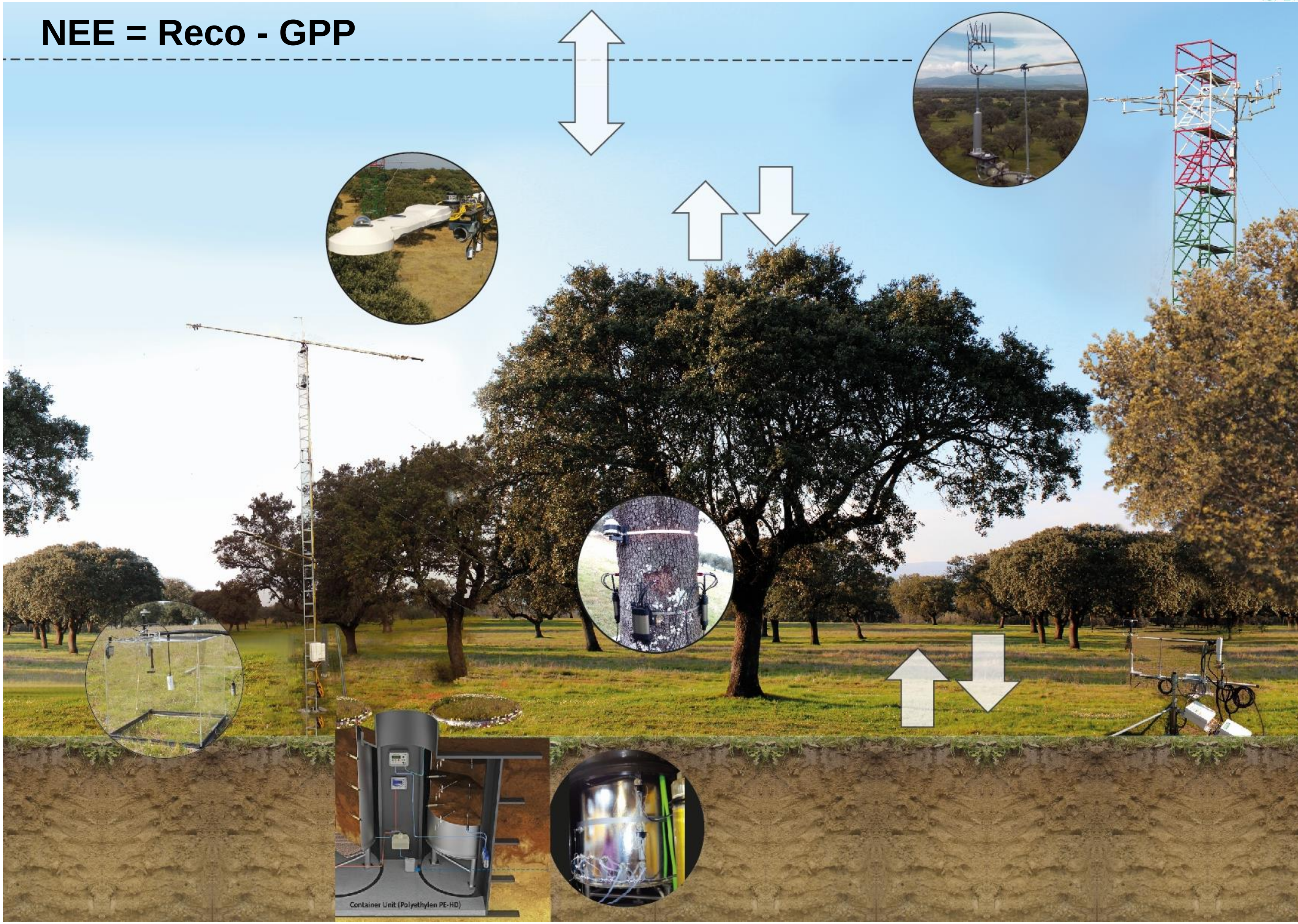

Experimental Site – Long Term EC station

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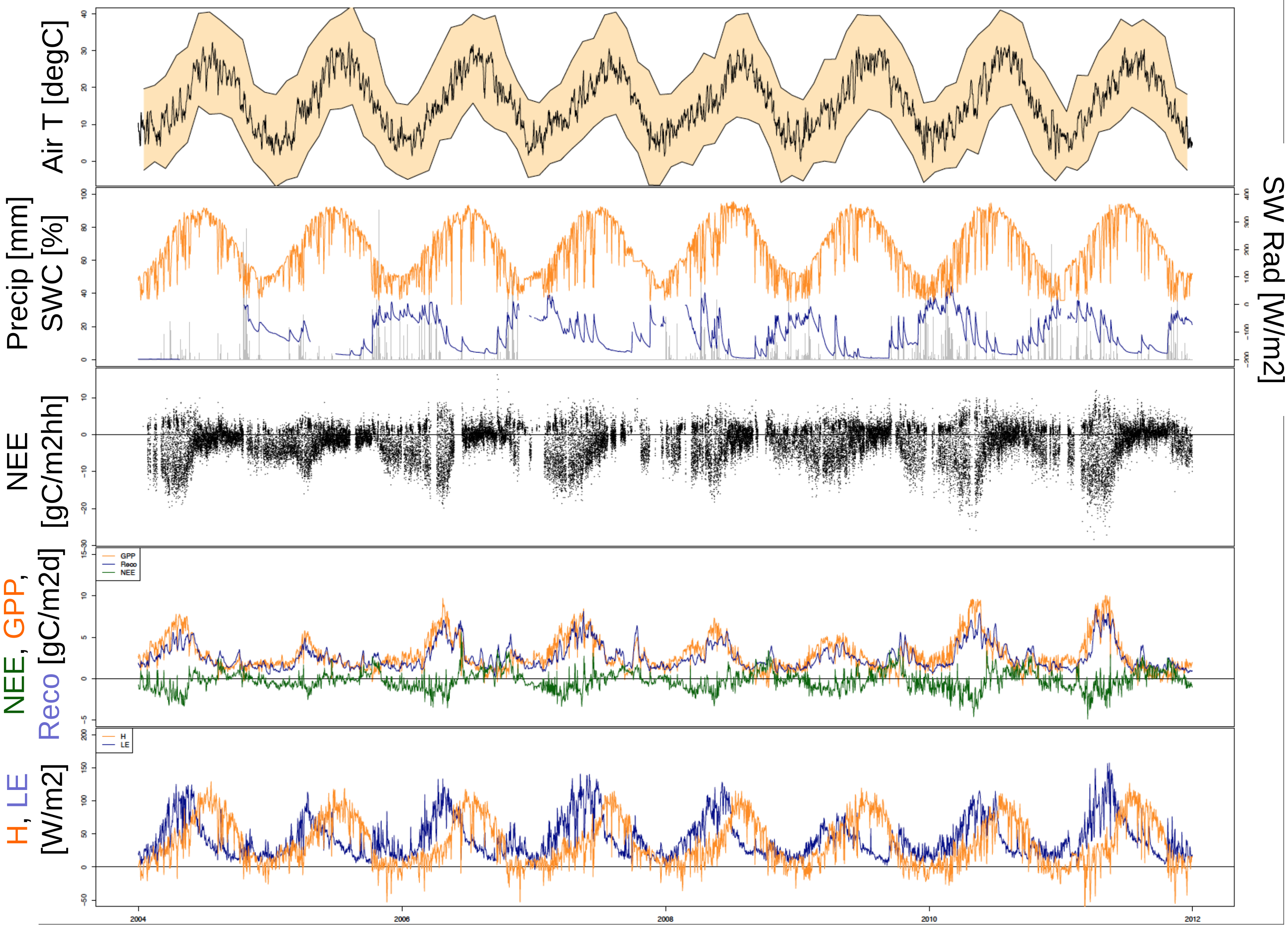

Data collected by CEAM – Valencia (PI Arnaud Carrara)

Experimental Site - Phenology

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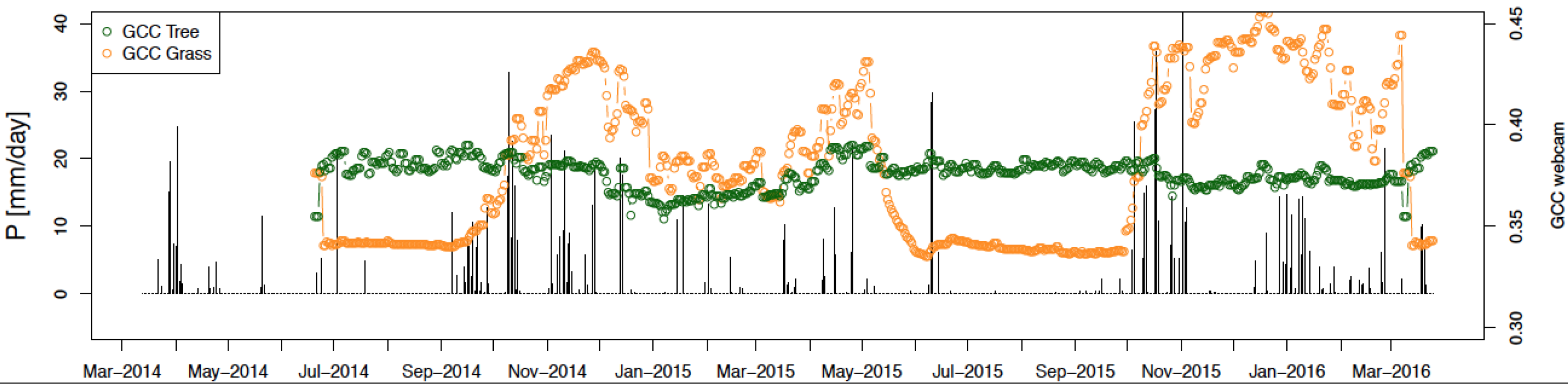
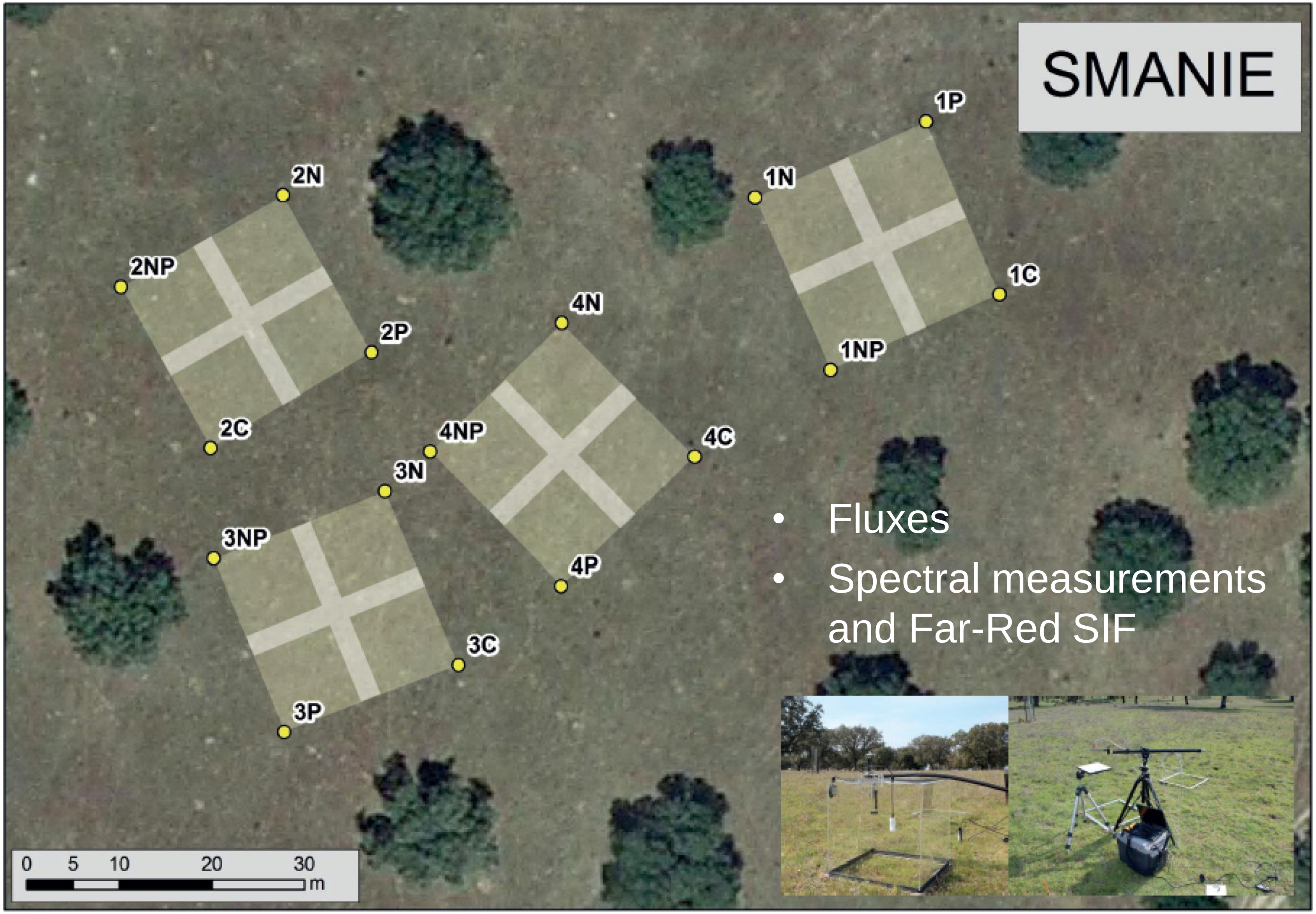


- **Typical Mediterranean ecosystem with dry summer**
- **Grass layer activity determined by water availability**
- **Evergreen Holm Oak**
- **Definition of phenophase based on grenness (e.g peak of season)**

Luo et al., AFM Submitted

Experimental Site – SMANIE



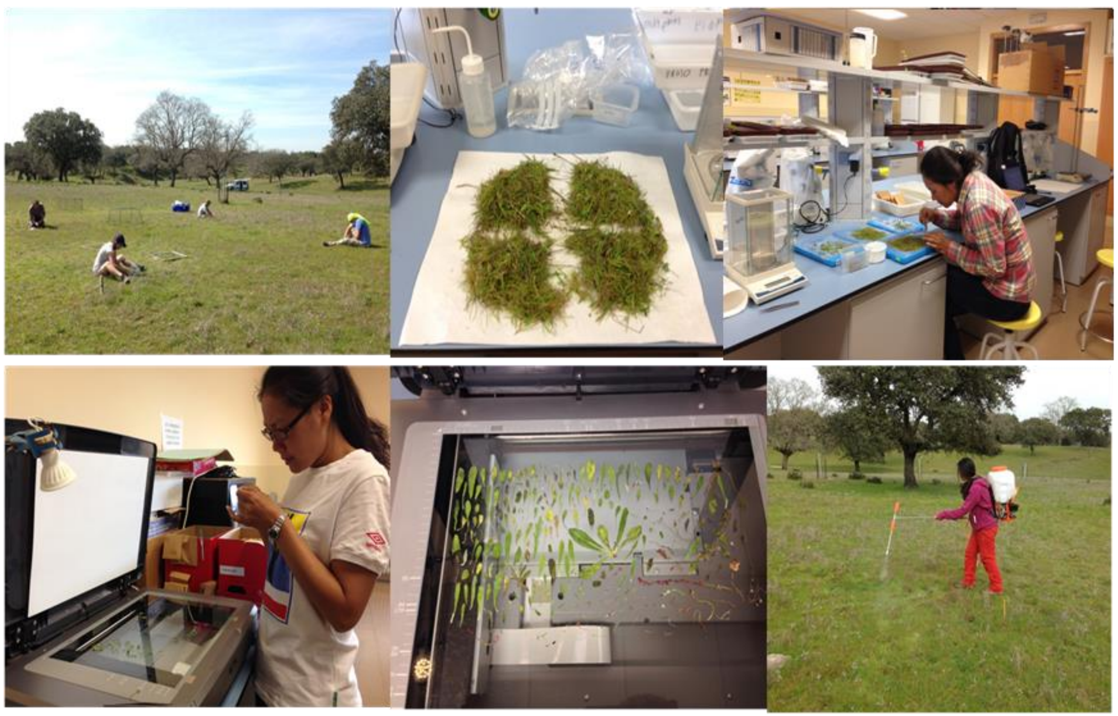
- Fluxes
- Spectral measurements and Far-Red SIF

Migliavacca et al., 2017 New Phytologist

Experimental Site – SMANIE

PLOT	Fertilizer	N, kg/ha	P, kg/ha	K, kg/ha
N	Potassium Nitrate (KNO_3) Ammonium Nitrate (NH_4NO_3)	44 156		123
P	Monopotassium Phosphate (KH_2PO_4)		100	123
N+P	Ammonium Nitrate (NH_4NO_3) Monopotassium Phosphate (KH_2PO_4)	200	100	123

Fertilization conducted in March 2014 and 2015



- Green/Dry biomass
- Direct LAI
- Canopy height
- Plant forms abundance
- Nutrient analysis in the main plant forms
- Soil C, N, and P content
- Top of the canopy images

Main Goals

1) **Effects of N and P availability on fluxes: Photosynthesis (GPP) and Total Ecosystem Respiration (Reco)**

2) **Effects on efficiencies: Light and Water Use**

3) **Detection of ecosystem functions with Sun Induced Fluorescence (SIF): Interplay between Photosyntehsis, Structural Changes and photosynthetic efficiencies**

…Ecosystem scale responses

Effects fertilization

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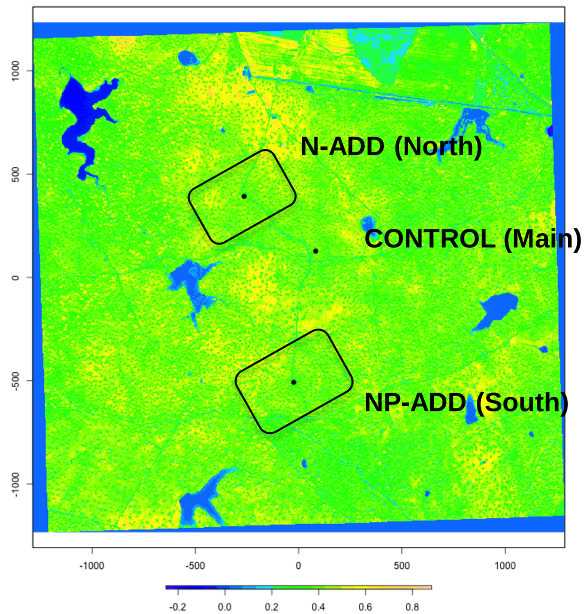
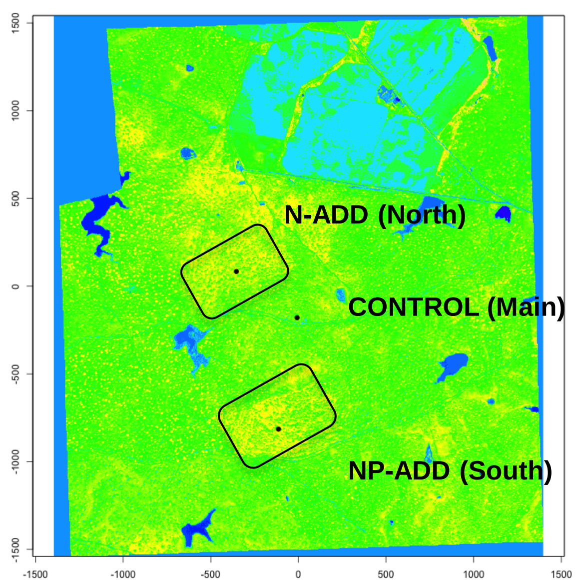
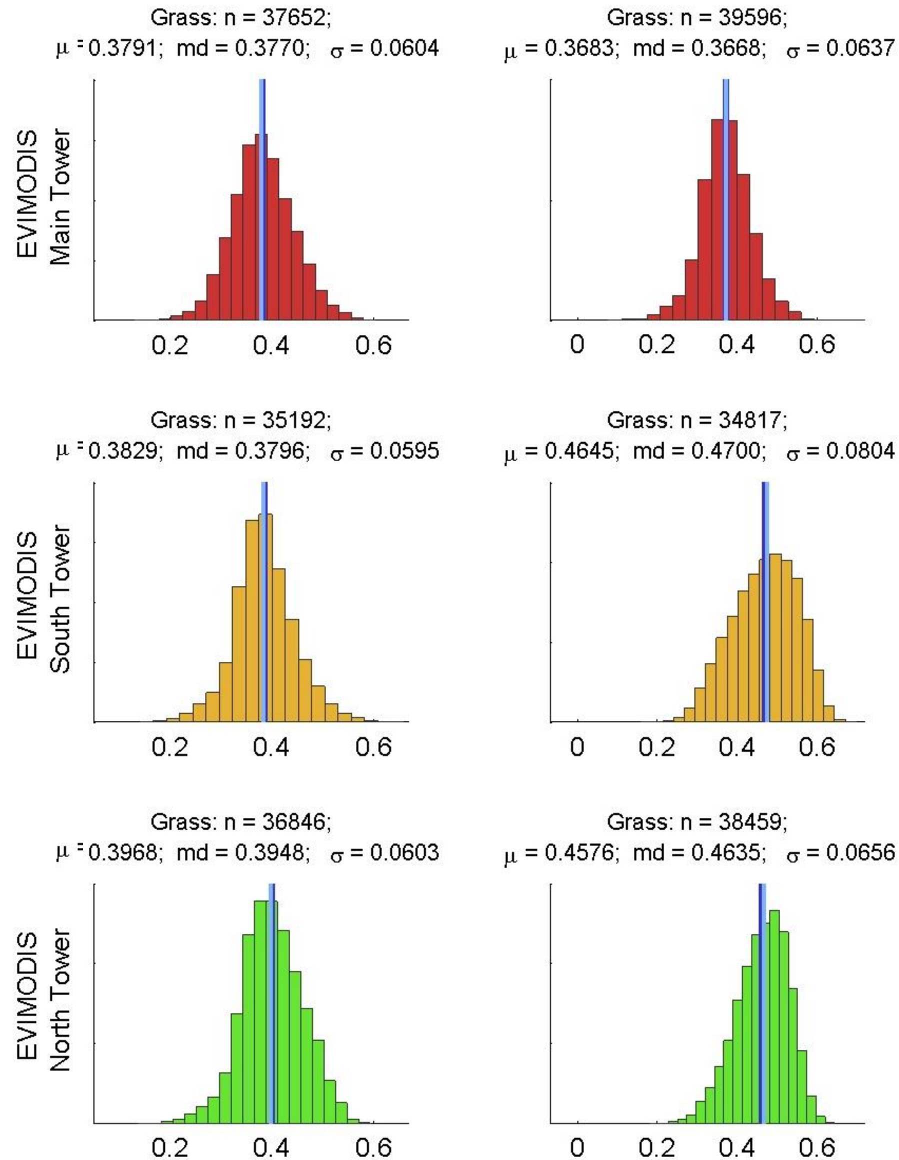
N-ADD (North)
CONTROL (Main)
NP-ADD (South)

Pre-fertilization



Post-fertilization





Effects fertilization

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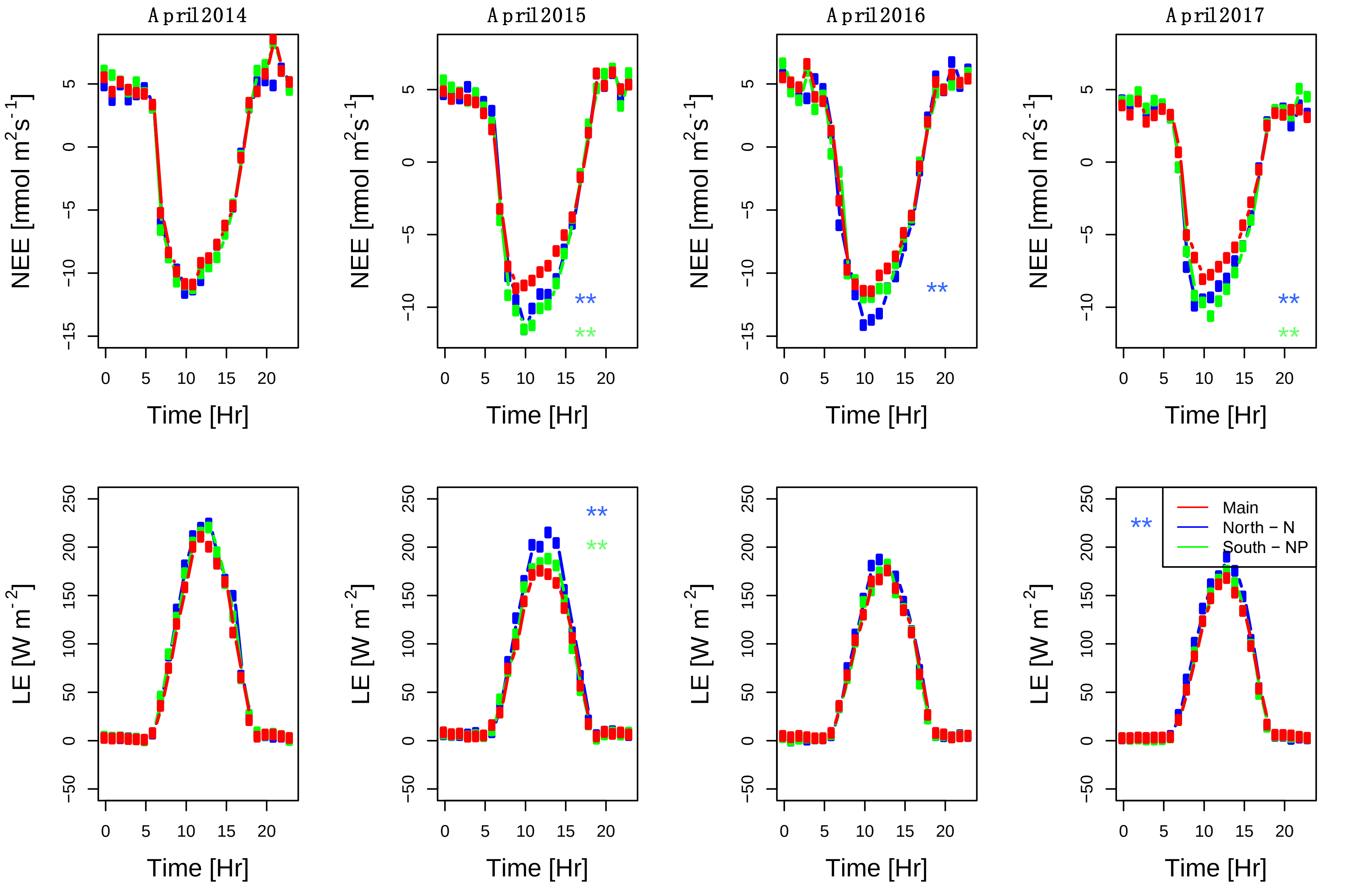
Faster phosphate turnover in plot fertilized with nitrogen or phosphorus implying co-limitation

Site	Treatment	$\delta^{18}O_P$ (‰)	Bioavailable P concentration (µg/g soil)	Organic P concentration (µg/g soil)	C concentration (mg/g soil)	N concentration (mg/g soil)
MANIP	Control	23.8 ± 0.8	4.6 ± 0.3	15.9 ± 0.5	10.1 ± 1.8	0.9 ± 0.2
	Control - Tree	24 ± 0.8	9.4 ± 0.3	19.2 ± 3.1	20.8 ± 5.6	1.8 ± 0.5
	N	23.1 ± 0.2	5.3 ± 1.1	10.7 ± 1.6	11.1 ± 0.6	1.0 ± 0.1
	N - Tree	23.6 ± 1.1	4.4 ± 2.8	19.6 ± 2.6	17.9 ± 4.3	1.7 ± 0.3
	P	25.1 ± 2.2	10.8 ± 9.9	10.0 ± 1.6	8.0 ± 3.1	0.7 ± 0.3
	P - Tree	25.8 ± 0.7	12.7 ± 2.3	20.7 ± 5.2	22.9 ± 7.6	2.0 ± 0.5
	NP	23.6 ± 0	9.1 ± 0.1	16.7 ± 0.5	11.8 ± 1.7	1.1 ± 0.1
	NP - Tree	25.1 ± 0.1	10.6 ± 1.3	22.9 ± 6.3	19.4 ± 2.0	1.8 ± 0.2
SMANIE	Control	23.1 ± 0.4	4.1 ± 0.4			
	N	23.2 ± 0.8	4.9 ± 0.8			
	P	25.2 ± 0.6	21.2 ± 4			
	NP	24.4 ± 0.4	16.2 ± 1.7			

Weiner et al., (Submitted)

Response of fluxes



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Photosynthesis vs Ecosystem Respiration

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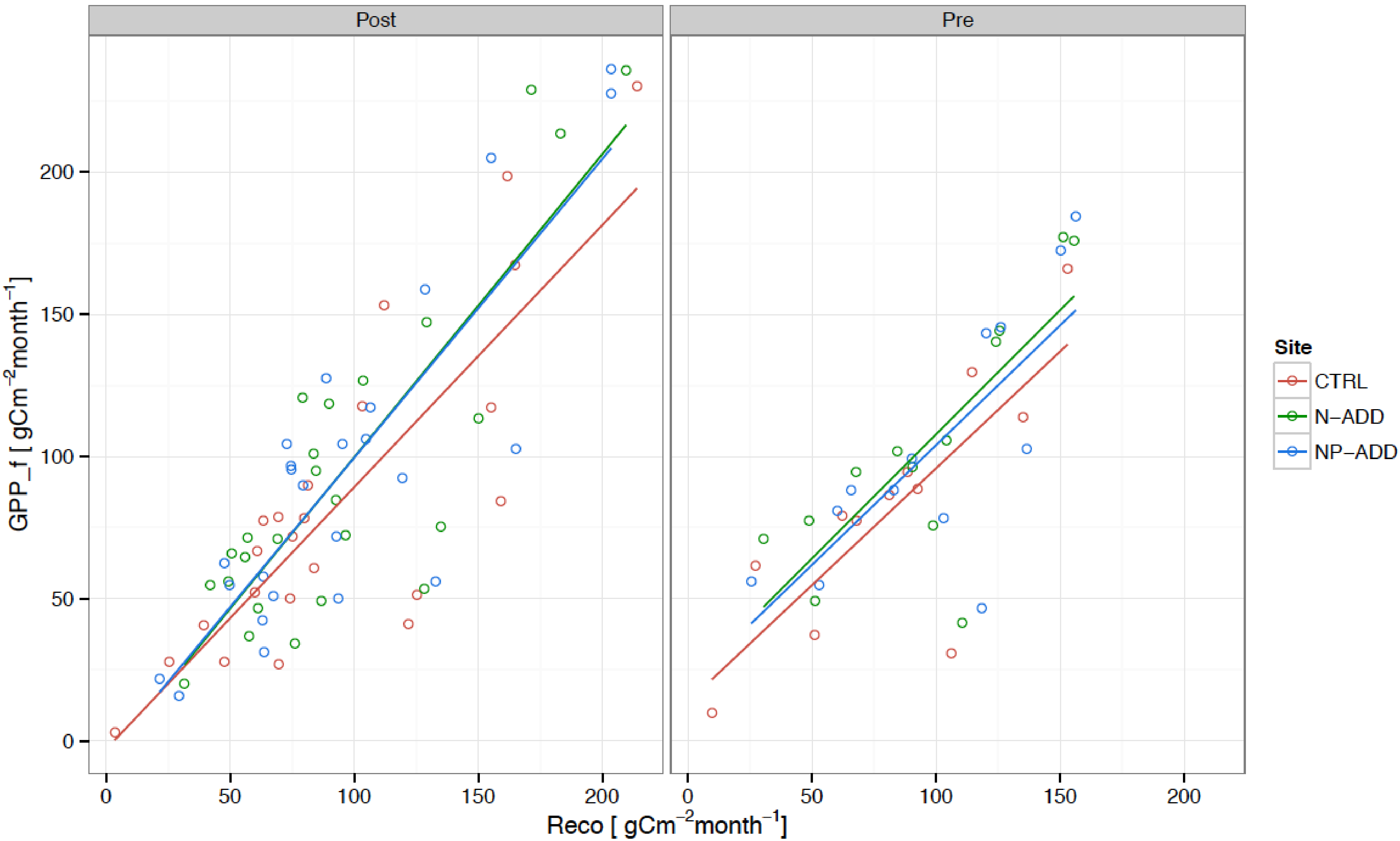

Statistical significant differences slope post fertilization ANCOVA ($p < 0.05$)

Response of Photosynthesis

MaNiP

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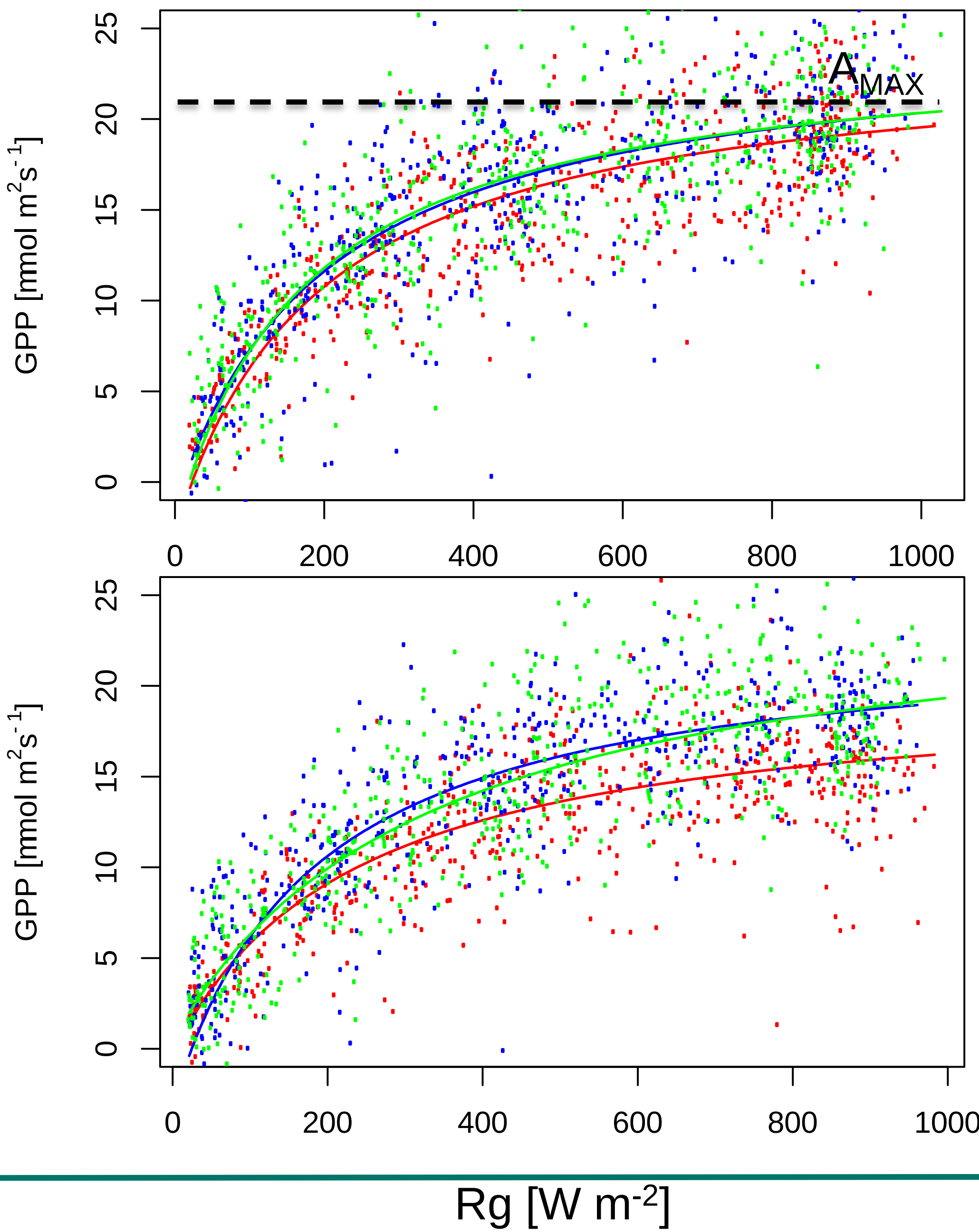
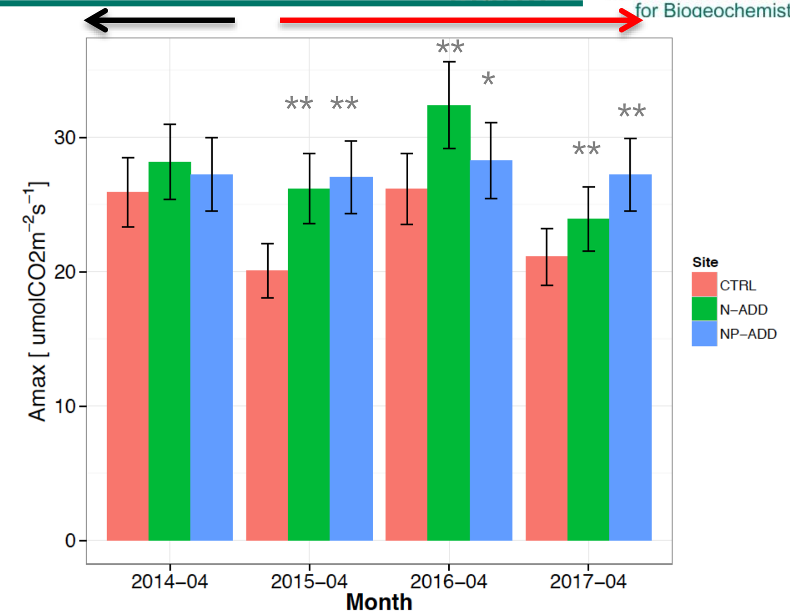
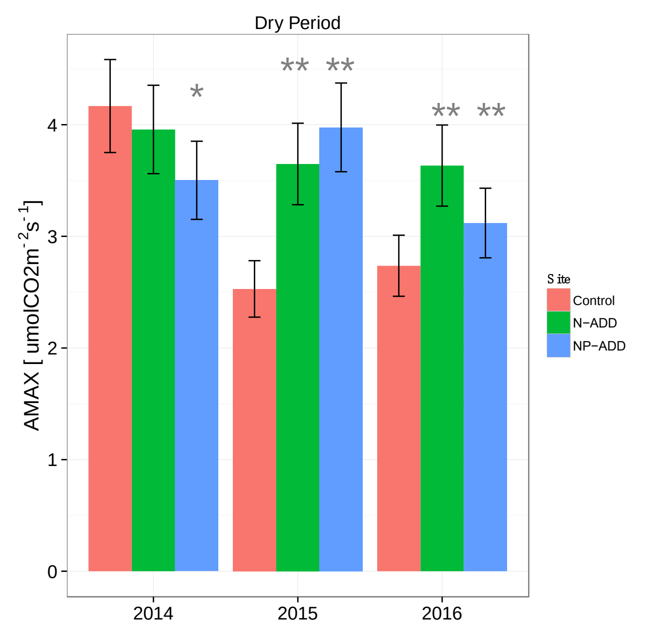
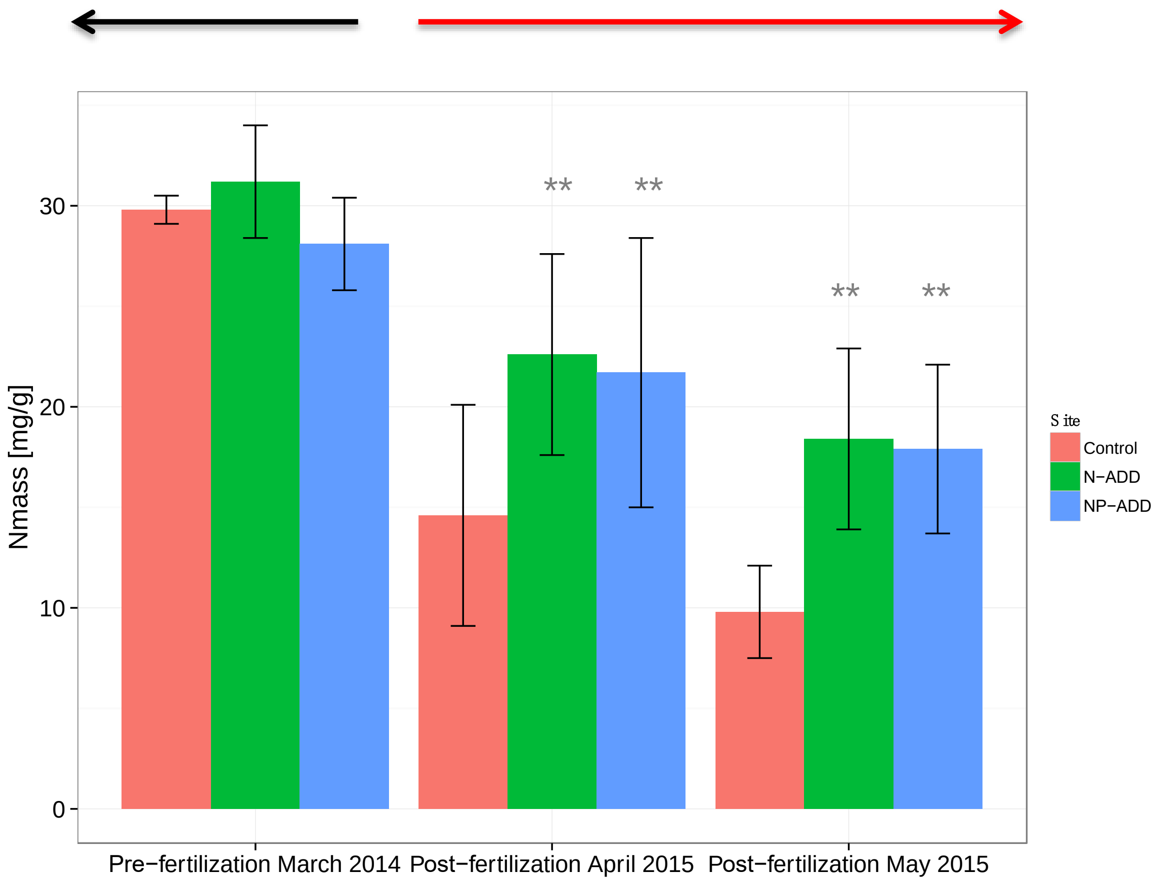
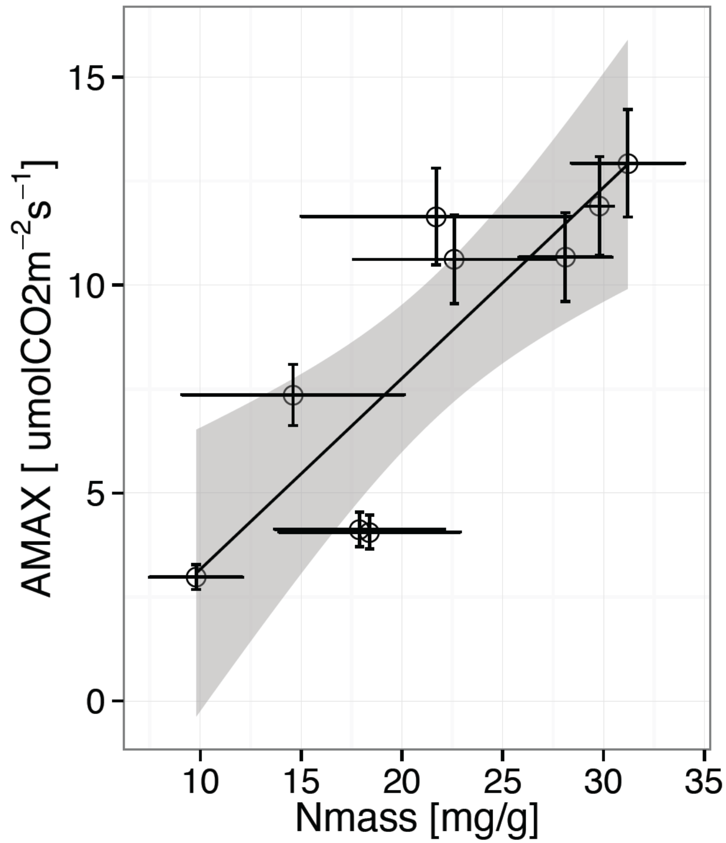




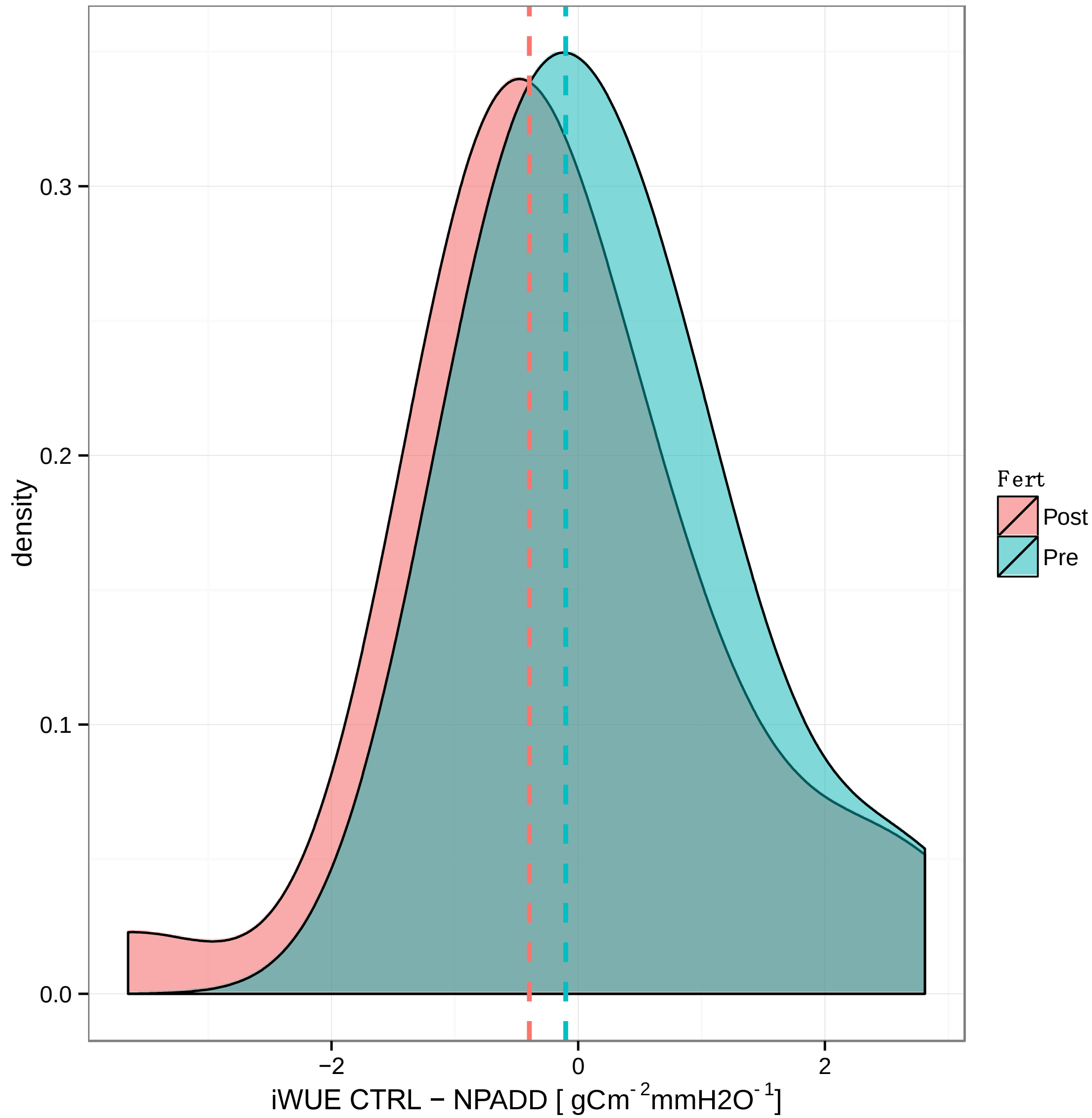


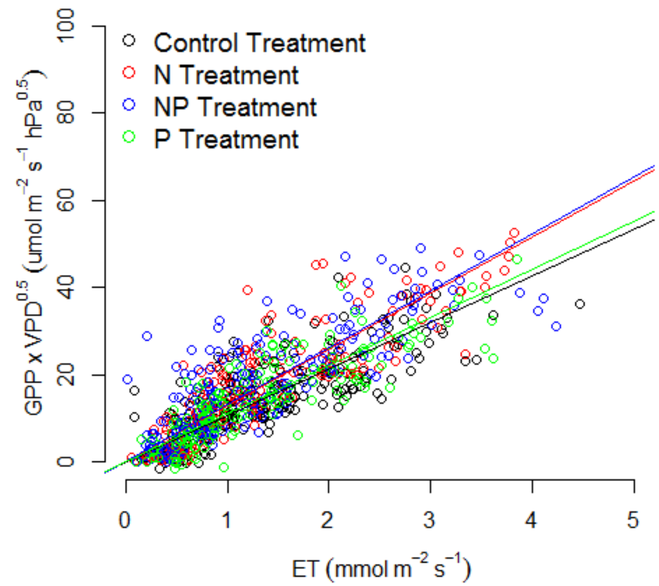
Response of Photosynthesis





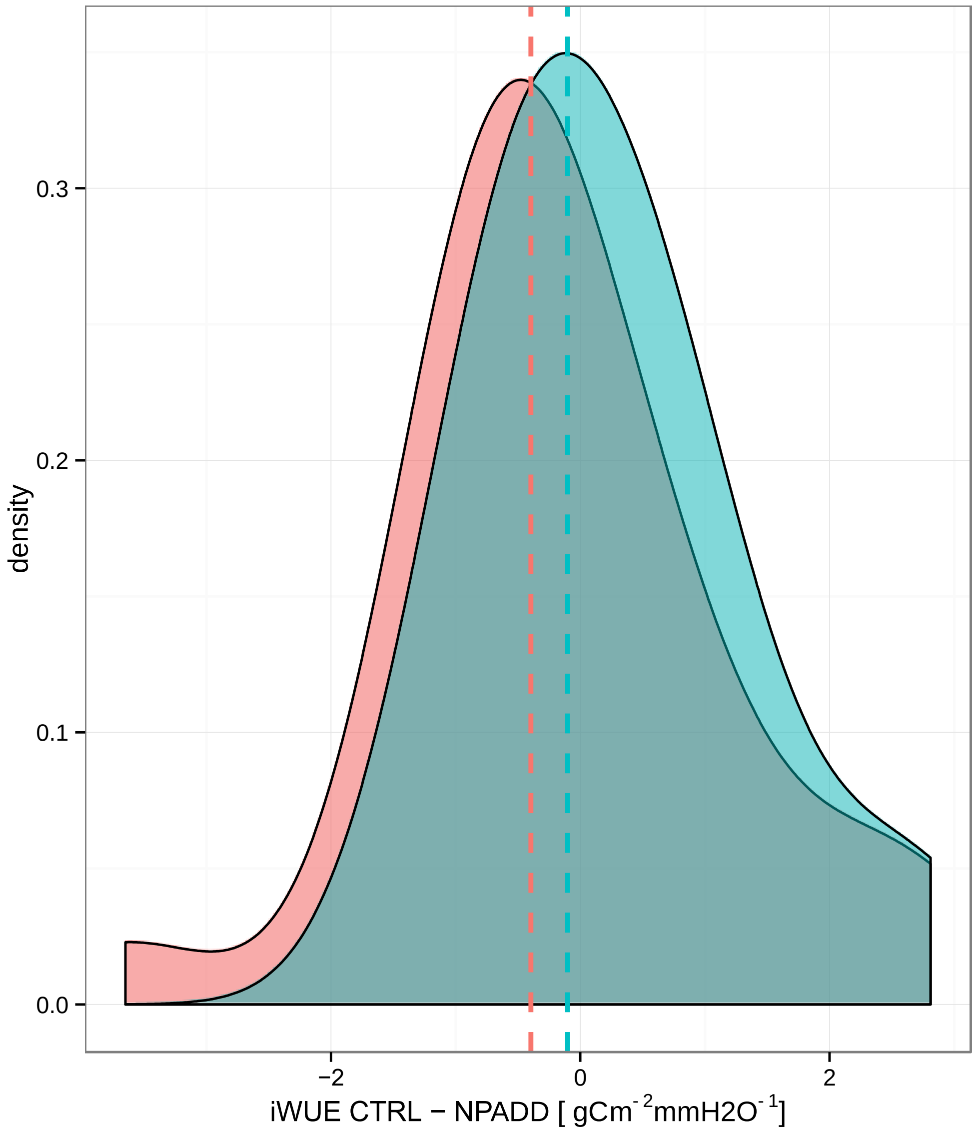
Response of Water Use Efficiency

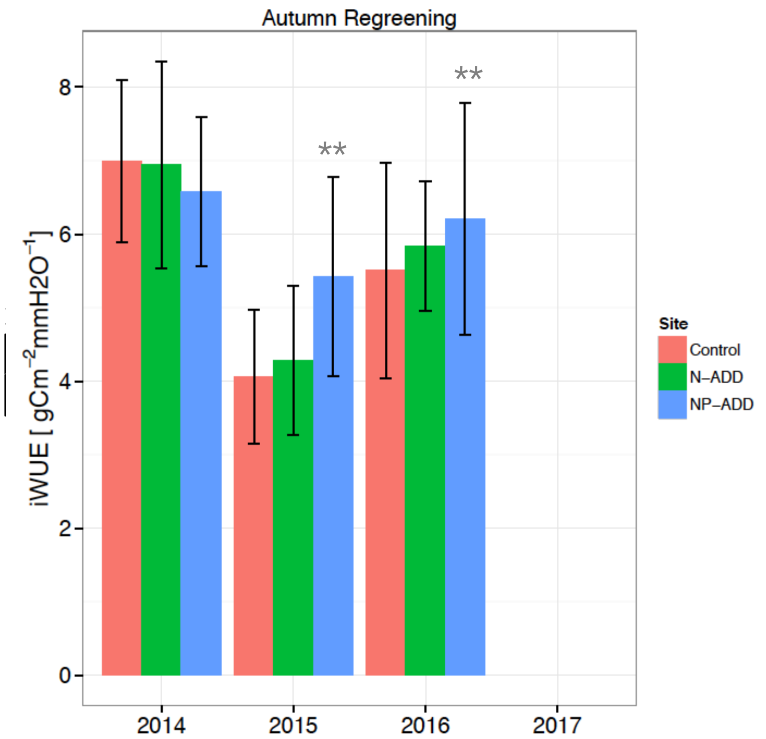




$$iWUE = \frac{GPP\sqrt{VPD}}{T}$$

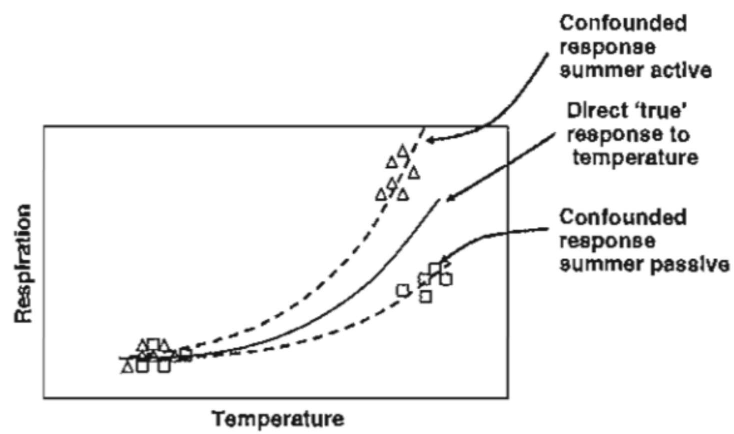
Response of Water Use Efficiency

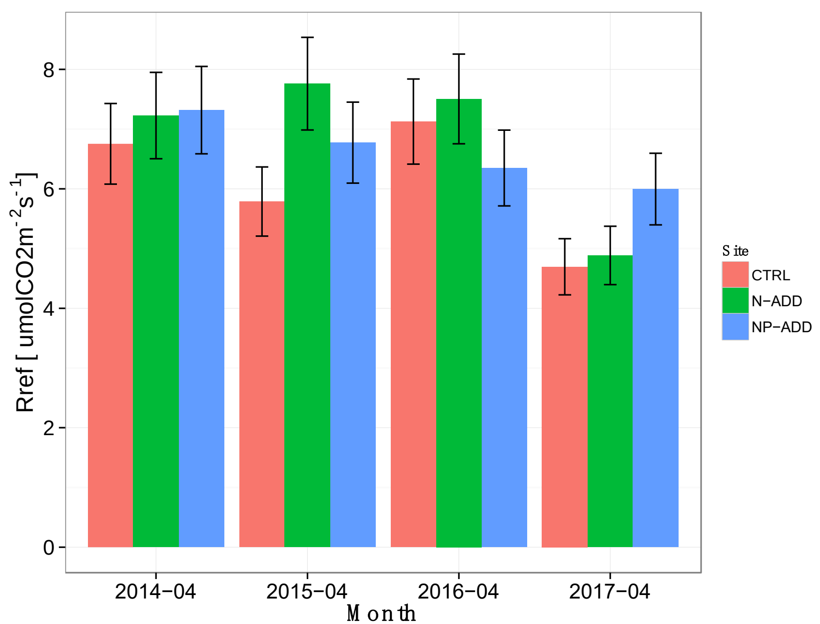


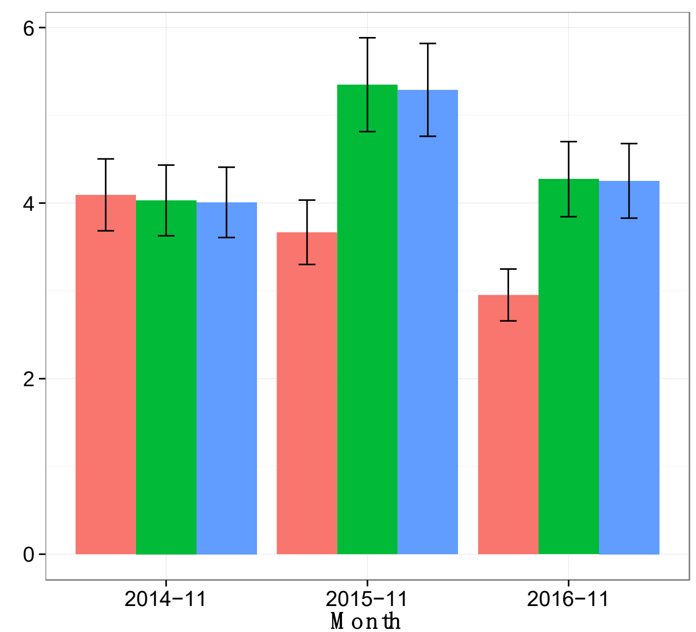


Response of Ecosystem respiration

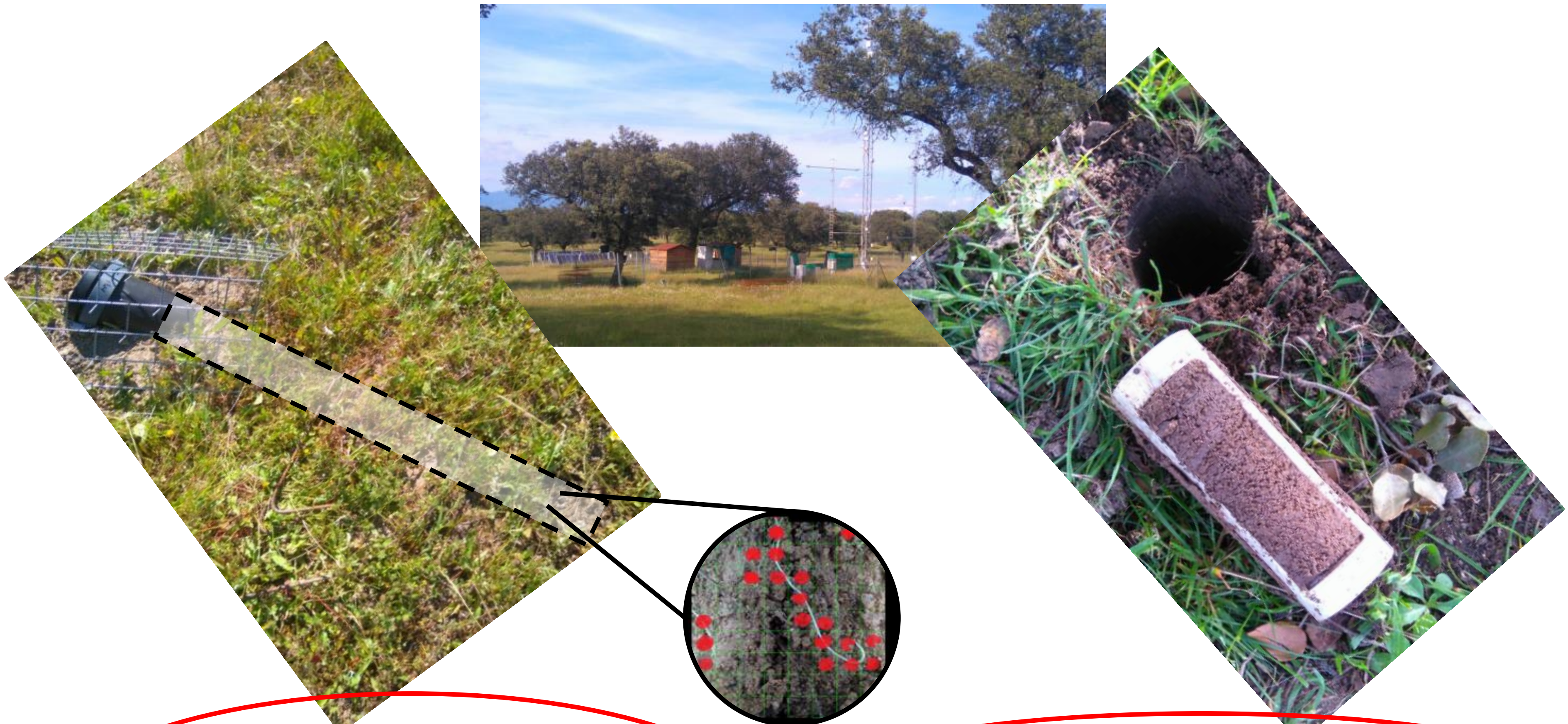
$$R_{eco} = R_{ref} e^{E_0(1/(T_{ref}-T_0)-1/(T-T_0))}.$$







Response of Ecosystem respiration



MINIRHIZOTRON MEASUREMENTS

'remote sensed' Root biomass

Root dynamics/phenology

INGROWTH CORES AND DIRECT SAMPLING

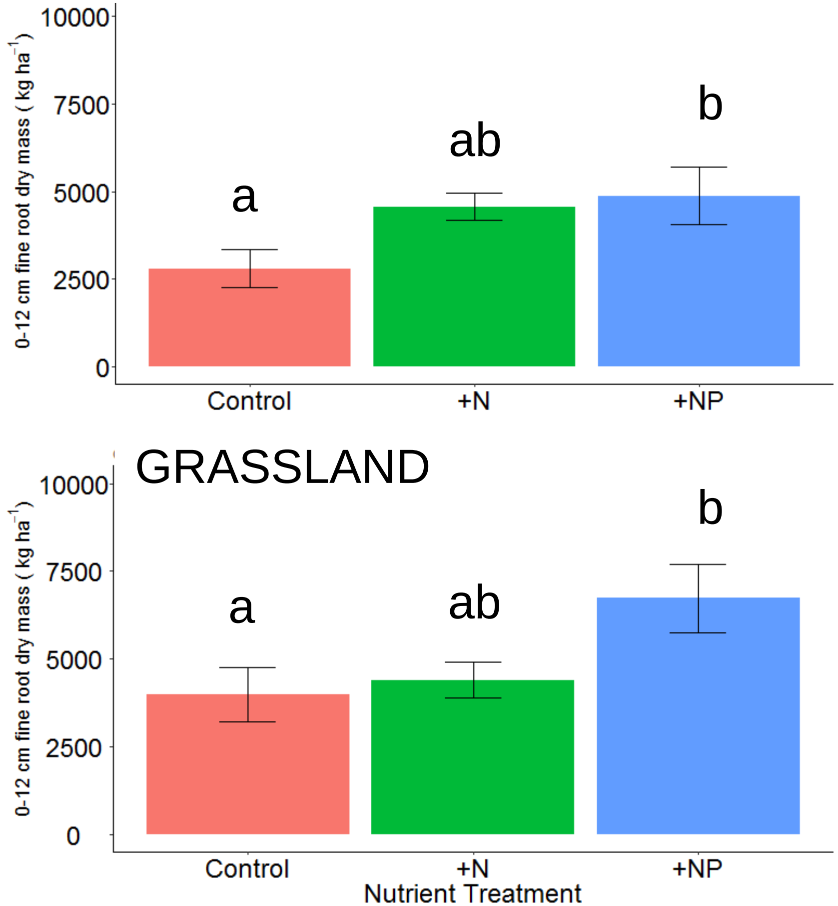
Root Biomass, Root C/N/P

INGROWTH CORES CONTAINING ^{15}N - LITTER

Soil ^{15}N partitioning / litter decomposition

Response of Ecosystem respiration

Fine root = root in ingrowth core



n = 15

Nair et al., In Prep

Response of Ecosystem respiration

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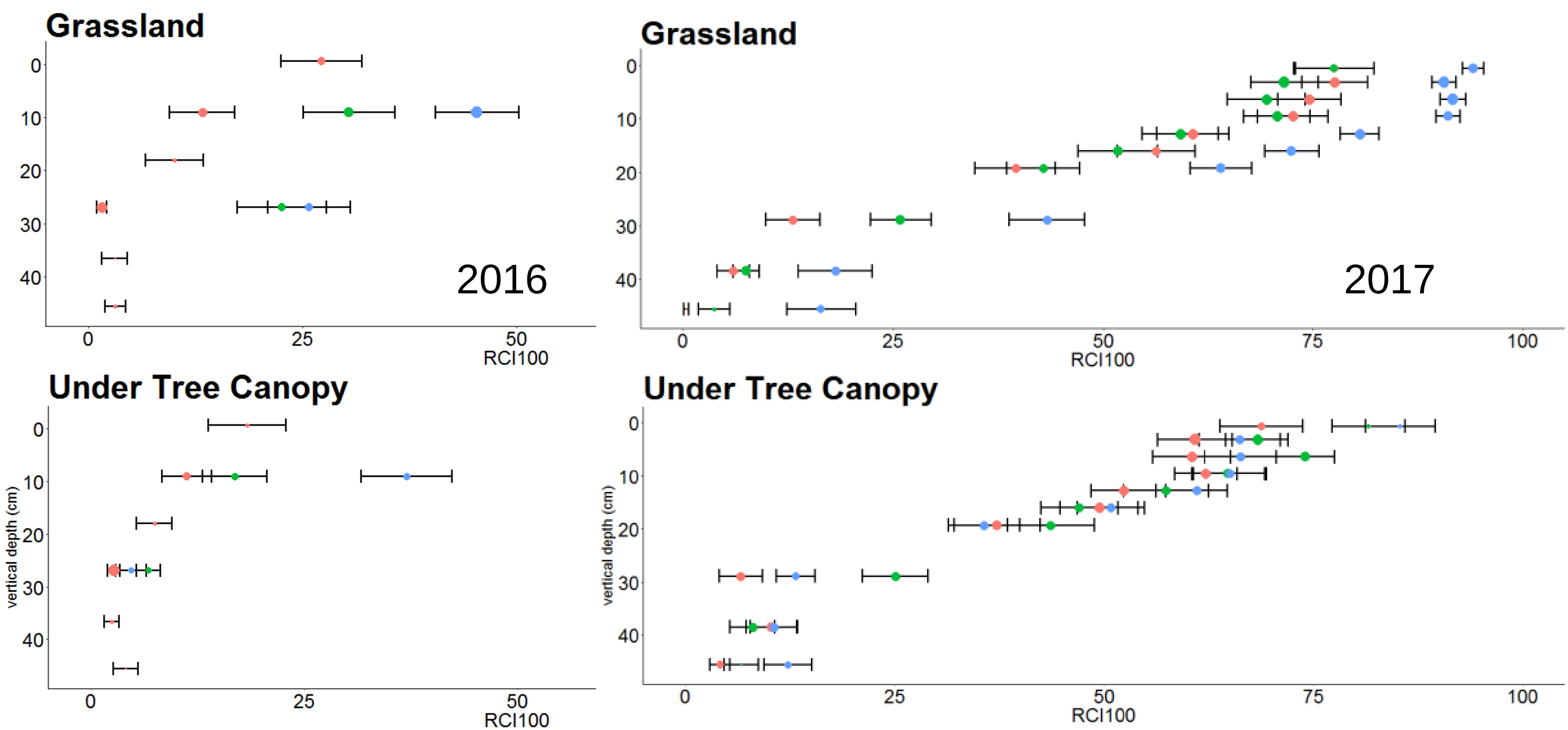
RCI: Root Cover 'Index'



+N + P treatment has more roots IN GRASSLAND

No treatment difference under tree canopy

Nair et al., In Prep

Response of Photosynthesis

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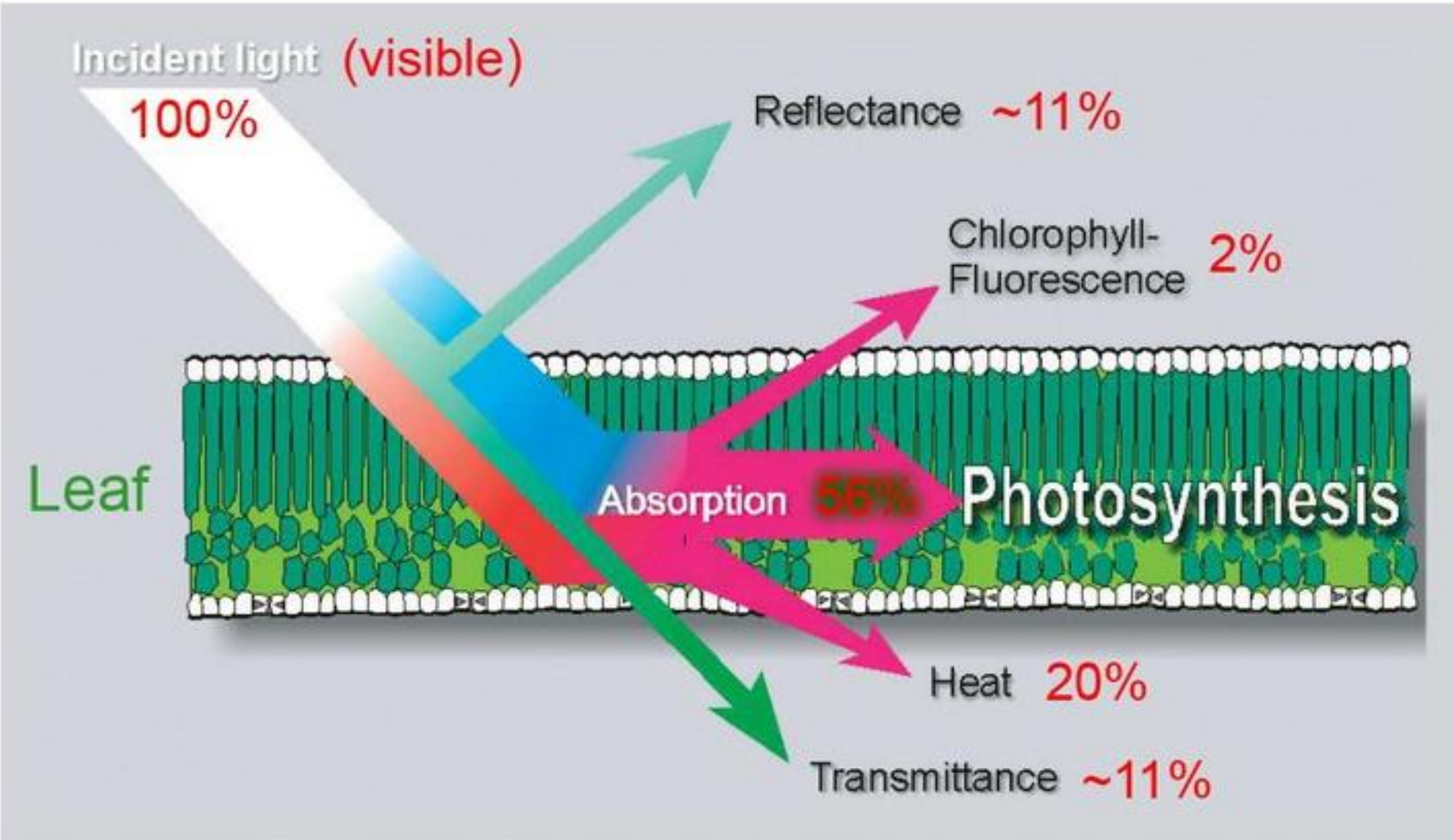
…a remote sensing perspective

Response of Photosynthesis



Mapping Photosynthesis from Space - a new vegetation-fluorescence technique
ESA bulletin. Bulletin ASE. European Space Agency. 11/2003; 116:34-37.

Response of Photosynthesis

Structural and physiological indices and SIF@760nm

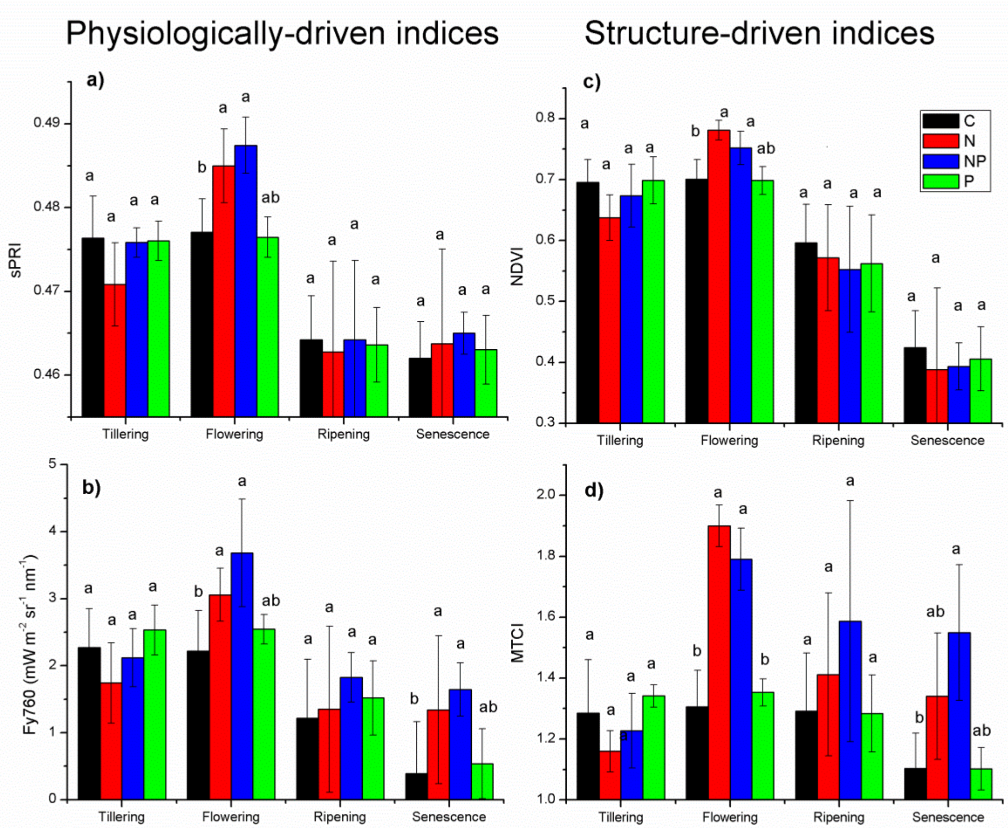


Fig 2. Seasonal time course of mean midday VIs; a)Fy760, b)sPRI, c) NDVI, and d) ND.750.705 among C, N, NP and P treatments in a Mediterranean grassland in Spain. Bars indicate SE, N=4. Different letters denote significant difference (Weilch t test, P0.05).

- MTCI strongly related with canopy N content (r=0.89***)
- sPRI and SIF@760 nm jointly used to detect LUE across treatments

Perez-Priego et al., 2015

Response of Photosynthesis

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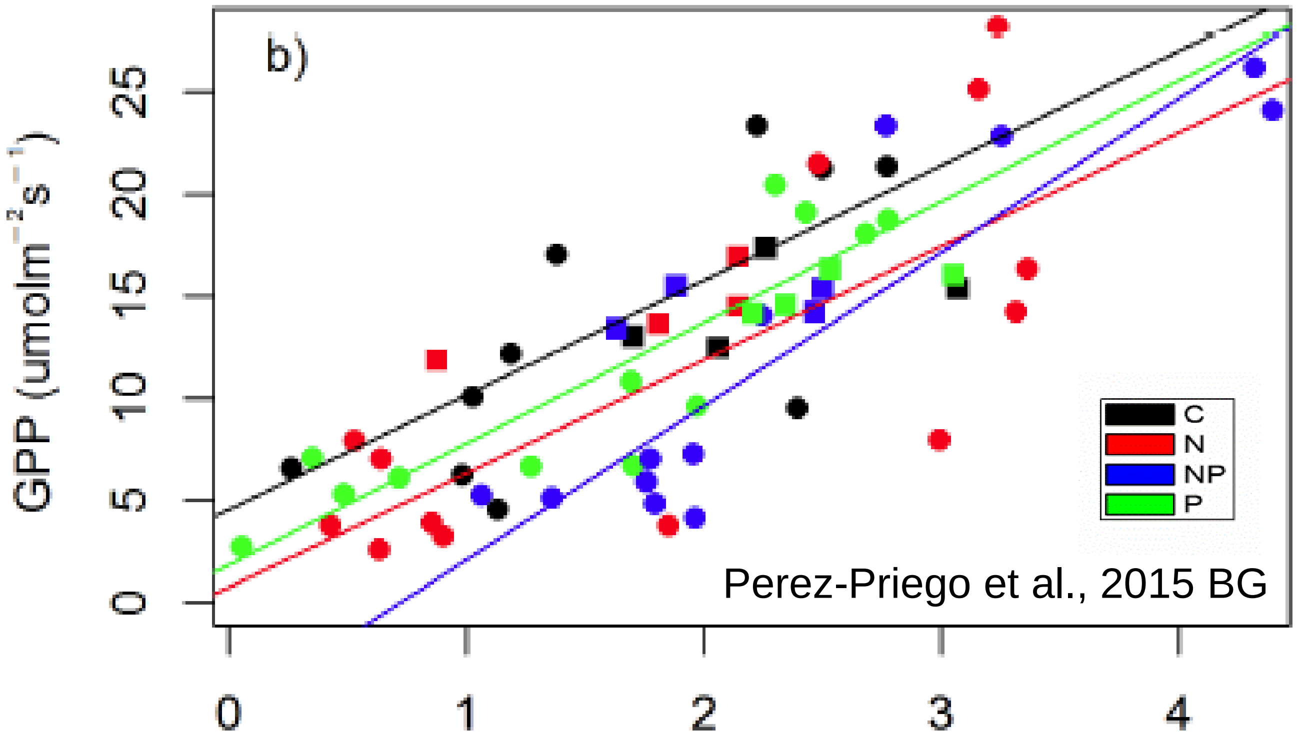

$$GPP \approx F760 \cdot \frac{LUE_p}{f_{esc} \cdot LUE_f}$$

….but also Damn et al., 2015 RSE; Wieneke et al., 2017 RSE; Liu et al., 2017; Guanter et al

Response of Photosynthesis - Modeling

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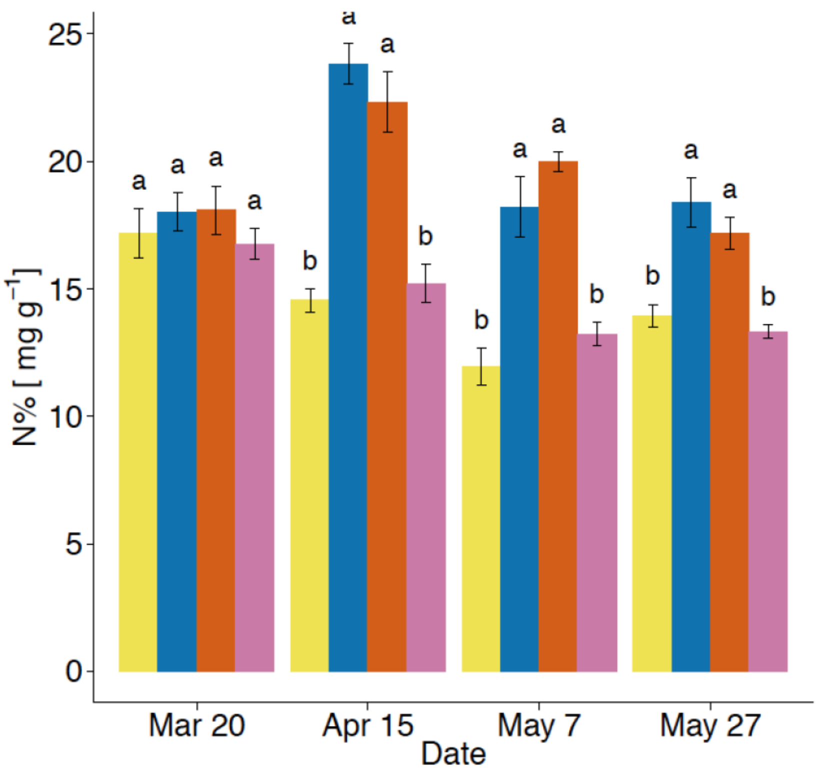
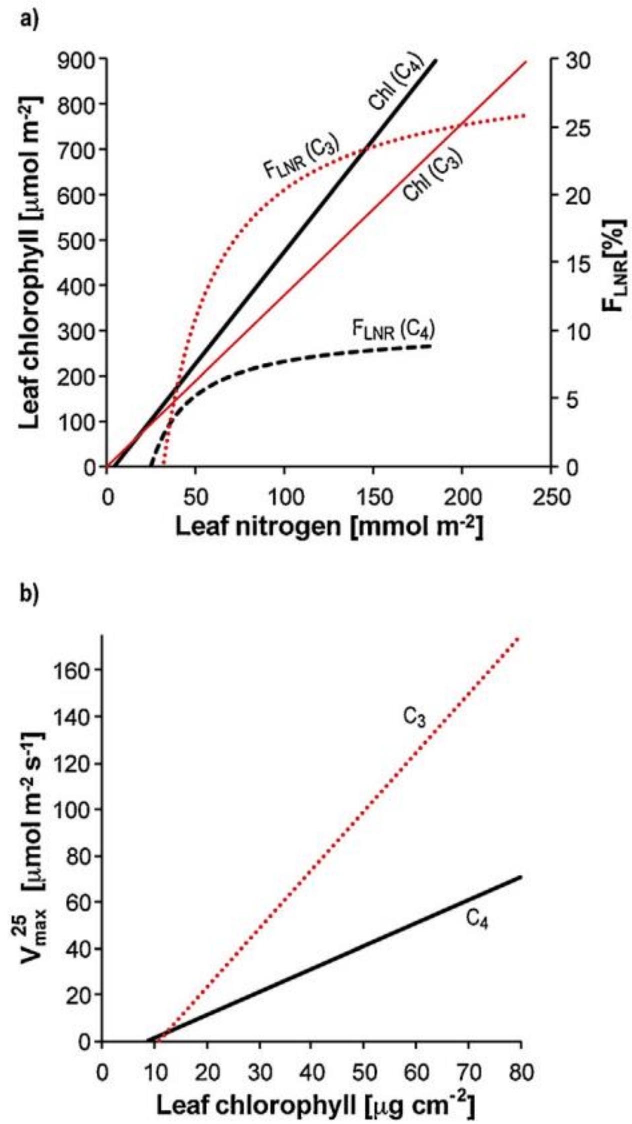
Effects of fertilization on functional traits

- changes in foliar N,P content and LMA
  → changes in Chl ab and Vcmax
- Walker et al., 2014; Hobourg et al., 2013; Feng and Dietze et al., 2013





Modified from Perez-Priego et al 2015 (BG)

Houborg et al 2013 (AFM)

Response of Photosynthesis - Modeling

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Effects of fertilization on biodiversity and canopy structure

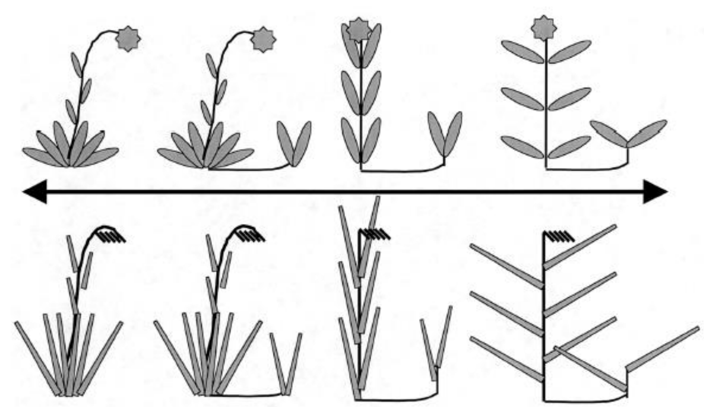
- Changes in the fraction of plant forms (%) lead to changes in leaf angle distribution
- Parameters recomputed accounting for a typical Leaf Angle Distribution the 3 main plant forms

Campaign	Treatment	Total PAI_g ($m^2\ m^{-2}$)	Total PAI_g ($m^2\ m^{-2}$)	Forbs f_{PAI}	Grass f_{PAI}	Legumes f_{PAI}
Date	–	mean	SD	%	%	%
no. 1	C	0.85	0.18	35.5	56.8	7.7
20 March 2014	N	0.76	0.21	39.2	45.1	15.0
Growing period	NP	1.03	0.30	29.1	54.3	12.9
Pretreatment	P	0.95	0.21	26.6	66.6	6.9
no. 2	C	2.02	0.43	14.5	85.2	0.3
15 April 2014	N	2.17	0.91	11.9	87.6	0.4
Growing period	NP	2.46	0.45	4.1	95.6	0.3
Posttreatment	P	1.66	0.58	14.2	85.7	0.1
no. 3	C	1.08	0.27	43.0	55.1	1.9
7 May 2014	N	1.29	0.58	28.3	70.7	1.0
Dry period	NP	0.84	0.21	27.2	71.8	1.0
	P	1.37	0.57	39.5	58.5	2.0
no. 4	C	0.44	0.10	66.7	33.3	0.0
27 May 2014	N	0.48	0.28	36.4	63.6	0.0
Dry period	NP	0.53	0.26	40.6	59.4	0.0
	P	0.71	0.31	56.1	43.9	0.0

Perez-Priego et al 2015 (BG)

LIDFa, **LIDFb** according to variation of plant forms % (Asner 1998, RSE):

Grass: erectophile
Legumes: planophile
Forbs: spherical



Craine et al 2001 (OIKOS)

Response of Photosynthesis

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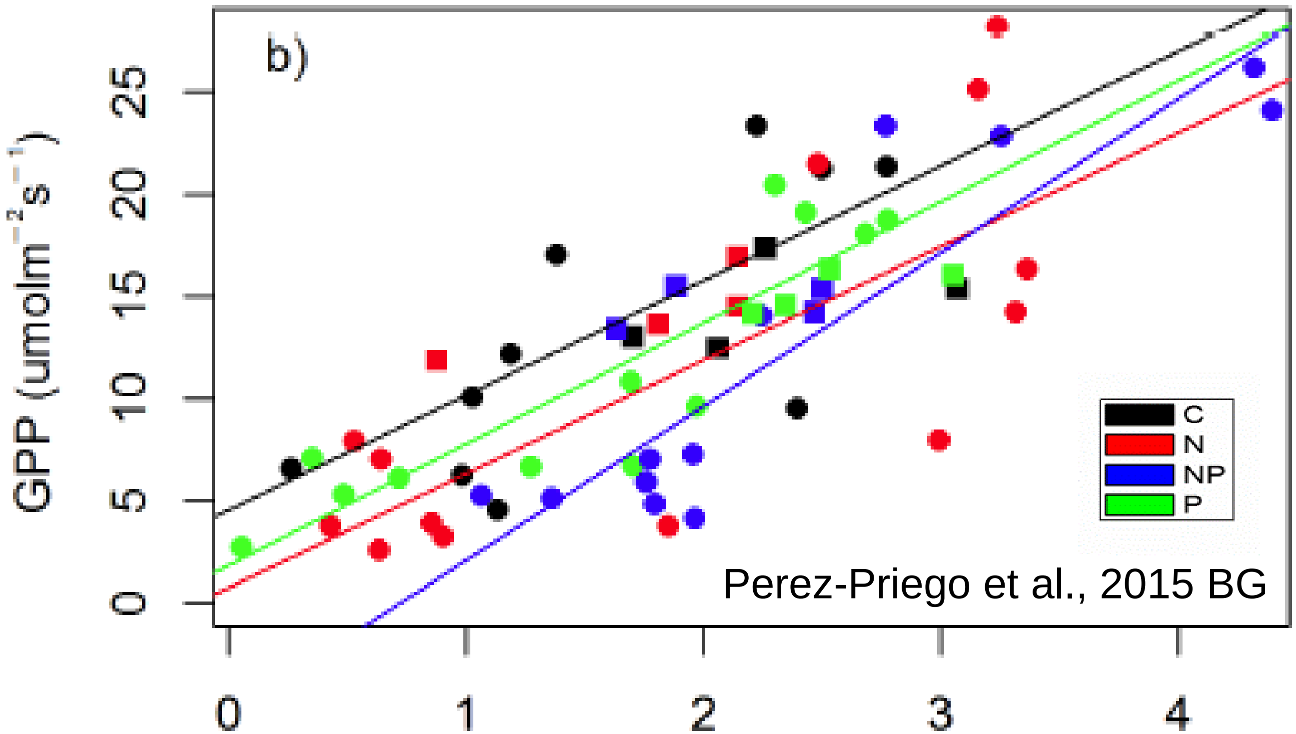

Structure?

Functional traits?

$$GPP \approx F760 \cdot \frac{LUE_p}{f_{esc} \cdot LUE_f}$$

….but also Damn et al., 2015 RSE; Wieneke et al., 2017 RSE; Liu et al., 2017; Guanter et al

Response of Photosynthesis

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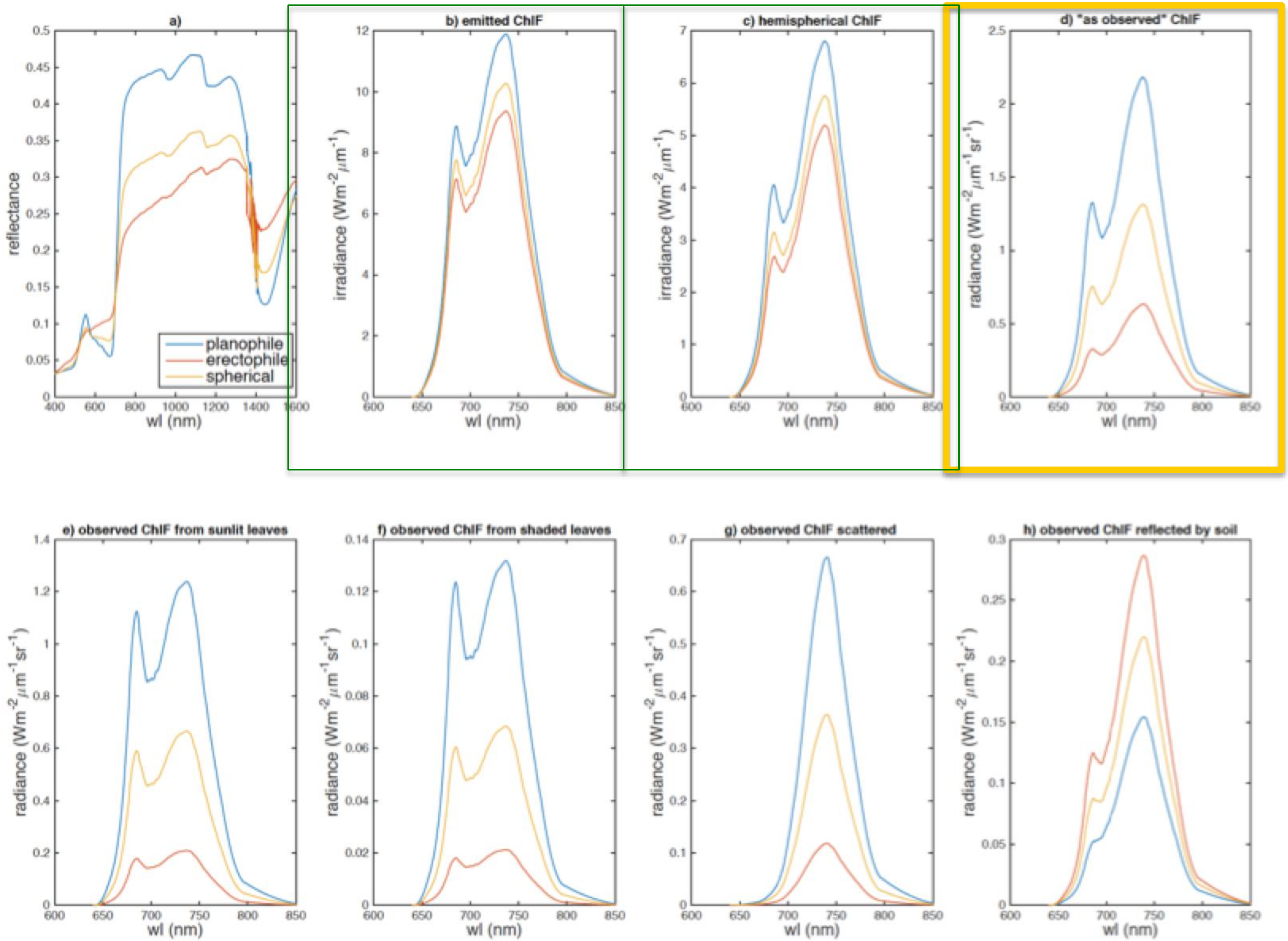
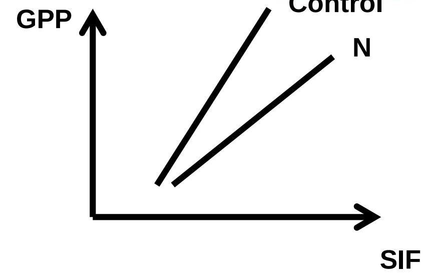
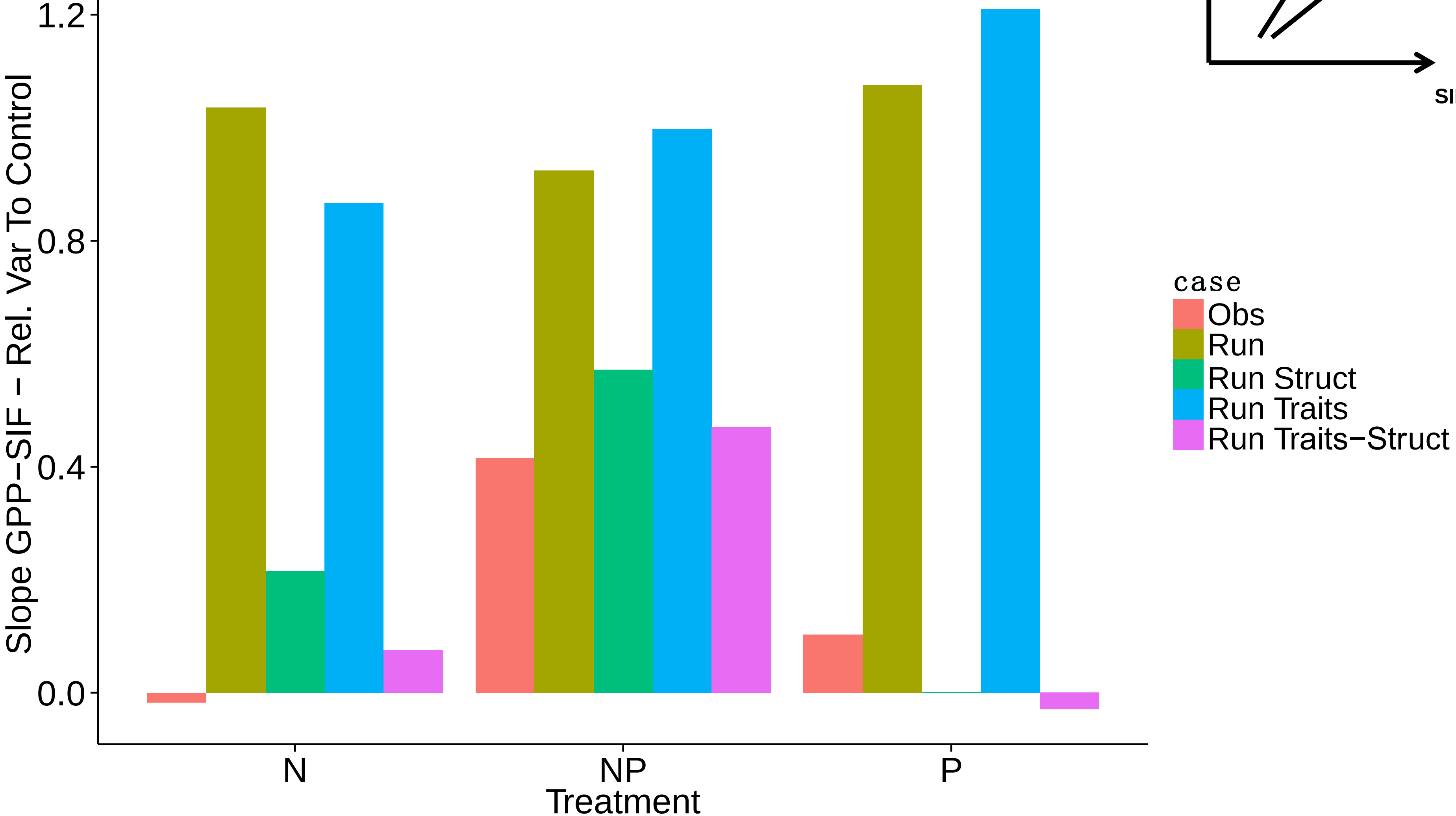


Migliavacca et al., *2017* (New Phytologist)

Response of Photosynthesis





Migliavacca et al., *2017* (New Phytologist)

Conclusions

- We presented 3-years round of EC data from a nutrient manipulation experiment

- Fertilization with N and NP **increased** the net C uptake, **GPP** and **Reco** at annual time scale
  - *Higher relative increase of **photosynthetic CO2 uptake** compared to **ecosystem respiration***
  - *Ecosystem response dominated by the response in the grass*

- **Barely significant** increase of the **water use efficiency** at annual time scale BUT…
  - *Significant differences between treatments observed in specific periods (e.g. the **dry-down** and the **autumn season)**;*
  - *NP treatment higher iWUE in autumn*

Conclusions

- Observed variability in F_{760} explained **primarily by change in canopy structure**
  - changes in biodiversity → plant forms abundance → LIDFa,b after fertilization
  - Secondarily by **functional traits** (N/P/LMA → Chl ab → Vcmax);

- Changes in canopy structure (leaf angle distribution) control the GPP-F_{760} relationship;

- Implication for global/regional scale modelling: **structural variability** (biodiversity) and **functional traits** could be important confounding factors when modeling GPP assuming a linear relationship with Far red SIF at PFT level

Collaborations and Institutes involved

Max Planck Institute
for Biogeochemistry

MAX-PLANCK-GESELLSCHAFT

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CEAM
FUNDACIÓN
CENTRO DE ESTUDIOS
AMBIENTALES DEL
MEDITERRÁNEO

CSIC
CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

UNIVERSITÀ DEGLI STUDI DI MILANO
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MCMLXXIII

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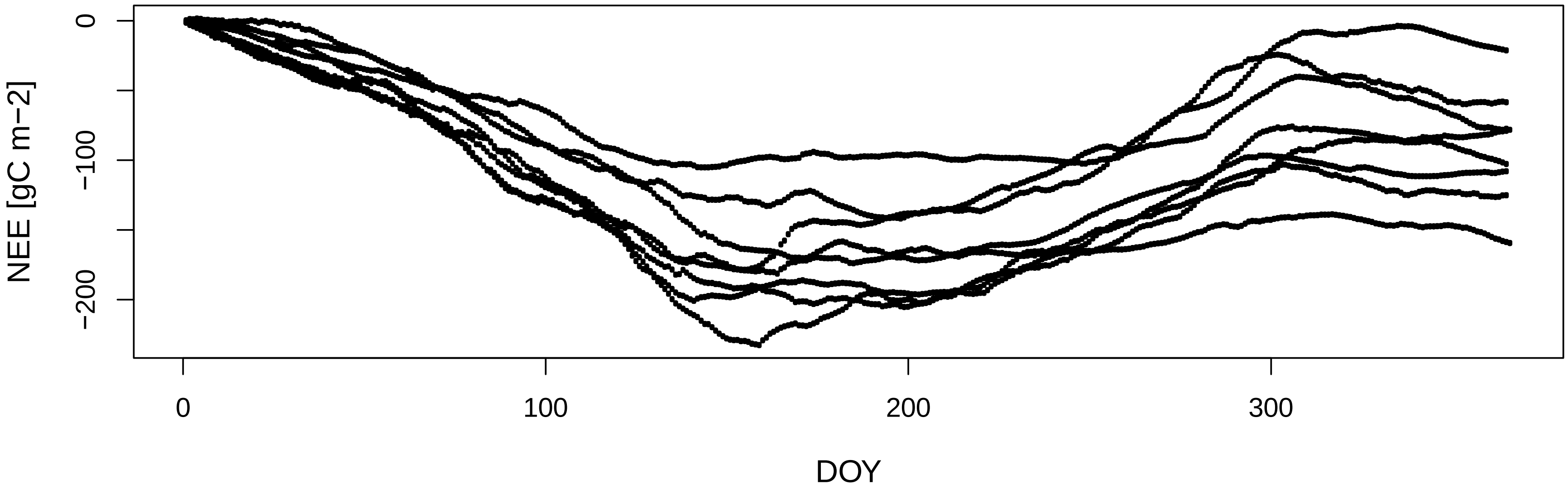
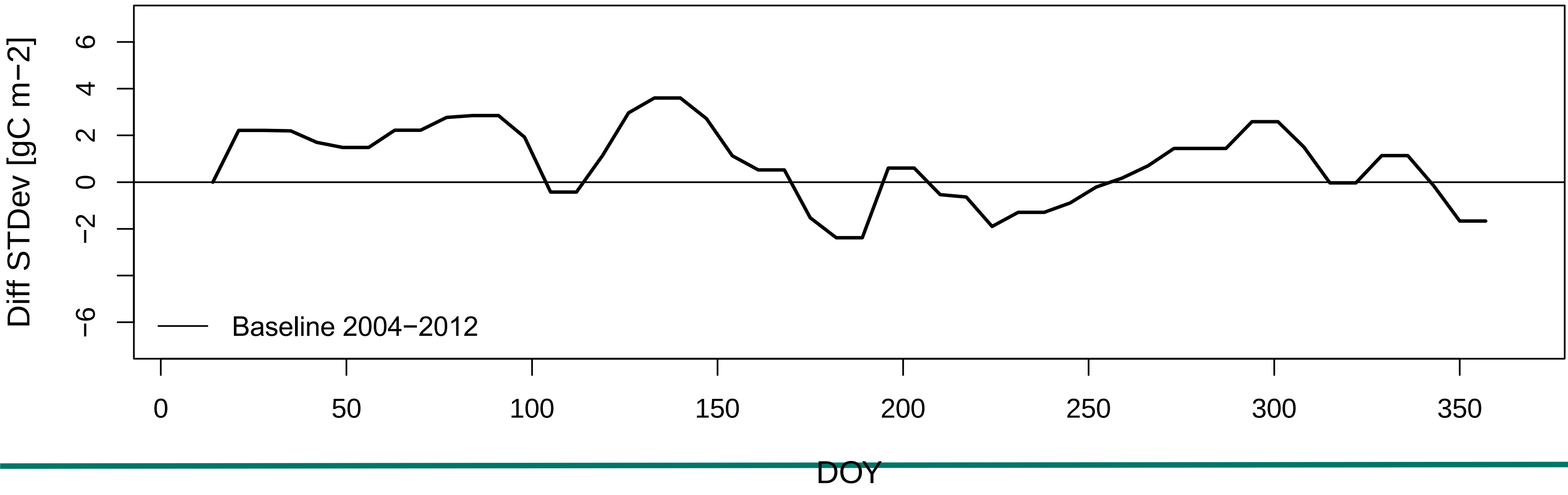
cost
EUROPEAN COOPERATION
IN SCIENCE AND TECHNOLOGY

Results – Interannual Variability





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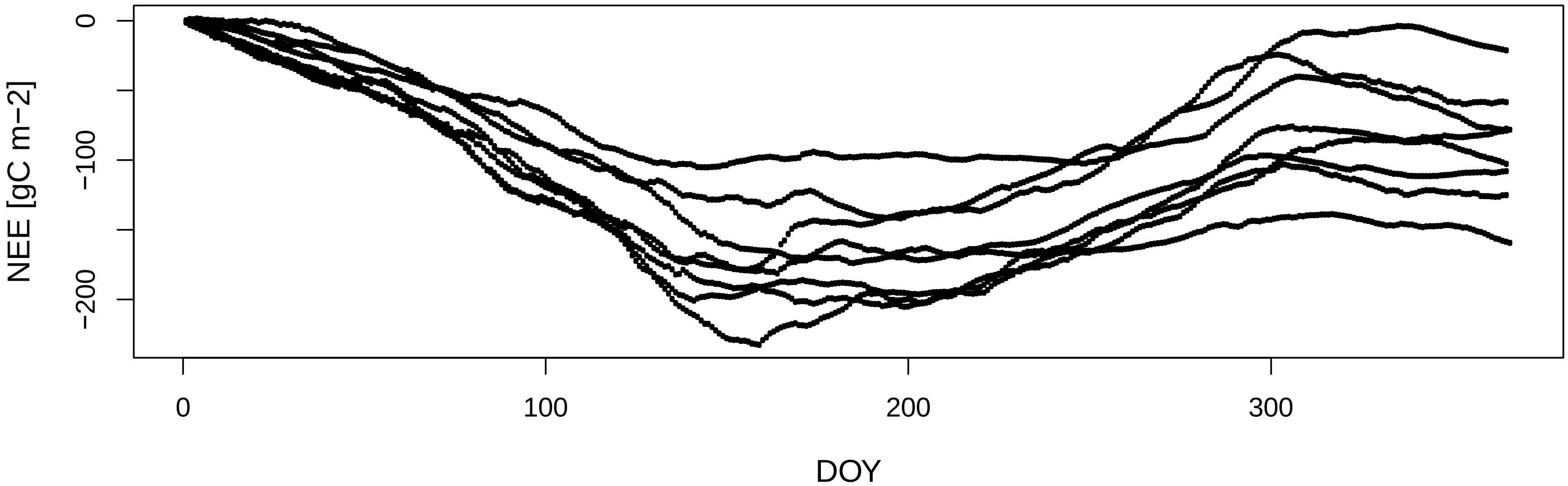
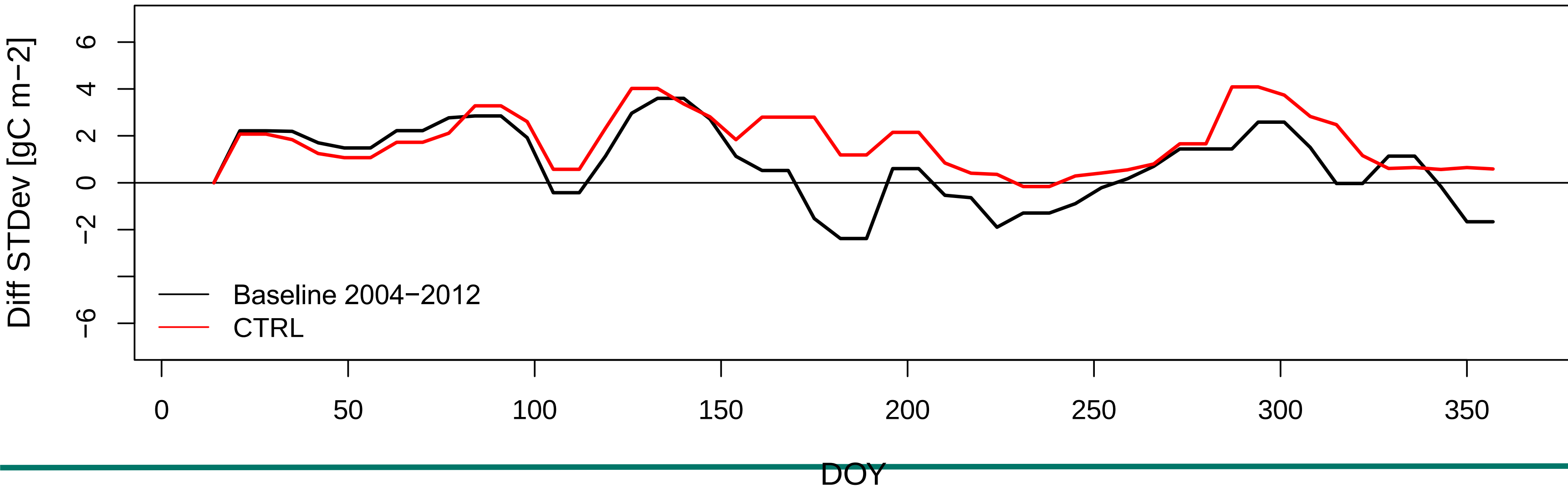
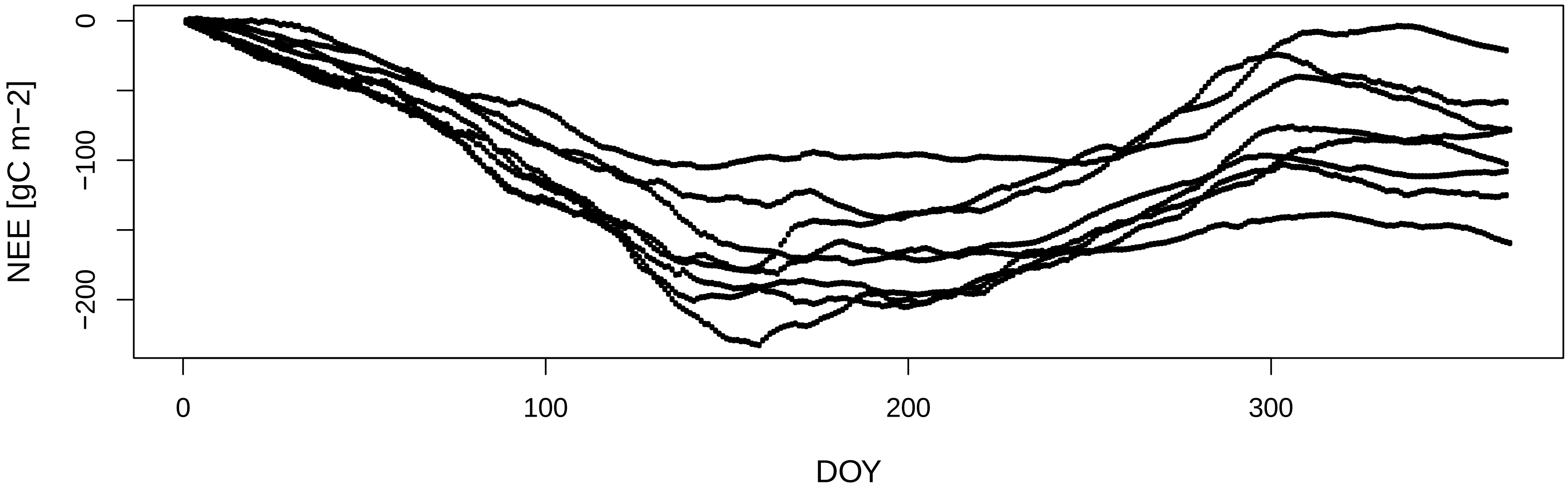
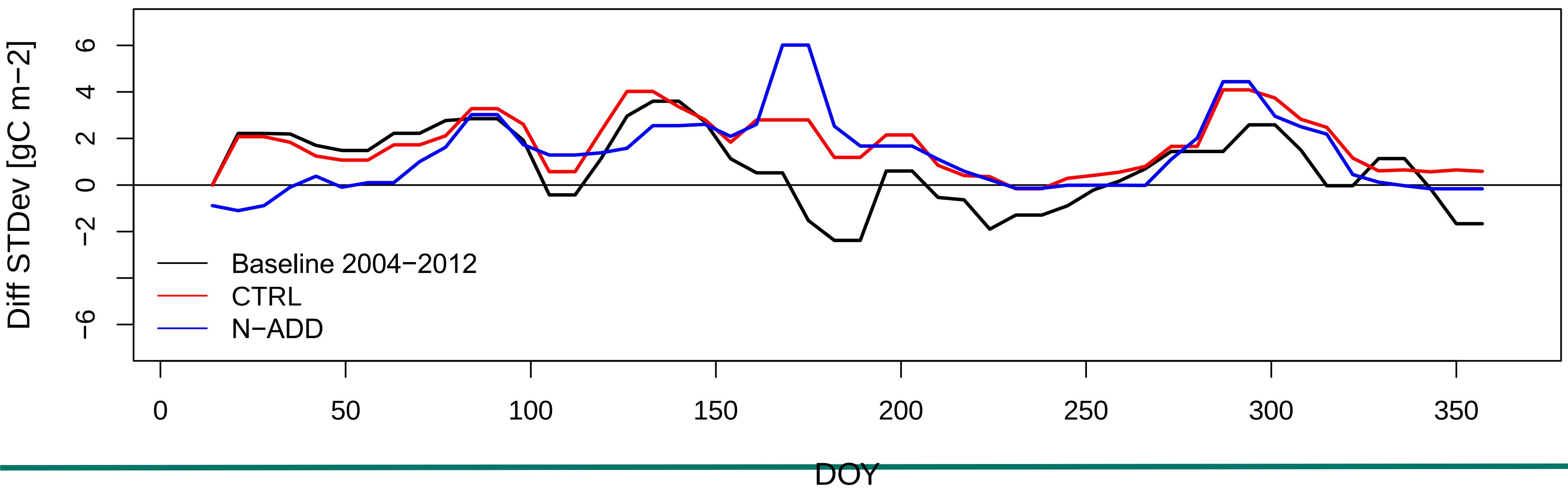
Results – Interannual Variability





Results – Interannual Variability





Results – Interannual Variability

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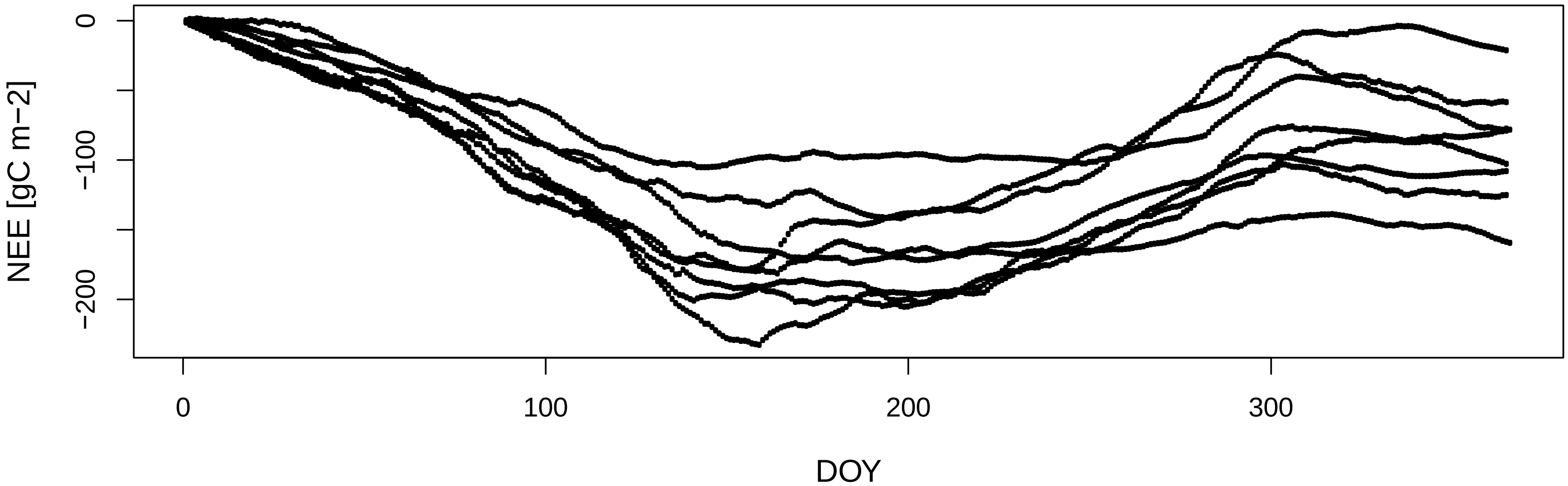

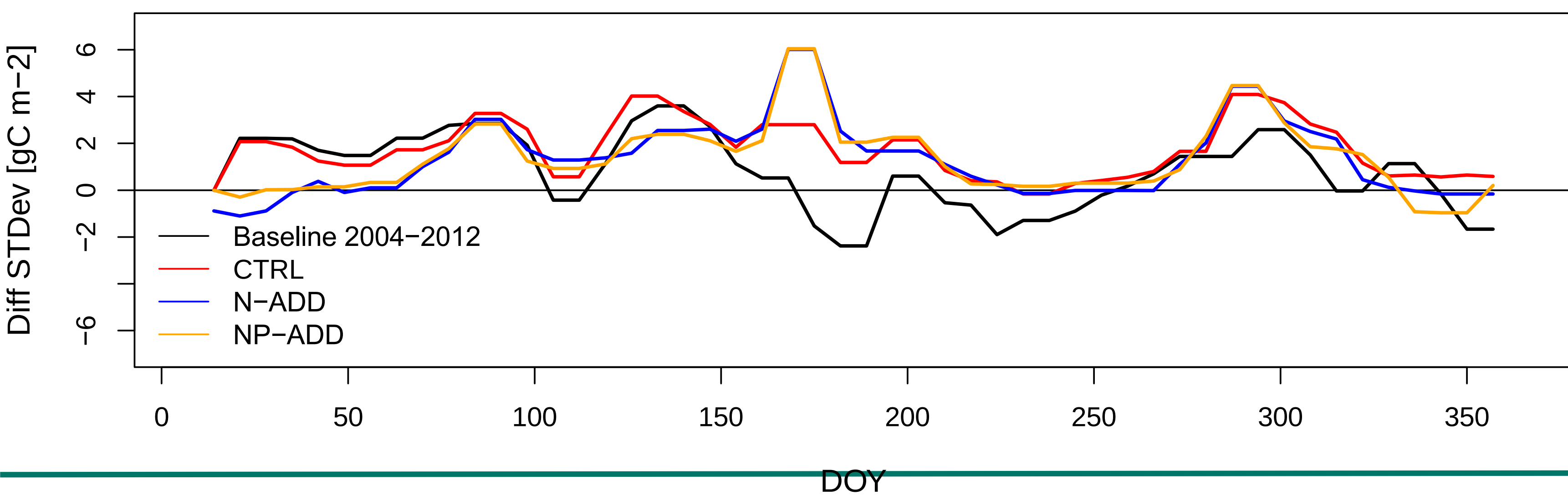

Response of Photosynthesis

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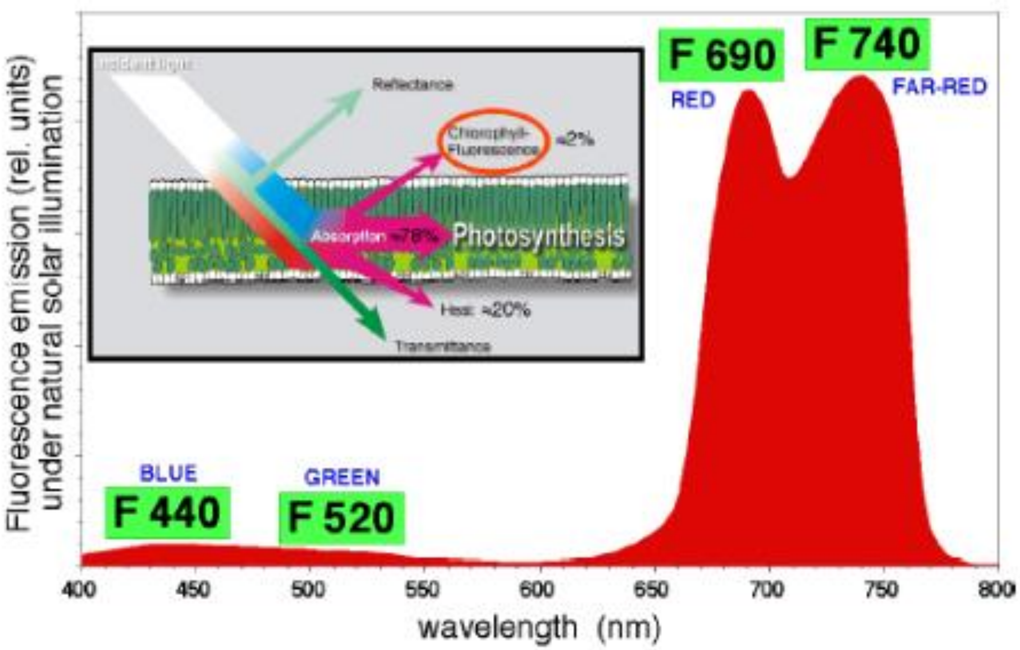
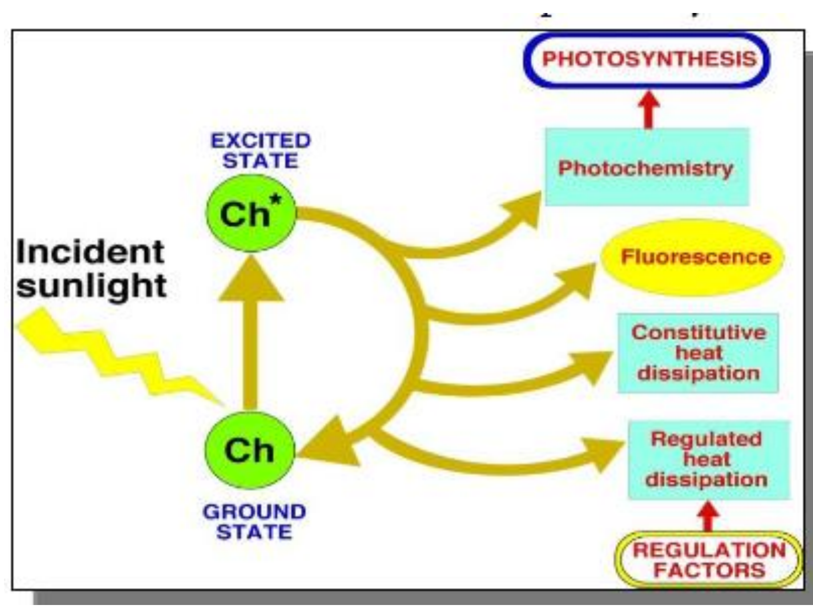
Pathways of solar energy after absorption by leaf chlorophylls (FLUORESCENCE)

- Under natural solar illumination conditions leaf level **SIF and photosynthesis are positively correlated**;
- Fluorescence at 690 and 740 nm are related to activity of PSII and PSI, respectively. Typically we measure fluorescence at 760 nm (Porcar-Castell et al., 2014)





Response of Photosynthesis

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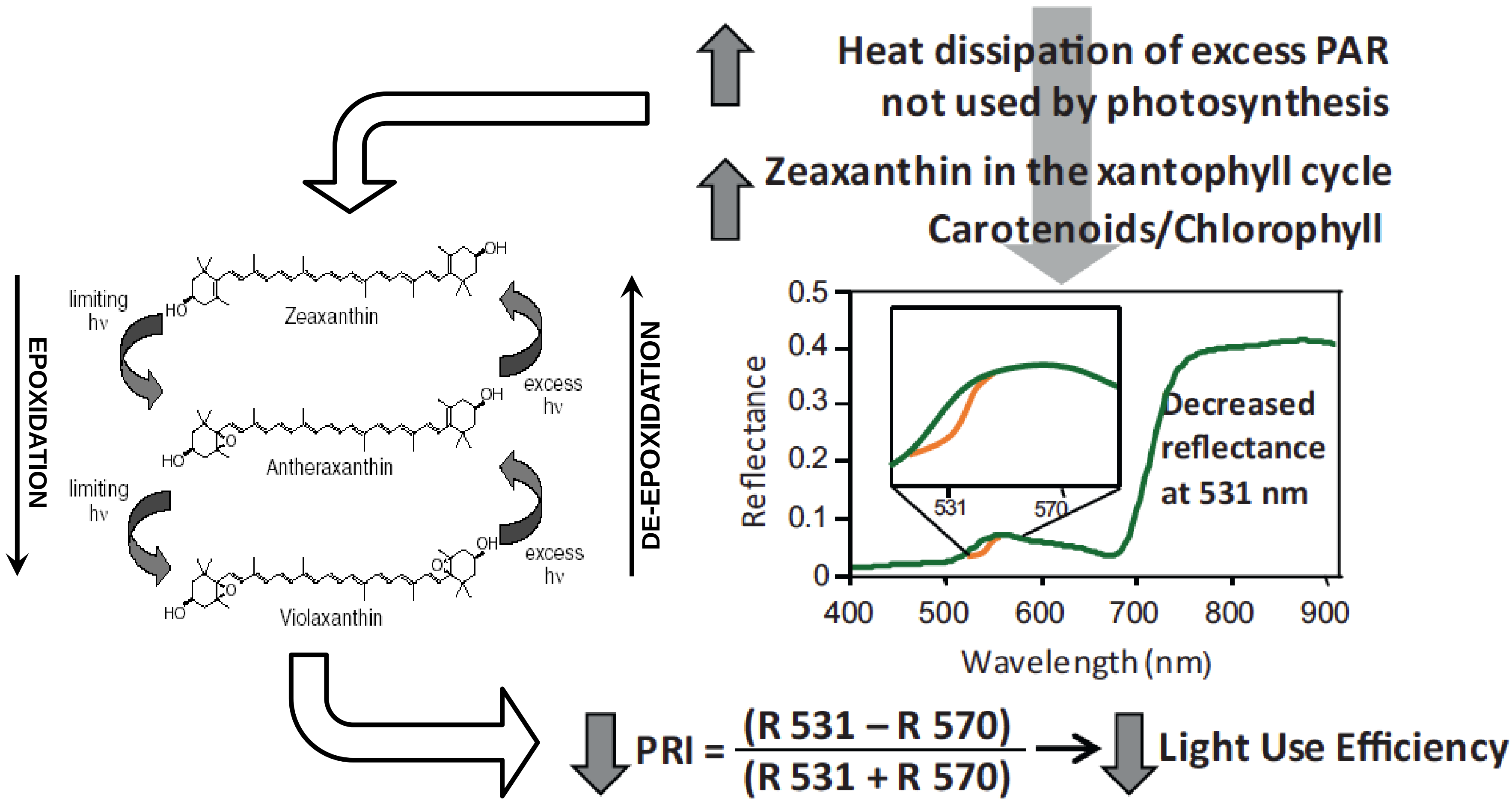
Pathways of solar energy after absorption by leaf chlorophylls (HEAT DISSIPATION)



Garbulski et al., 2014

Motivation

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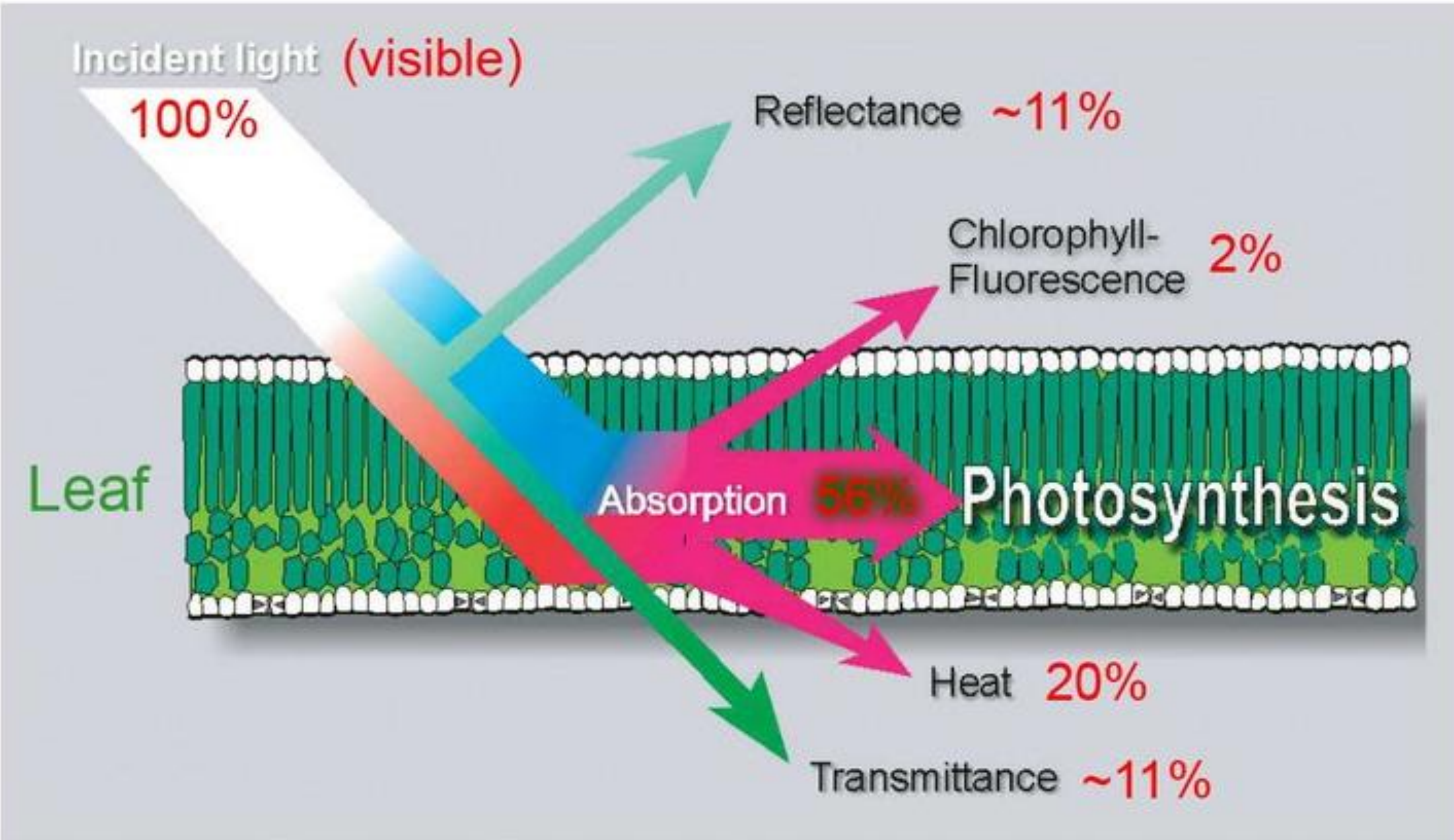

Mapping Photosynthesis from Space - a new vegetation-fluorescence technique
ESA bulletin. Bulletin ASE. European Space Agency. 11/2003; 116:34-37.

Motivation

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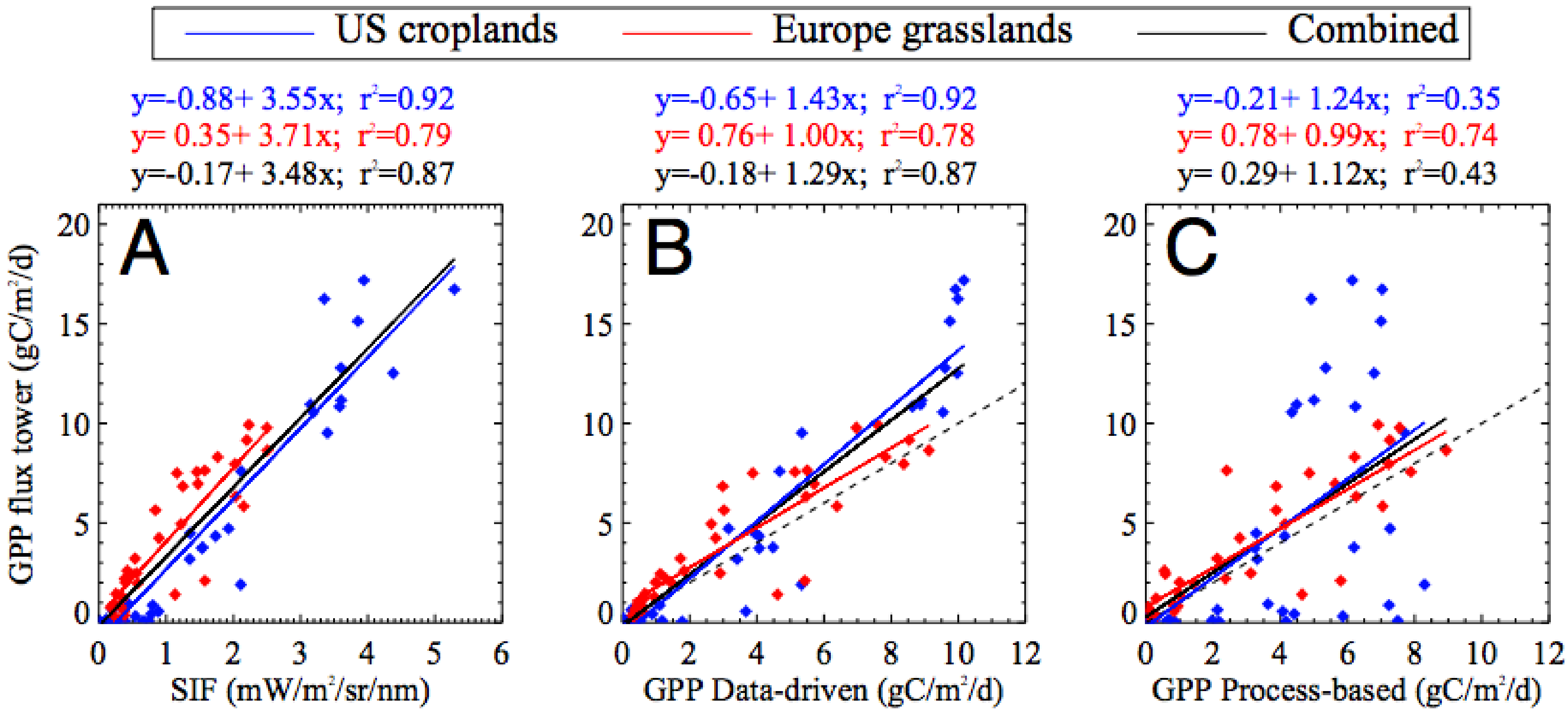

- **SIF** can be used to predict **GPP** (e.g. Guanter et al., 2014; Van der Tol et al., 2014);
- Current challenge is to understand the mechanisms controlling the **relationship** between **photosynthetic CO2 uptake (e.g. GPP) and SIF** (Guanter et al., 2014; Damn et al., 2015; Porcar-Castell et al., 2014);

Guanter et al., 2014 PNAS

Motivation

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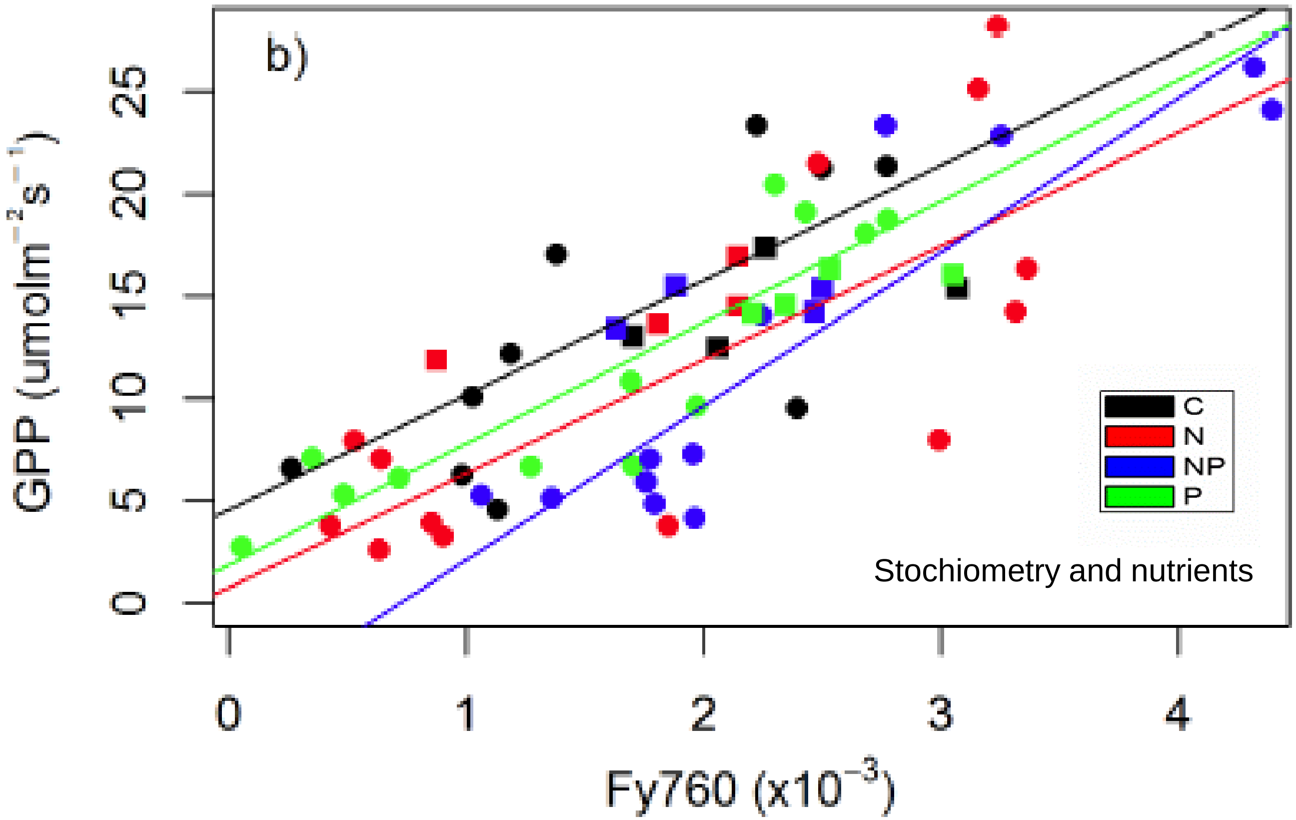

Perez-Priego et al., 2015 BG

….but also Damn et al., 2015 RSE; Wieneke et al., 2017 RSE; Liu et al., 2017; Guanter et al., 2014; Van der Tol et al., 2014; Porcar-Castell et al., 2014 and others

Motivation

Many confounding factors

- **Competition between the three processes** and modulation of the ratio between NPQ and fluorescence
  - Down-regulation NPQ as consequence of **relieved N** and **water limitation** (*Cendrero-Mateo 2015; Perez-Priego et al., 2015*);
  - Light quality and history (shade/sunlit) that affect the pool of carotenoids (*Niimenets et al., 2003*);

- Multiple scattering and probability of re-absorption of emitted SIF depends on **canopy structure and Leaf Angle Distribution (LIDFa, b)** (*e.g Van Wittenberghe et al., 2015; Verrelst et al., 2016*);

- Directional, atmospheric or instrumental effects (e.g. *Damm et al., 2015*)

Motivation

- How do changes in **canopy structure** (i.e. fertilization-induced changes in biodiversity) and and **functional traits** affect F_{760} signal?

- Why does the relationship between **GPP-F_{760}** change across treatments?

Hypotheses

- ***Biochemistry*** *– Nutrient mediated changes in foliar biochemistry (changes in Vcmax, Chl ab)*

- ***Canopy Structure induced by changes in Biodiversity*** *– Nutrient mediated changes in canopy structure (Fertilization changes the compositions of the plant forms, leaf angles and canopy height)*

MANIP – Small Scale Manipulation

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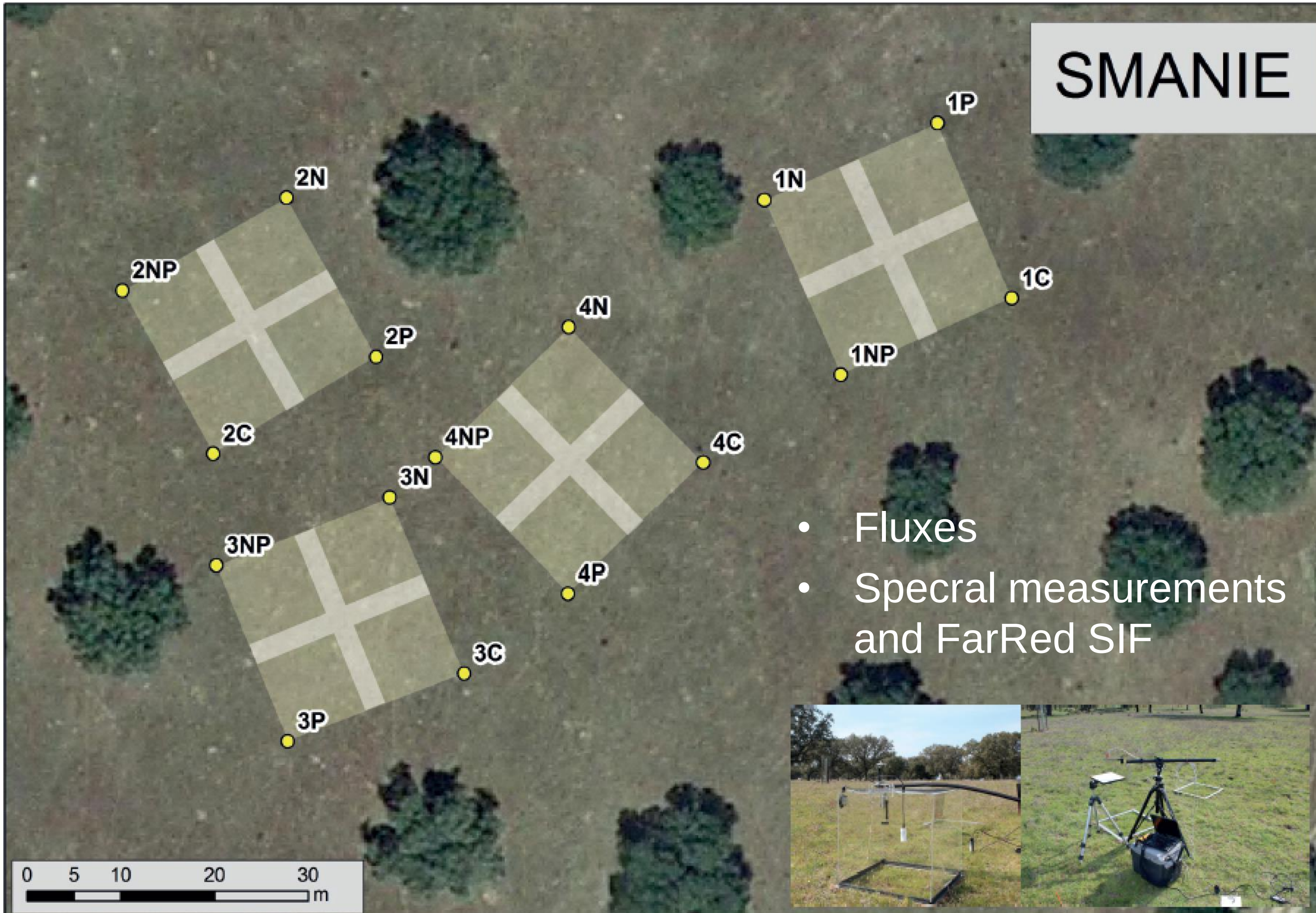

- Fluxes
- Specral measurements and FarRed SIF

MANIP – Linking RS data and fluxes

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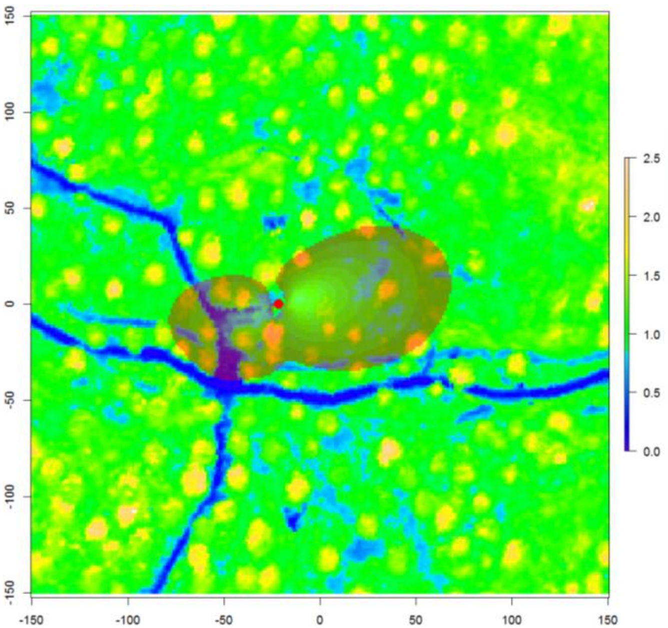
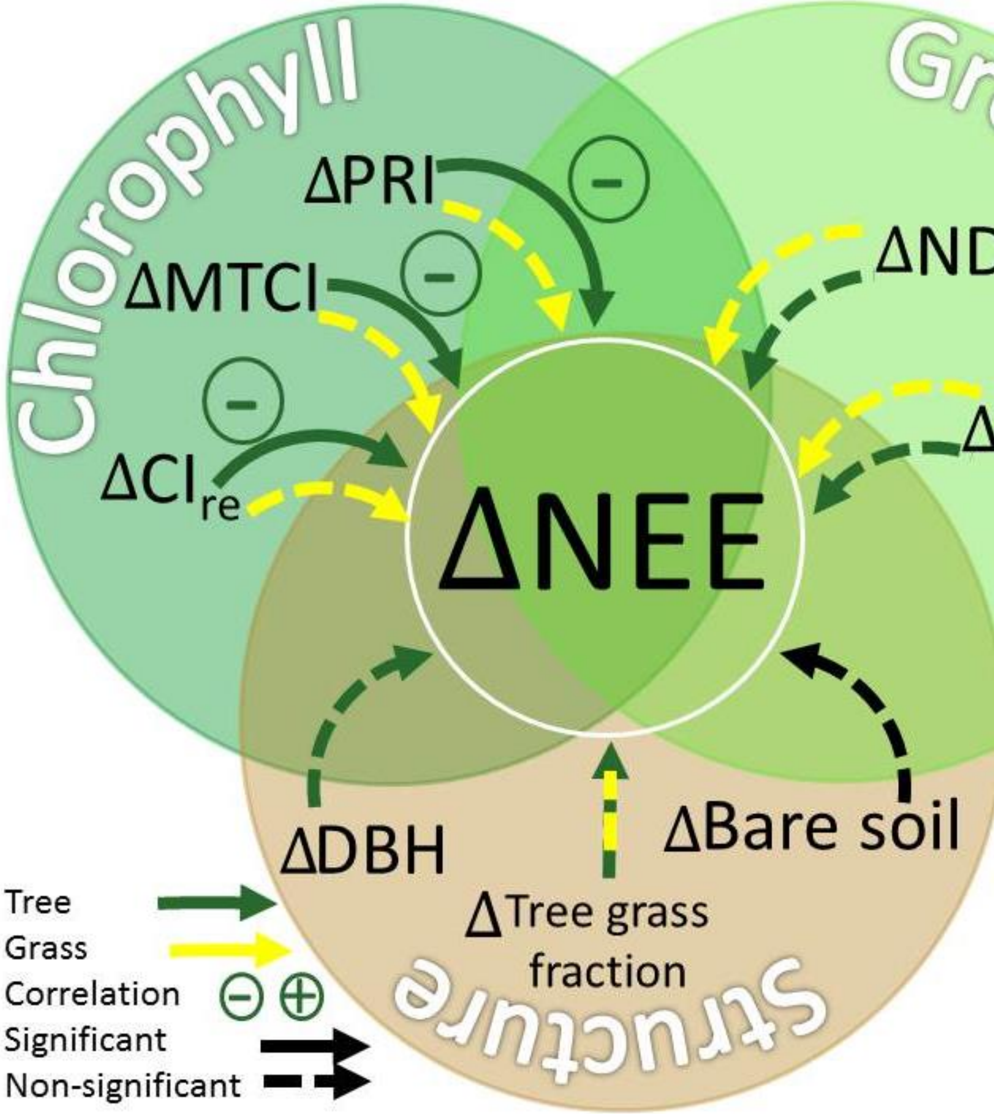
CIre: Red Edge Chlorophyll Index





El-Madany et al., in prep

Data

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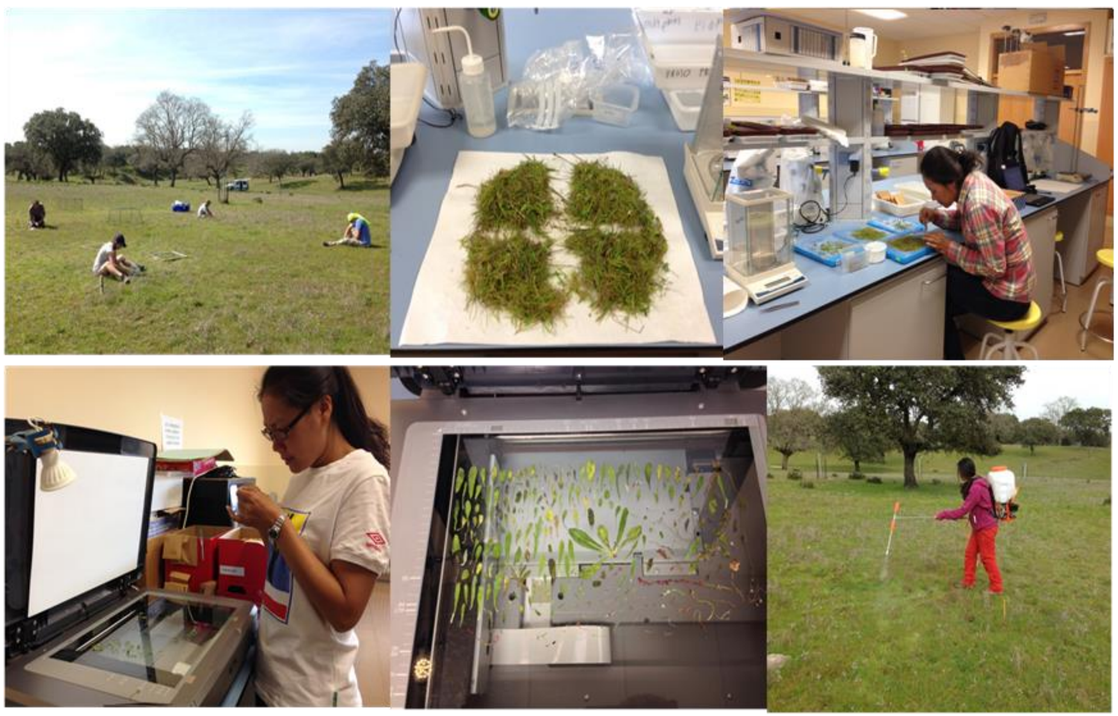
PLOT	Fertilizer	N, kg/ha	P, kg/ha	K, kg/ha
N	Potassium Nitrate (KNO_3) Ammonium Nitrate (NH_4NO_3)	44 156		123
P	Monopotassium Phosphate (KH_2PO_4)		100	123
N+P	Ammonium Nitrate (NH_4NO_3) Monopotassium Phosphate (KH_2PO_4)	200	100	123

Fertilization conducted in March 2014 and 2015



- Green/Dry biomass
- Direct LAI
- Canopy height
- Plant forms abundance
- Nutrient analysis in the main plant forms
- Soil C, N, and P content
- Top of the canopy images

Modeling – Factorial runs with SCOPE

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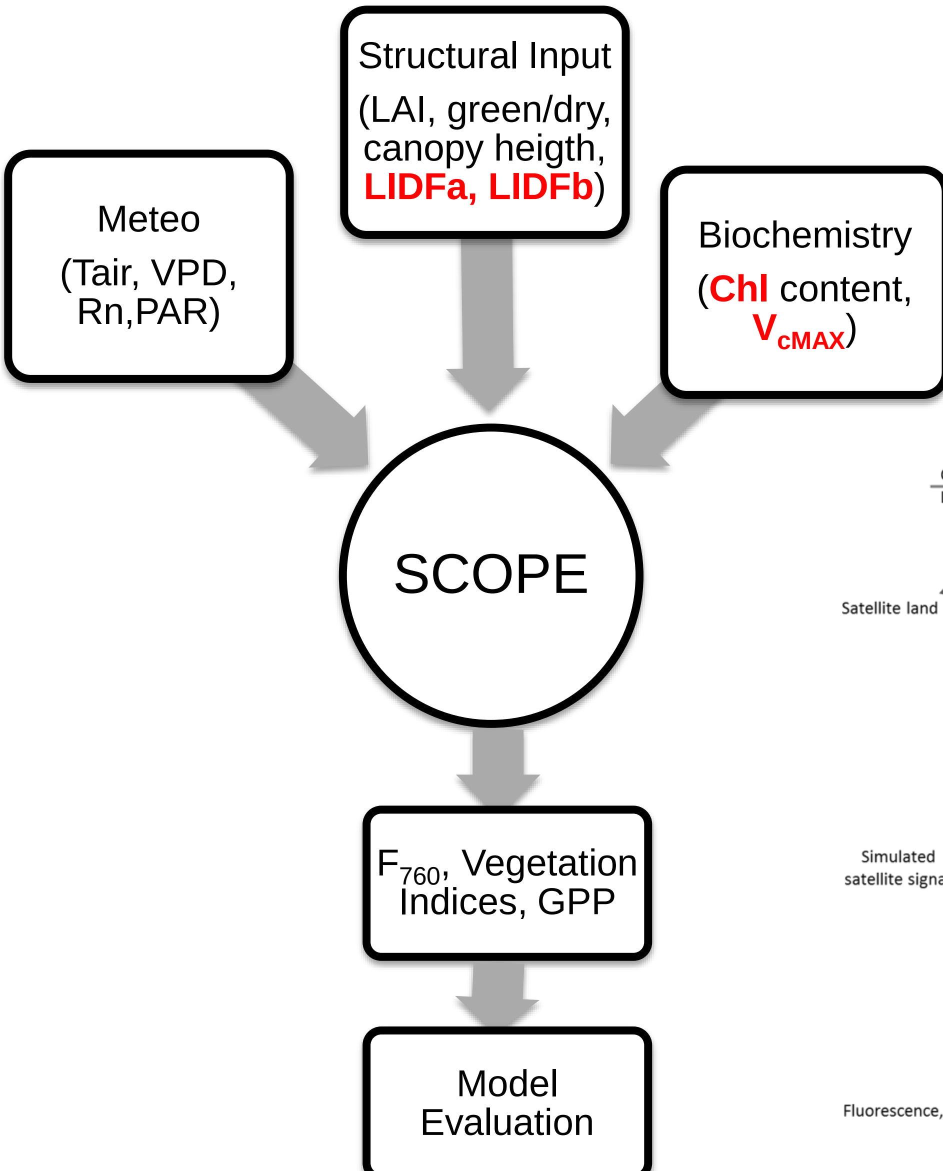

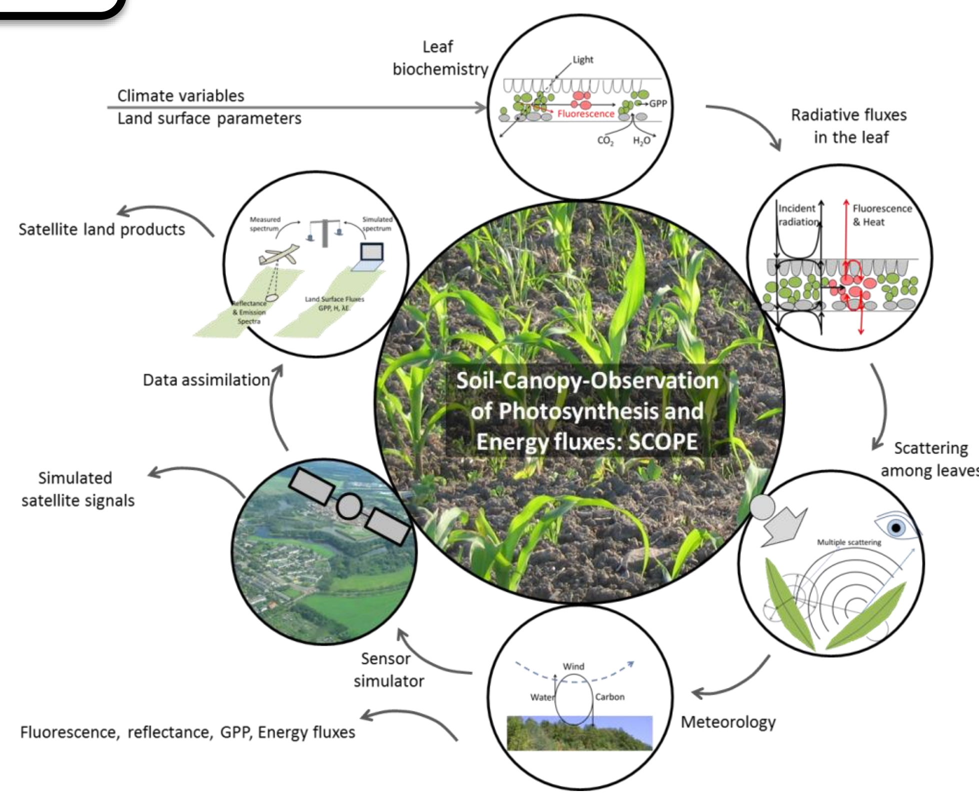

Courtesy of C. Van der Tol, Abel Summer School presentation

Modeling – SCOPE parameterization

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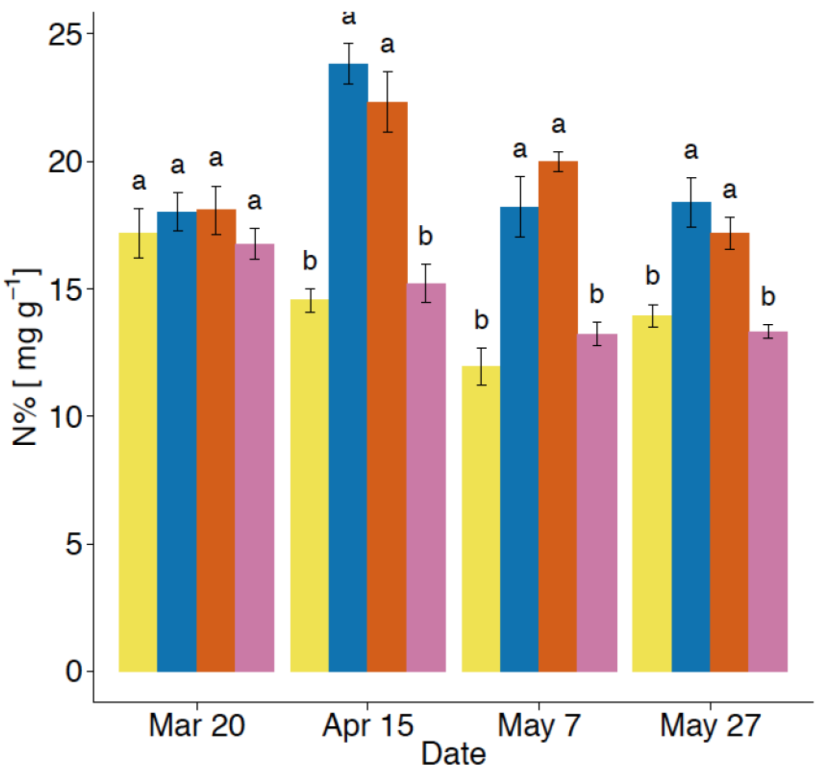
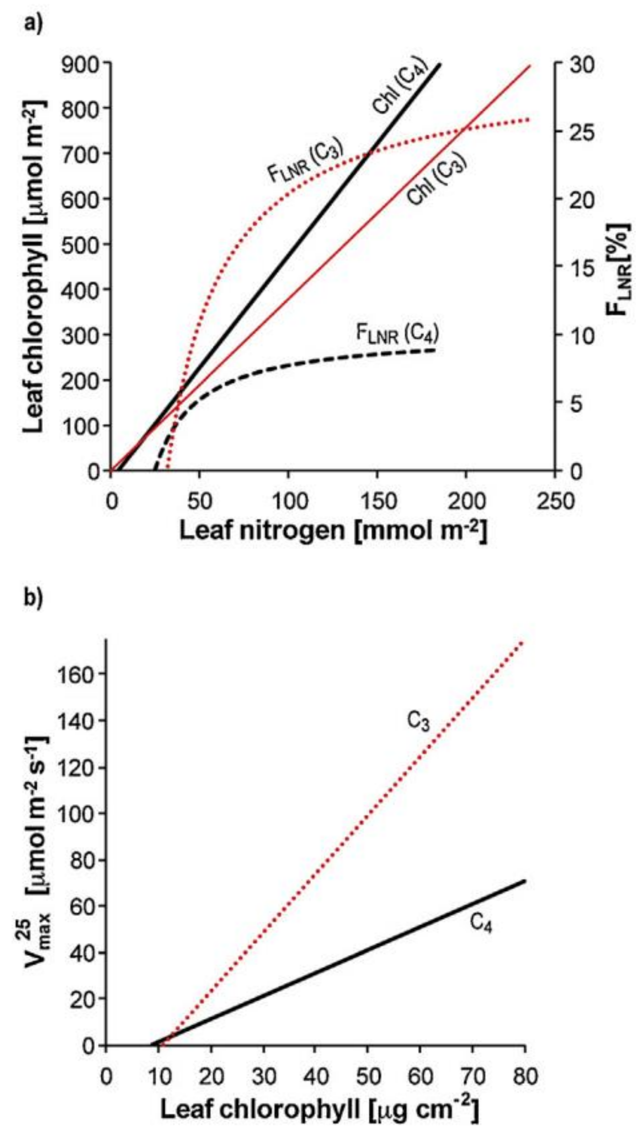
Effects of fertilization on functional traits

- changes in foliar N,P content and LMA
  → changes in Chl ab and Vcmax
- Walker et al., 2014; Hobourg et al., 2013; Feng and Dietze et al., 2013





Modified from Perez-Priego et al 2015 (BG)

Houborg et al 2013 (AFM)

Modeling – SCOPE parameterization

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Effects of fertilization on biodiversity and canopy structure

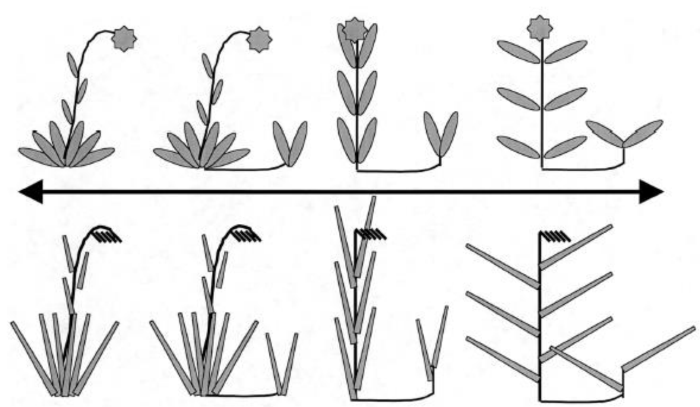
- Changes in the fraction of plant forms (%) lead to changes in leaf angle distribution
- Parameters recomputed accounting for a typical Leaf Angle Distribution the 3 main plant forms

Campaign	Treatment	Total PAI_g ($m^2\,m^{-2}$)	Total PAI_g ($m^2\,m^{-2}$)	Forbs f_{PAI}	Grass f_{PAI}	Legumes f_{PAI}
Date	–	mean	SD	%	%	%
no. 1	C	0.85	0.18	35.5	56.8	7.7
20 March 2014	N	0.76	0.21	39.2	45.1	15.0
Growing period	NP	1.03	0.30	29.1	54.3	12.9
Pretreatment	P	0.95	0.21	26.6	66.6	6.9
no. 2	C	2.02	0.43	14.5	85.2	0.3
15 April 2014	N	2.17	0.91	11.9	87.6	0.4
Growing period	NP	2.46	0.45	4.1	95.6	0.3
Posttreatment	P	1.66	0.58	14.2	85.7	0.1
no. 3	C	1.08	0.27	43.0	55.1	1.9
7 May 2014	N	1.29	0.58	28.3	70.7	1.0
Dry period	NP	0.84	0.21	27.2	71.8	1.0
	P	1.37	0.57	39.5	58.5	2.0
no. 4	C	0.44	0.10	66.7	33.3	0.0
27 May 2014	N	0.48	0.28	36.4	63.6	0.0
Dry period	NP	0.53	0.26	40.6	59.4	0.0
	P	0.71	0.31	56.1	43.9	0.0

Perez-Priego et al 2015 (BG)

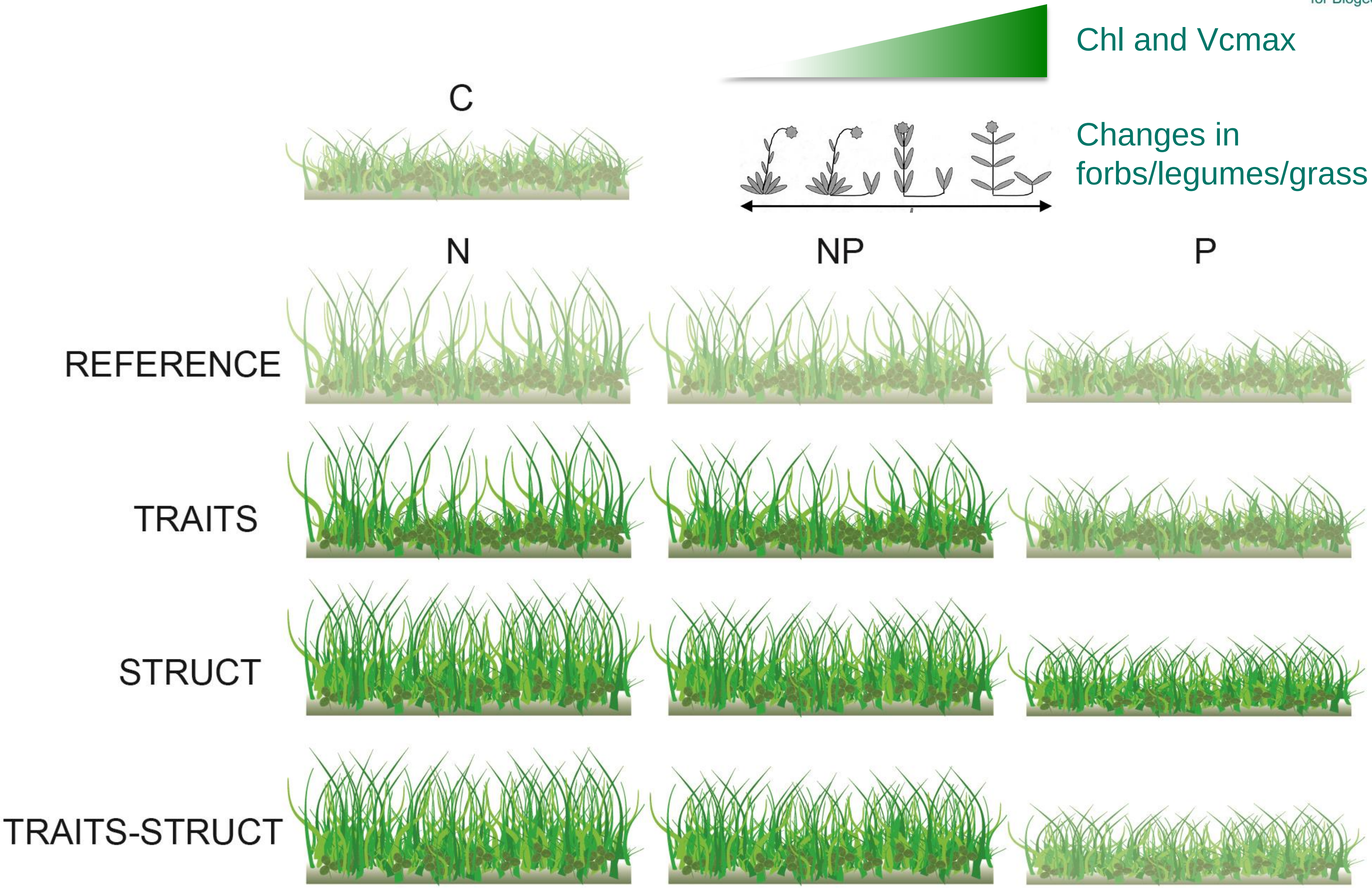
LIDFa, **LIDFb** according to variation of plant forms % (Asner 1998, RSE):

Grass: erectophile
Legumes: planophile
Forbs: spherical



Craine et al 2001 (OIKOS)

Modeling – Factorial runs



Migliavacca et al., *2017* (New Phytologist)

Results – Model evaluation

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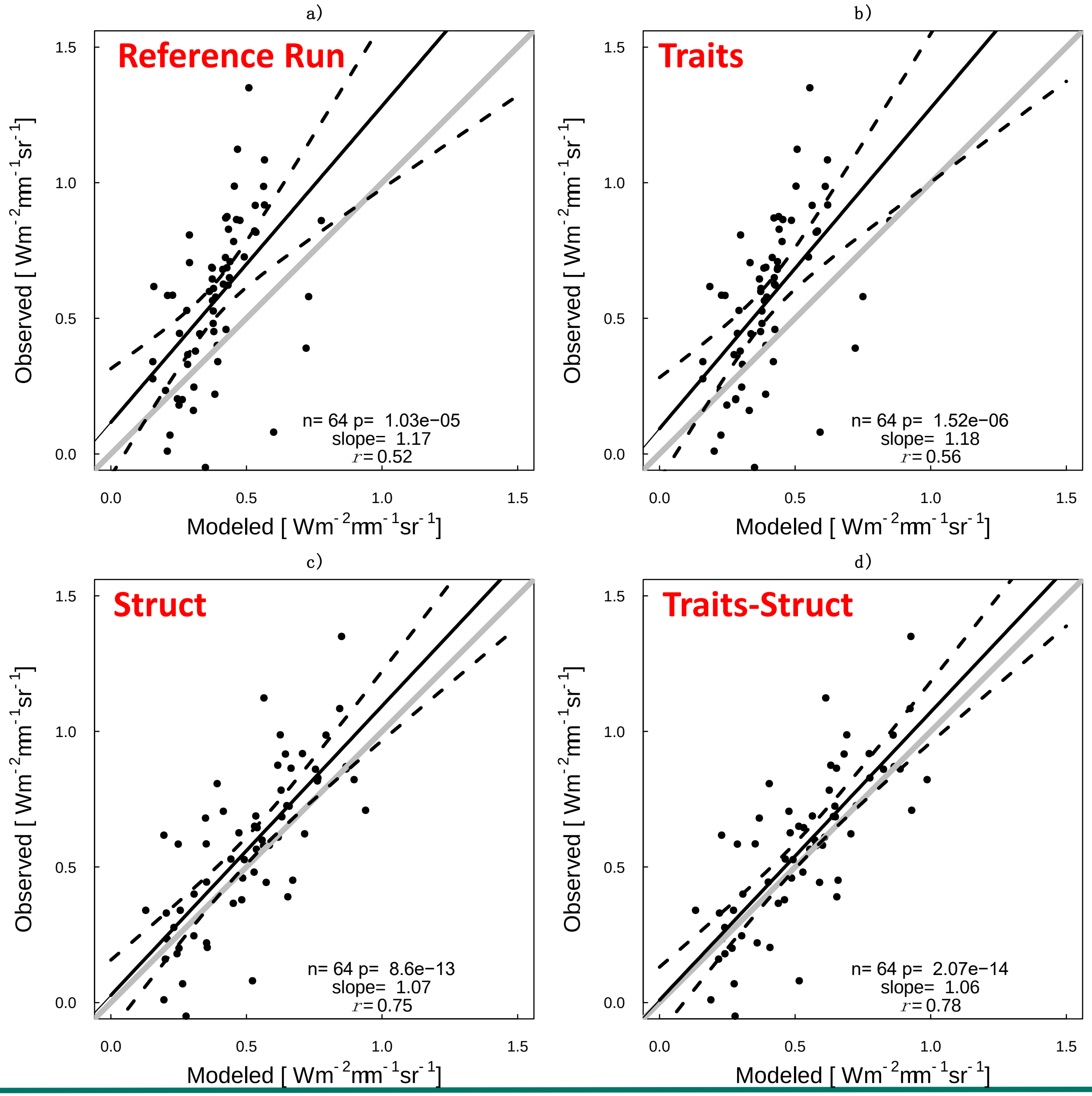

Migliavacca et al., 2017 (New Phytologist)

Results – Model evaluation

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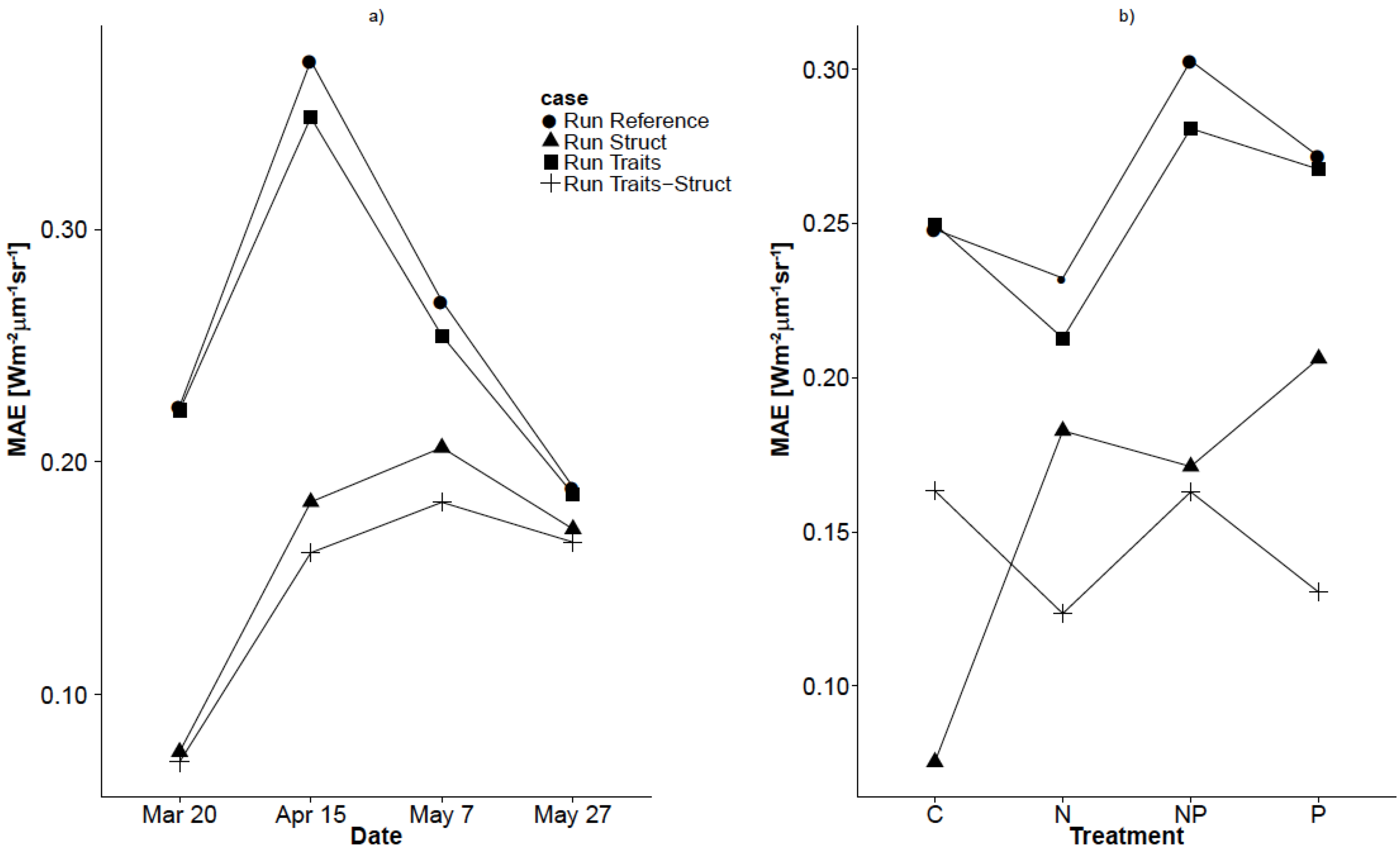
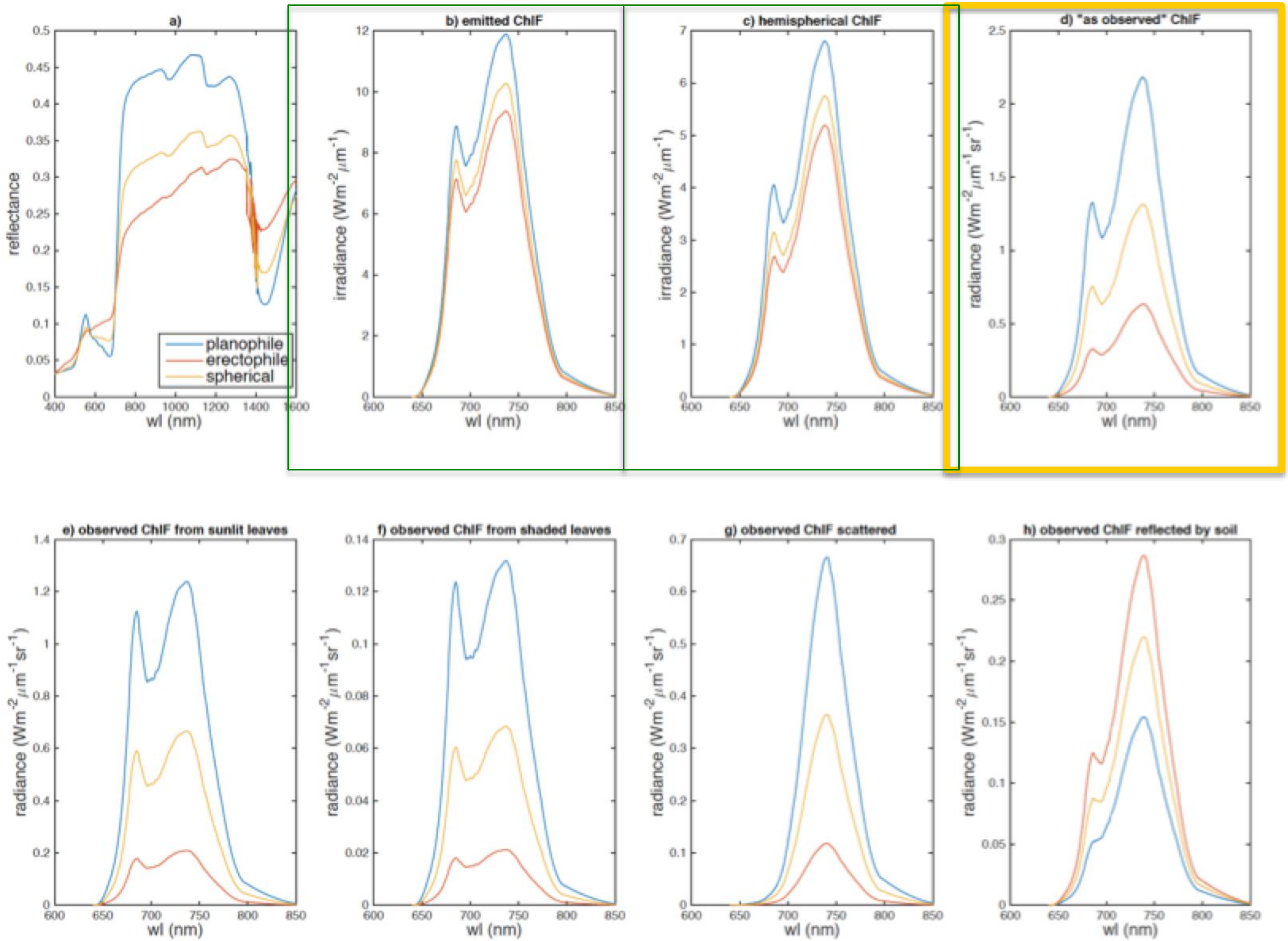
Model Evaluation for each field campaign and treatment



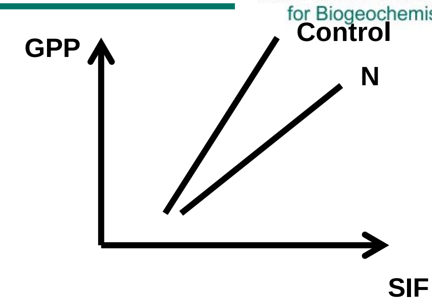
Migliavacca et al., *2017* (New Phytologist)

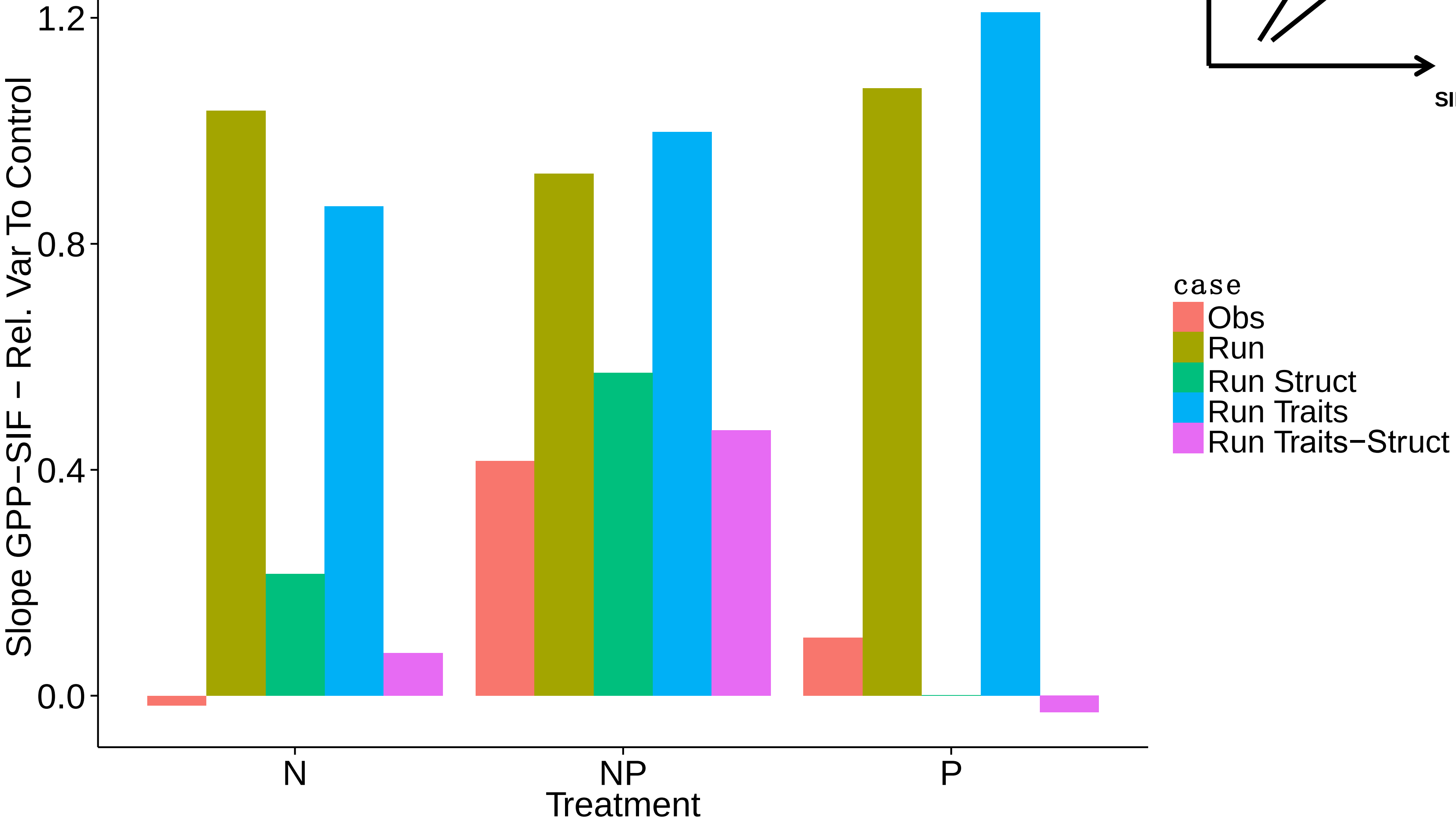
Results – F_{760} and canopy structure



Migliavacca et al., *2017* (New Phytologist)

Results – F_{760} and GPP





Migliavacca et al., *2017* (New Phytologist)

Conclusions

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- Observed variability in F_{760} explained **primarily by change in canopy structure**
  - changes in biodiversity → plant forms abundance → LIDFa,b after fertilization
  - Secondarily by **functional traits** (N/P/LMA → Chl ab → Vcmax);

- Changes in canopy structure (leaf angle distribution) control the GPP-F_{760} relationship;

- Implication for global/regional scale modelling: **structural variability** (biodiversity) and **functional traits** could be important confounding factors when modeling GPP assuming a linear relationship with Far red SIF at PFT level

Thanks to….

Max Planck Institute
for Biogeochemistry

Collaborations and Institutes involved

Thanks to:

Freiland, Verena Bessenbacher, Andreas Bukart, Roberto Colombo, Jin-Hong Guan, Marion Schrumpf, Arnaud Carrara, Ramon Jimenez, Tommaso Julitta, Gerardo Moreno, Uwe Rascher, Micol Rossini, Markus Reichstein

COST is supported by the EU Framework Programme Horizon 2020

Thanks for your attention

More info:
www.bgc-jena.mpg.de/bgi/index.php/Research/BAIE


BACKUP MATERIAL

Replicates?

-Temporal variability preferred

-Footprint analysis as surrogate

Results – Impact on Autumn phenology

MaNiP
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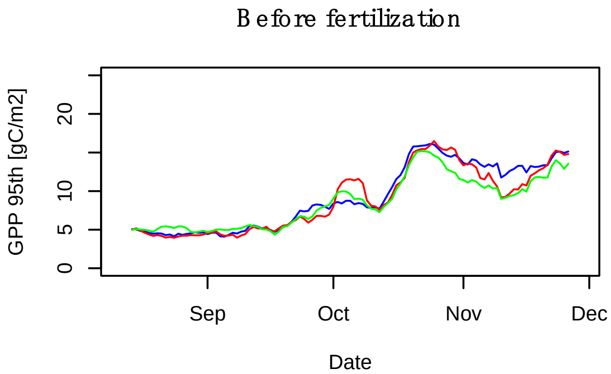

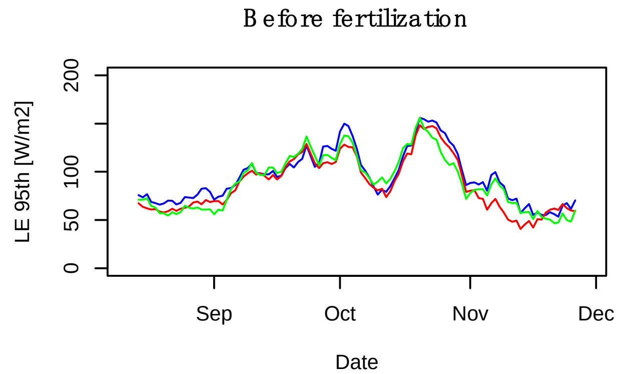

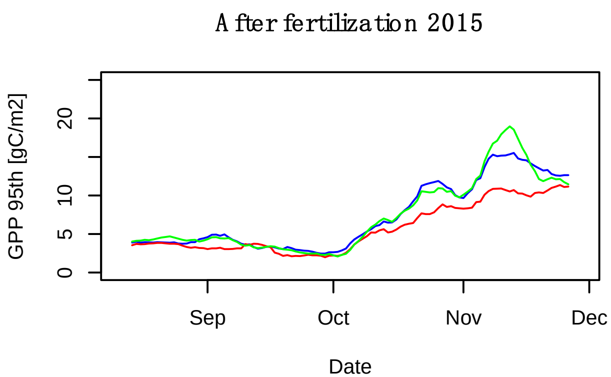

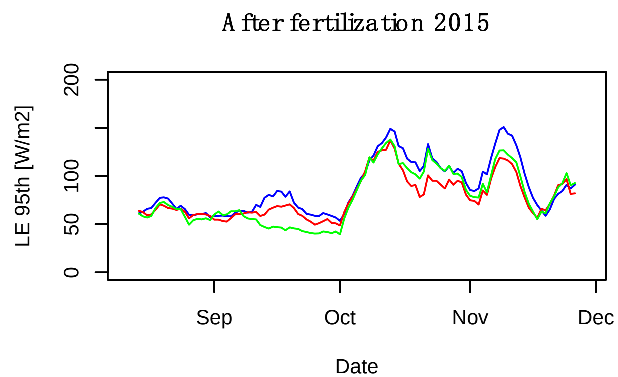

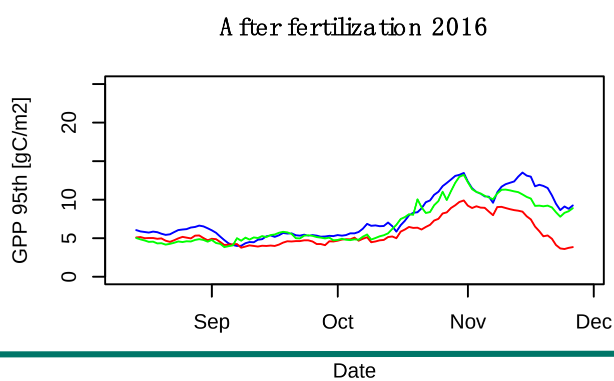

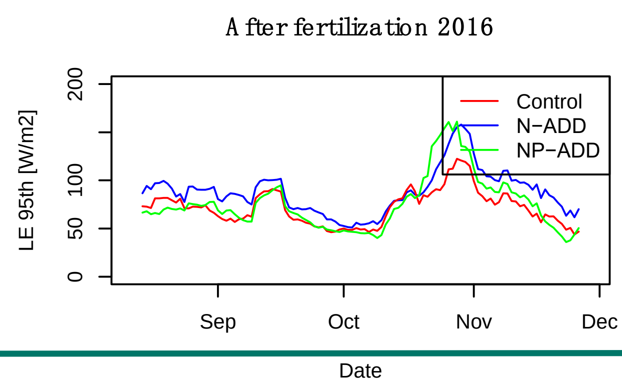

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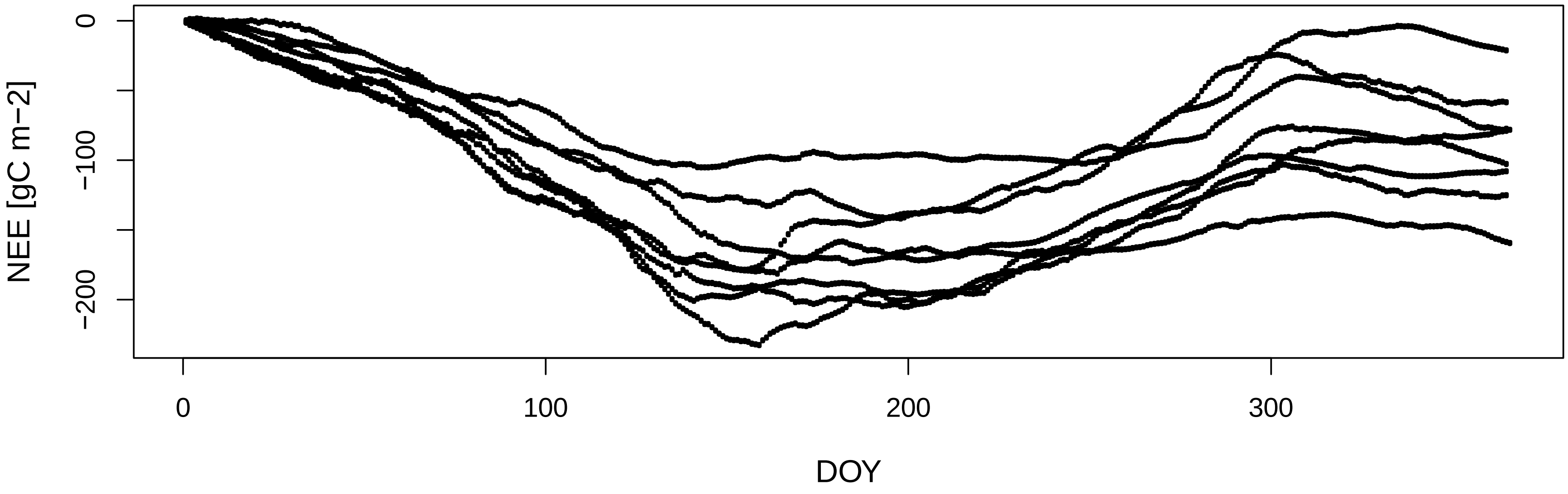

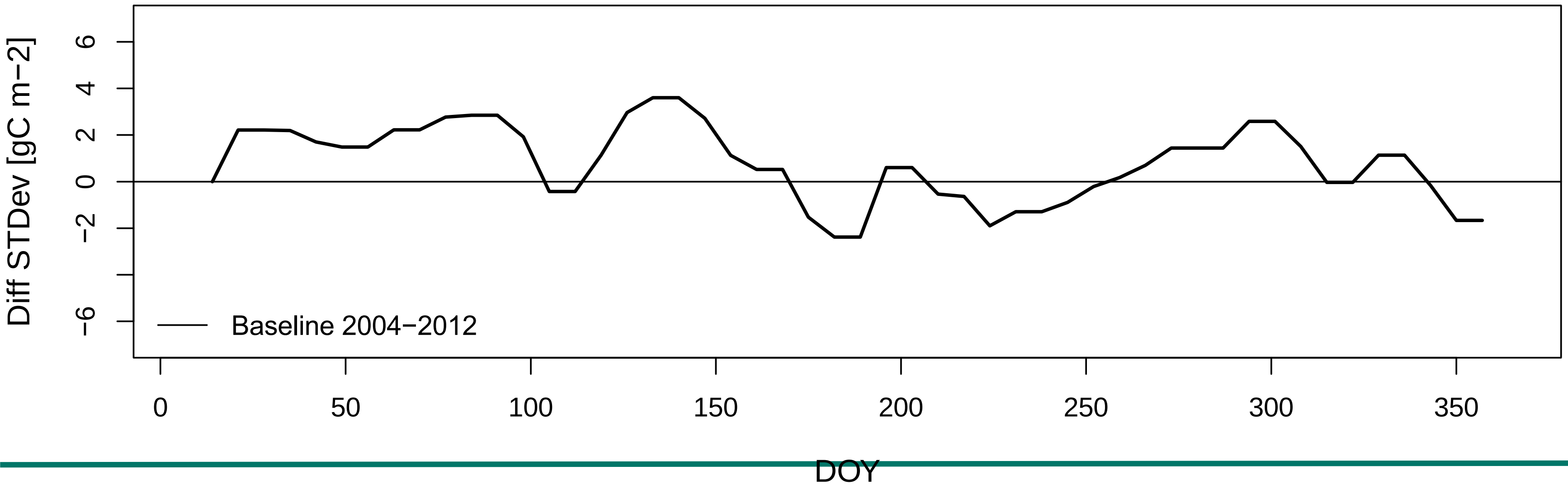

Results – Interannual Variability

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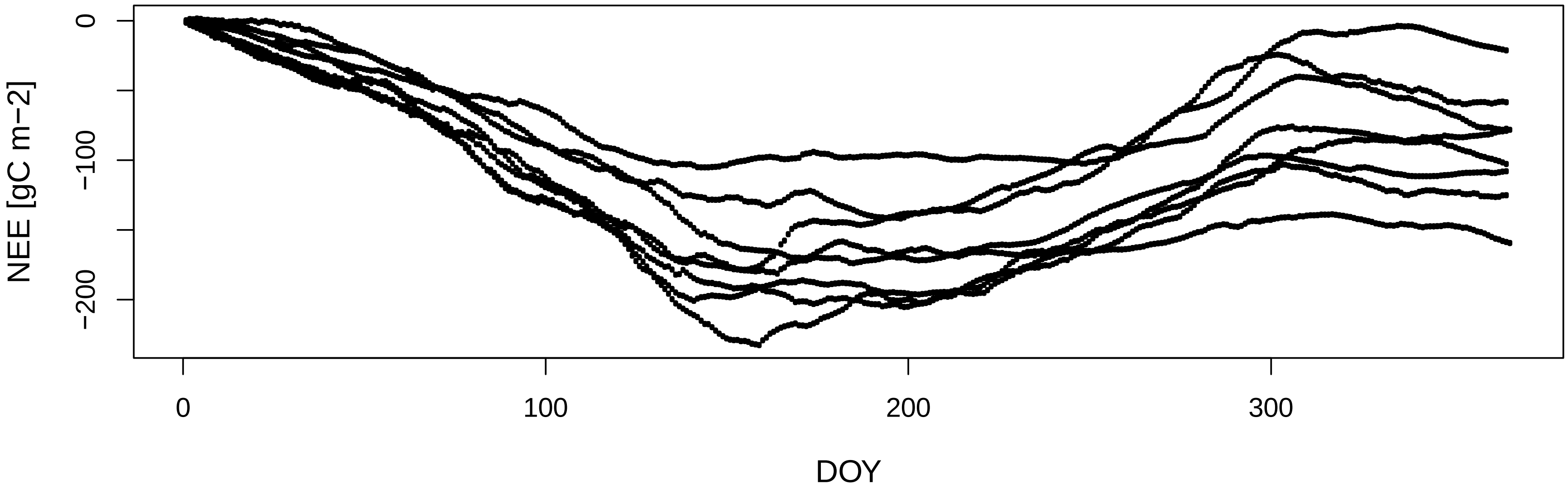

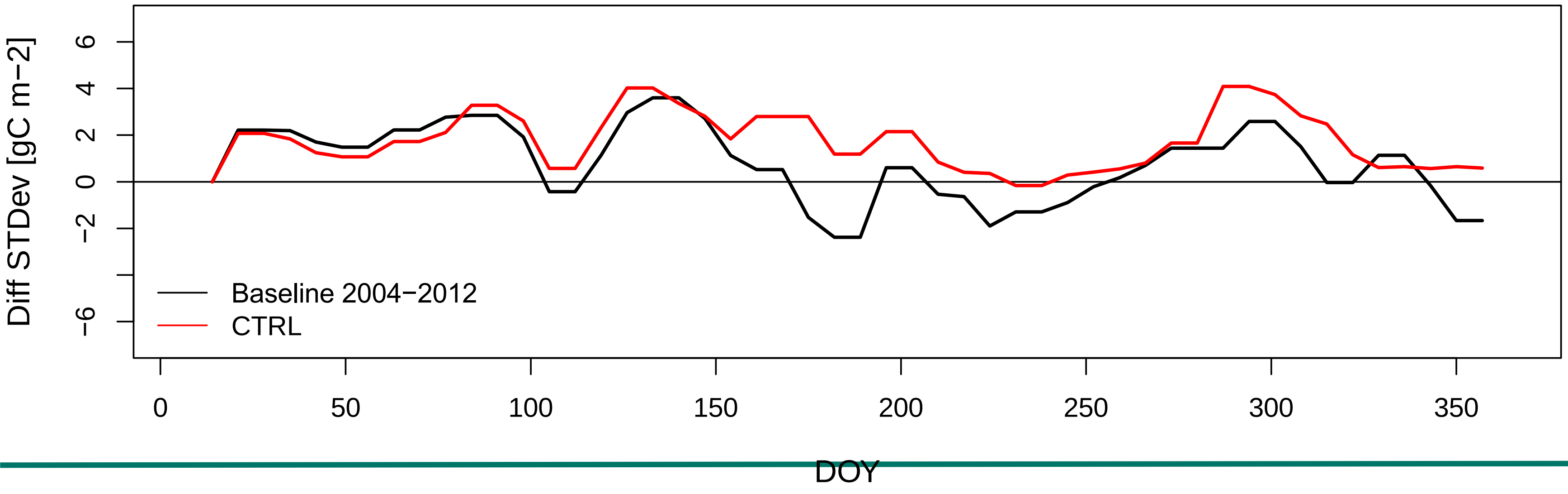

Results – Interannual Variability

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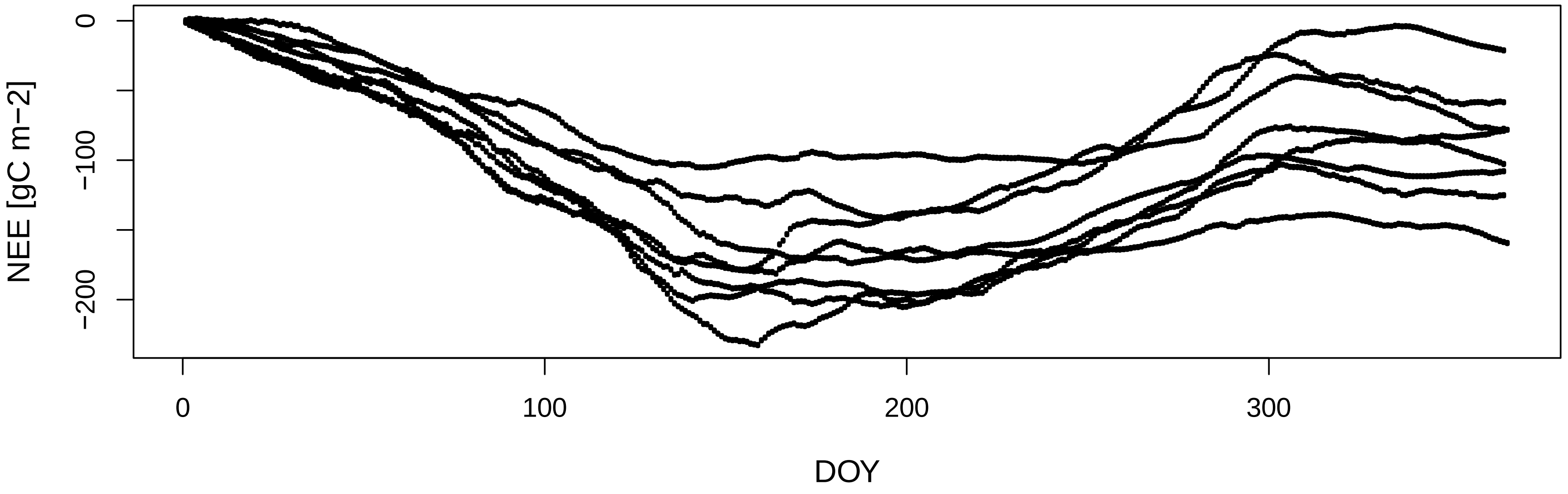

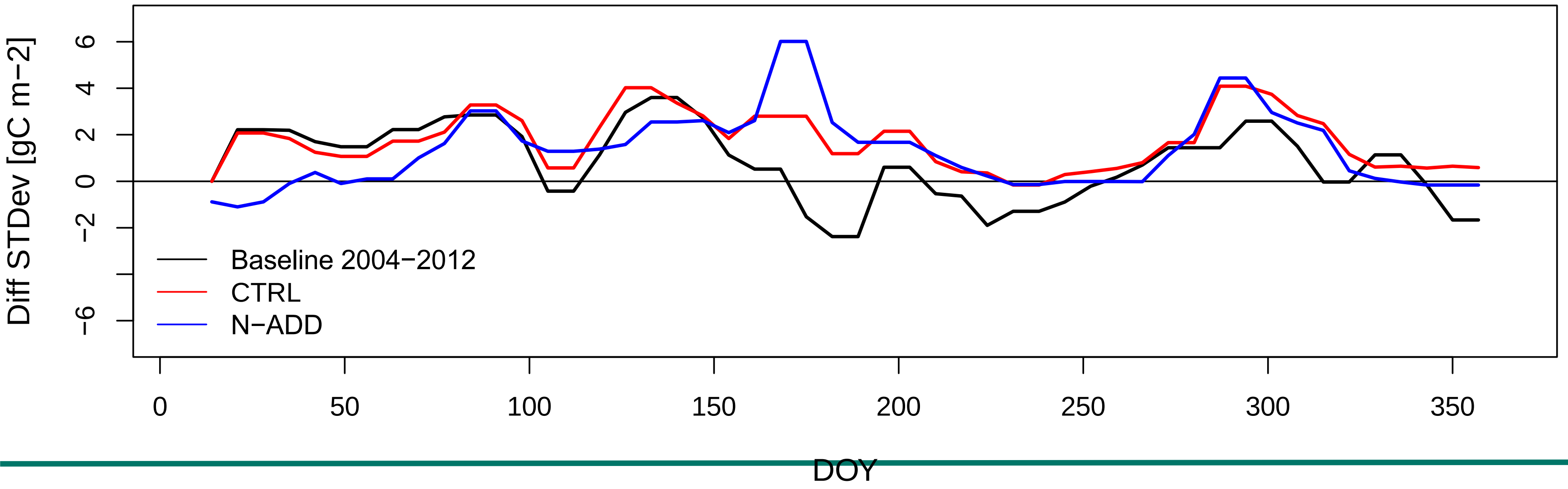

Results – Interannual Variability

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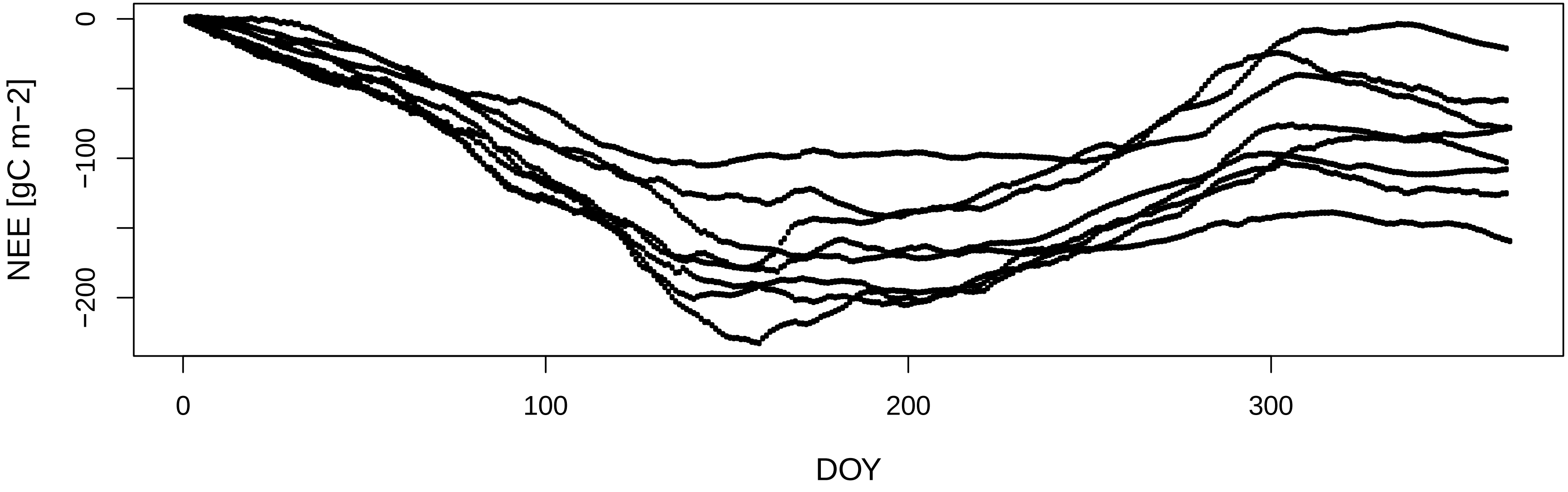
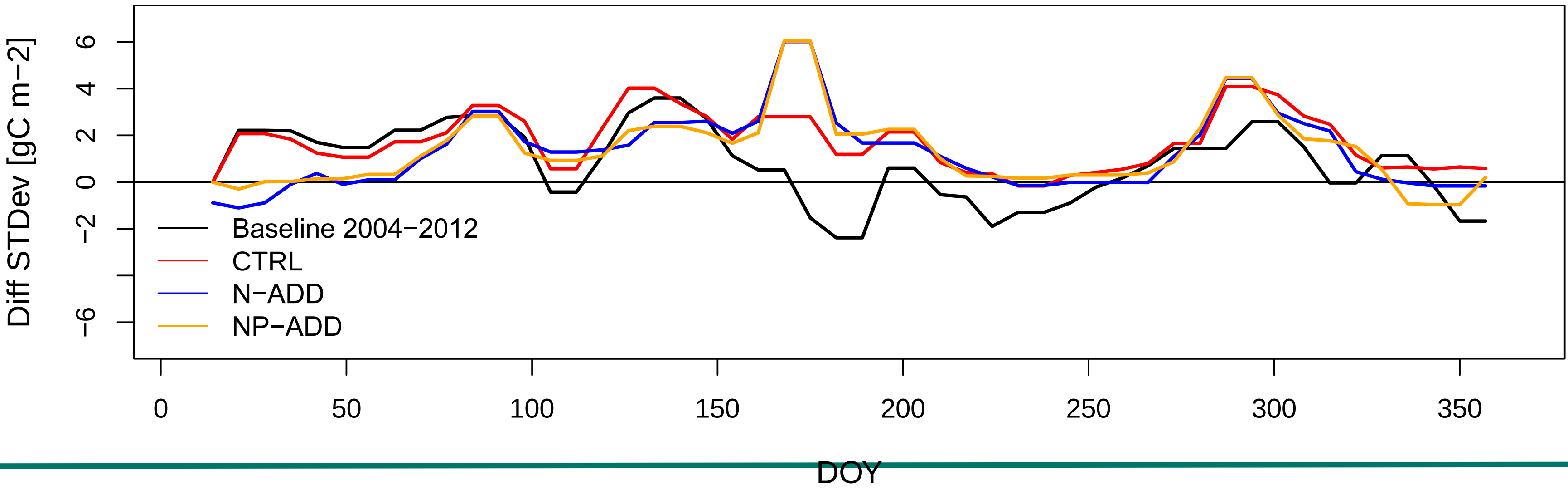
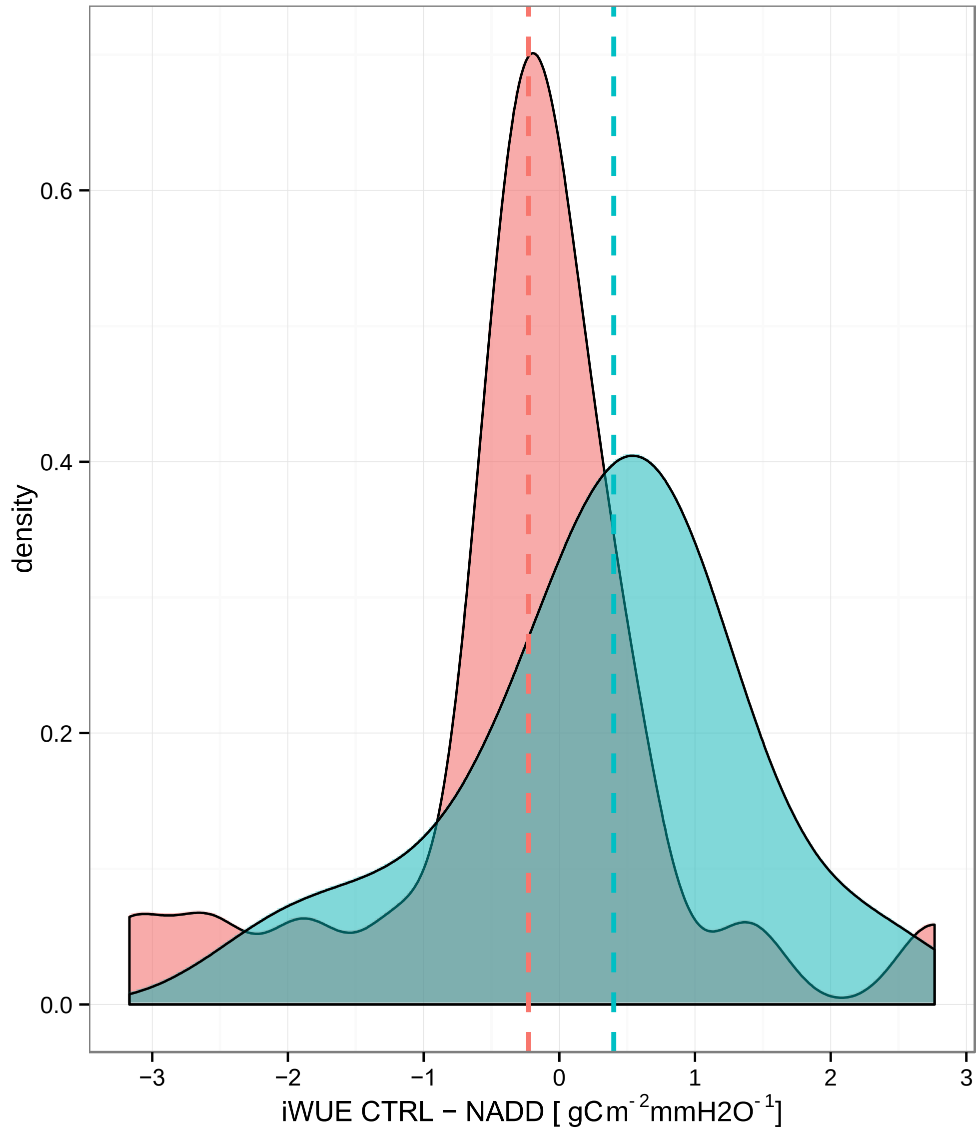
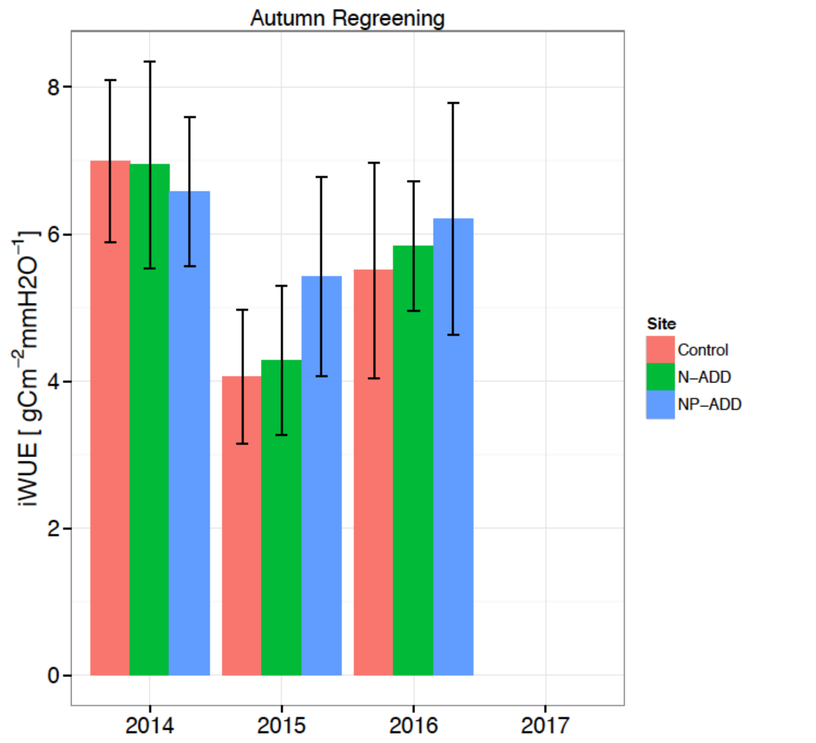




Results – Water Use Efficiency





Results – year to year variability of fluxes

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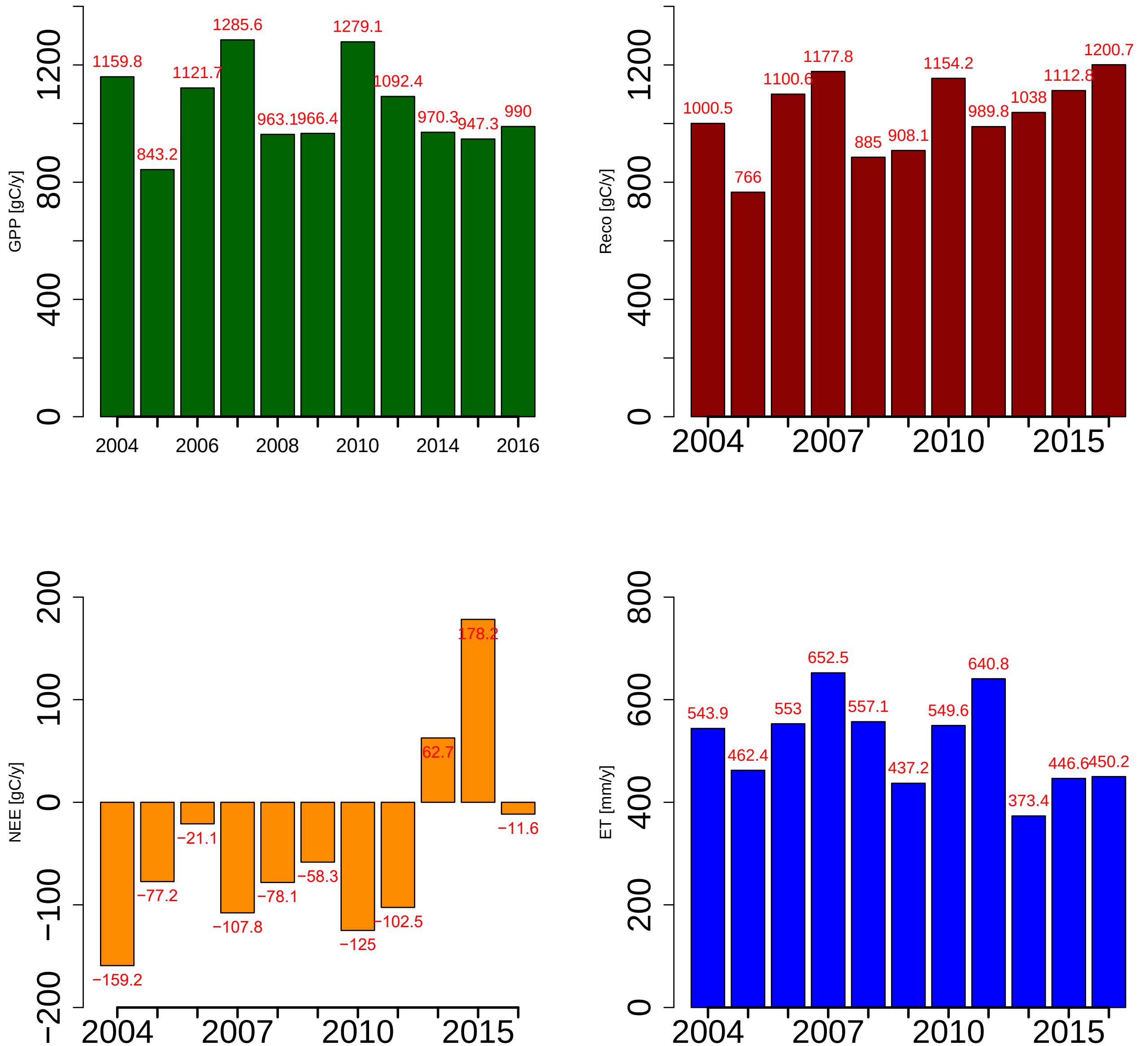
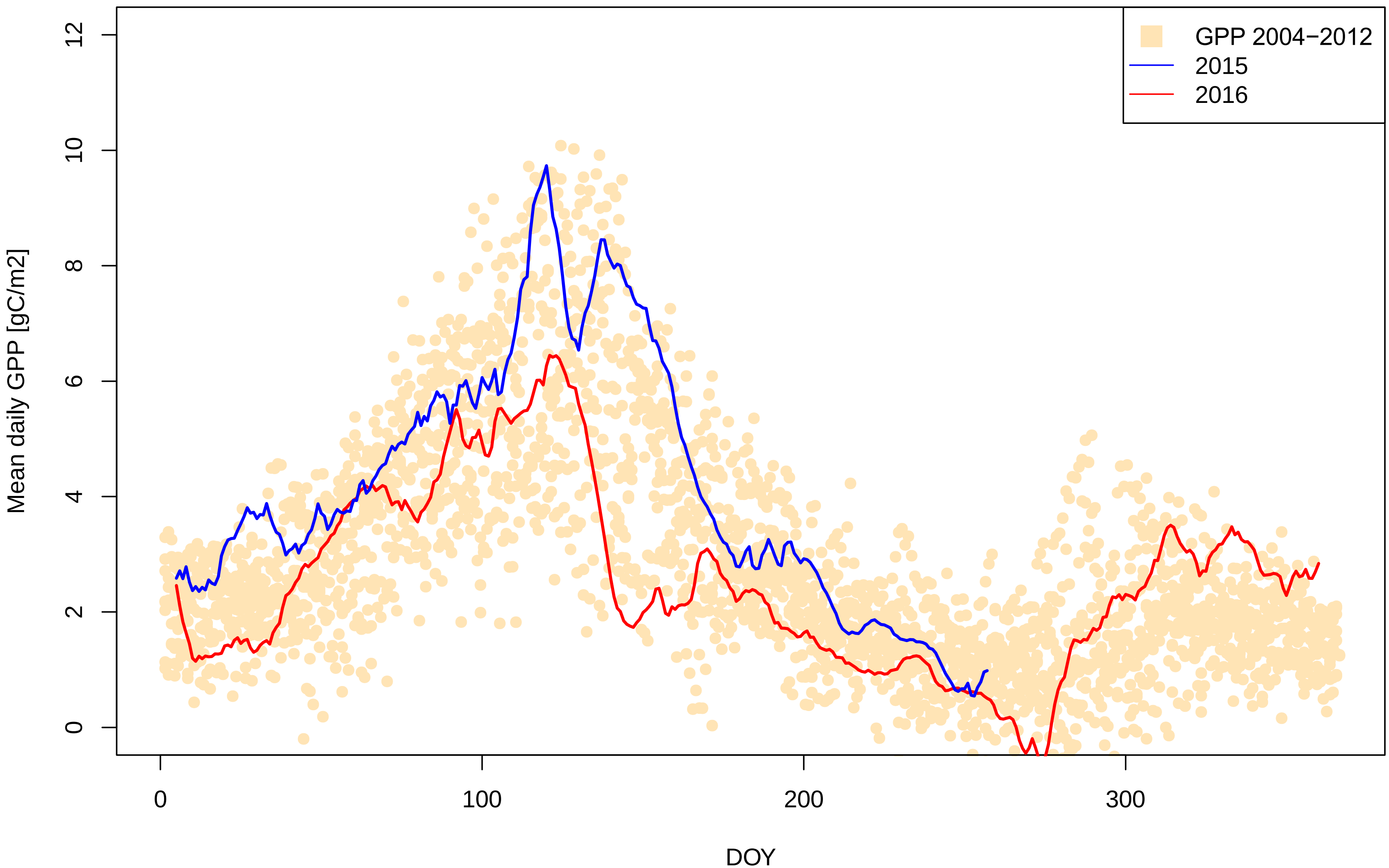


Results – year to year variability of fluxes

Max Planck Institute for Biogeochemistry



Experimental Site

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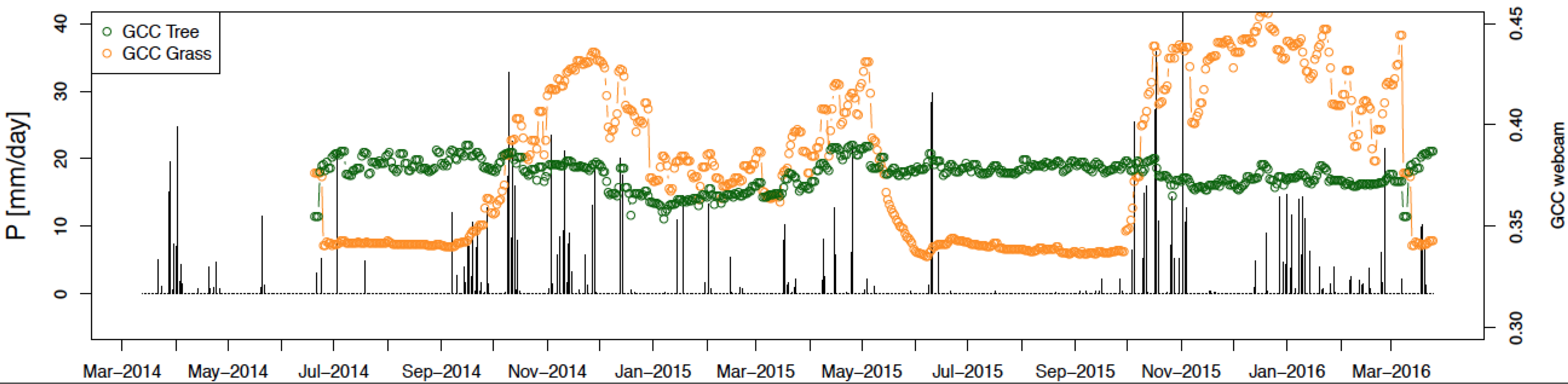

- **Typical Mediterranean ecosystem with dry summer**
- **Grass layer activity determined by water availability**
- **Evergreen Holm Oak**
- **Definition of phenophase based on grenness (e.g peak of season)**

Luo et al., In preparation

Results – year to year variability of fluxes

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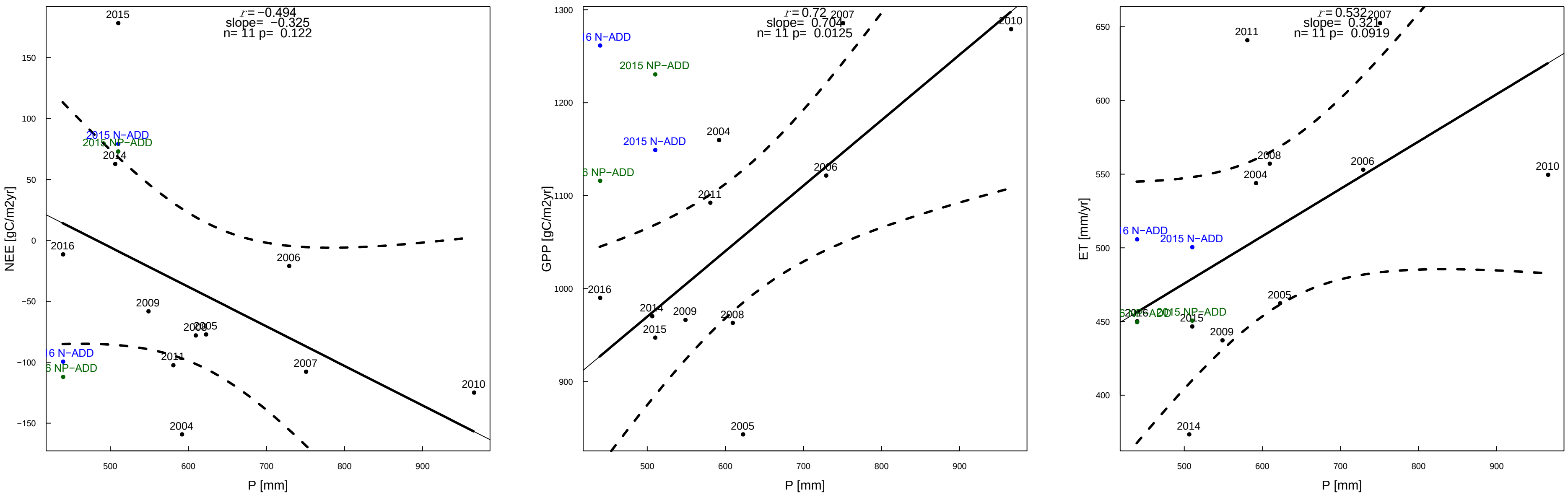

MANIP – Small Scale Manipulation

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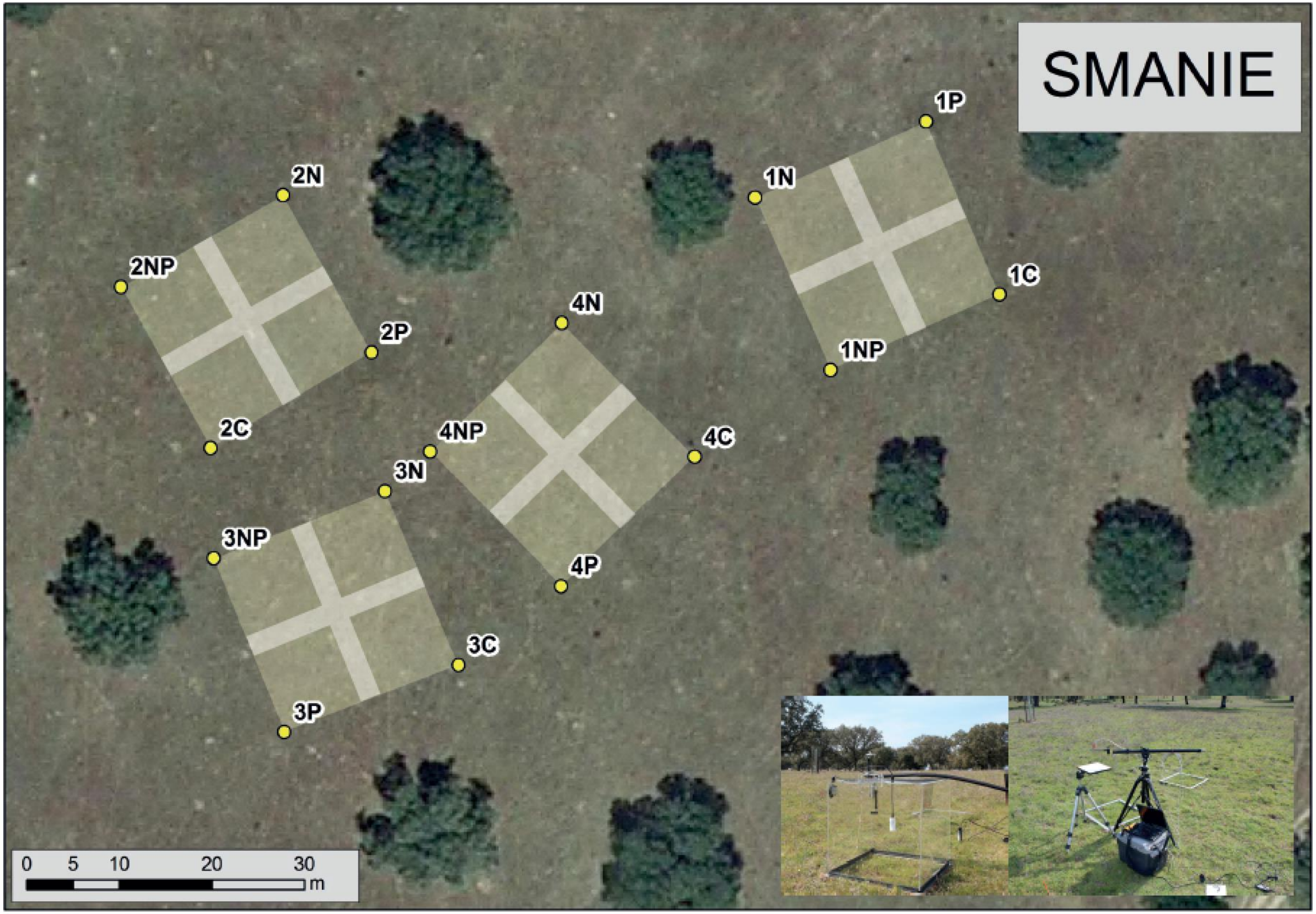

Experimental Site – Long Term EC station

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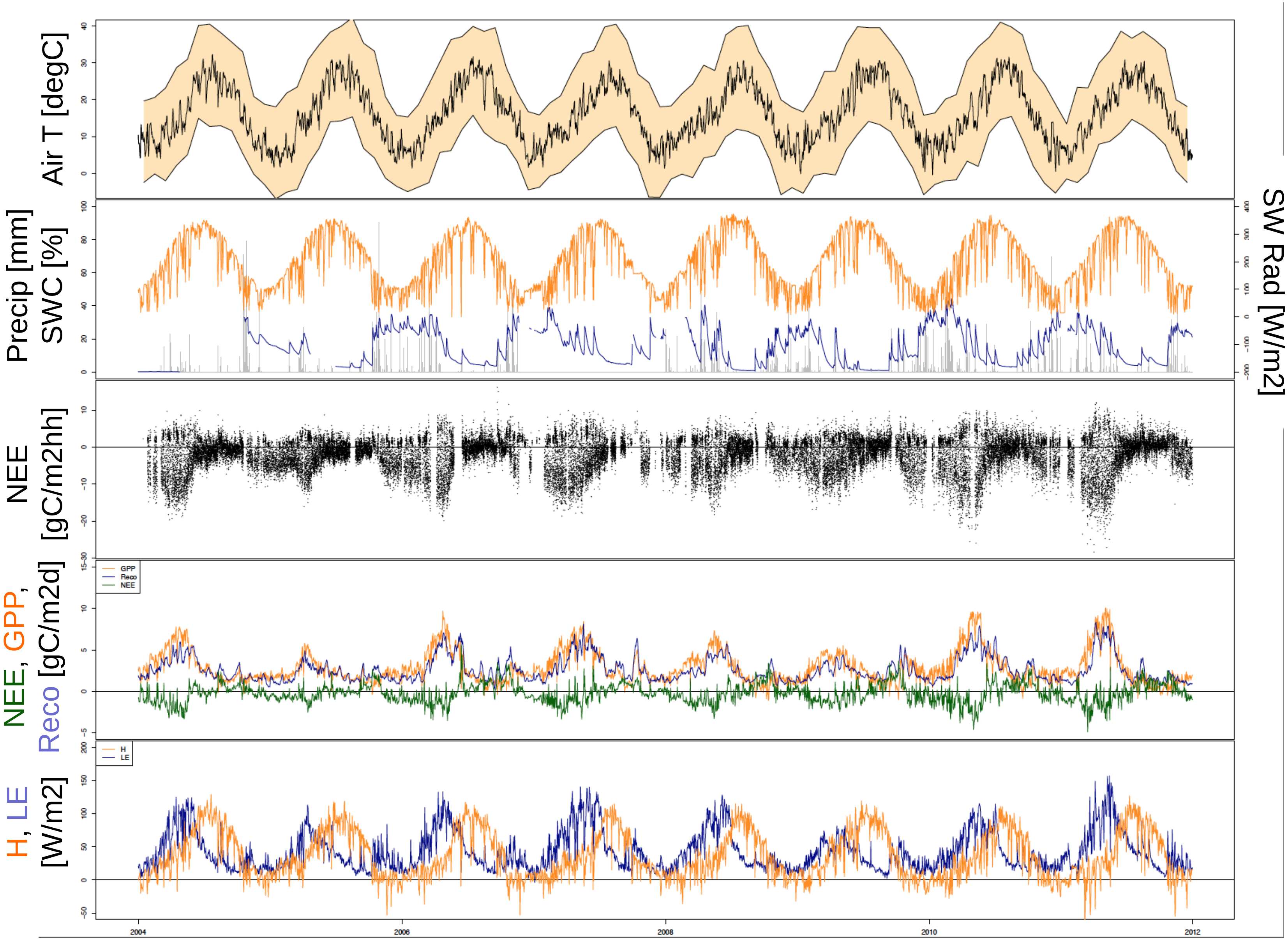

Data collected by CEAM – Valencia (PI Arnaud Carrara)

Results – Impact on C, H_2O fluxes

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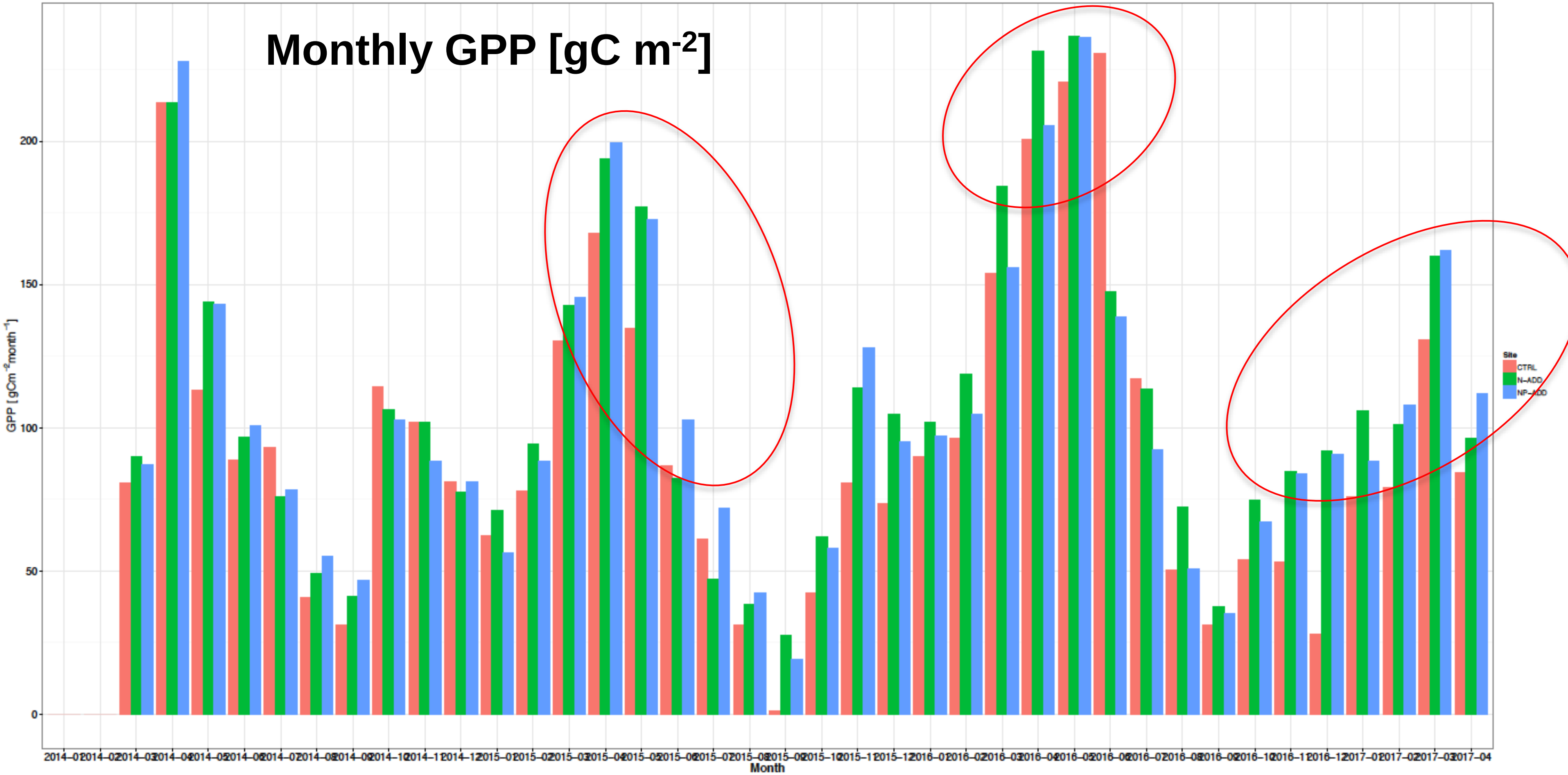
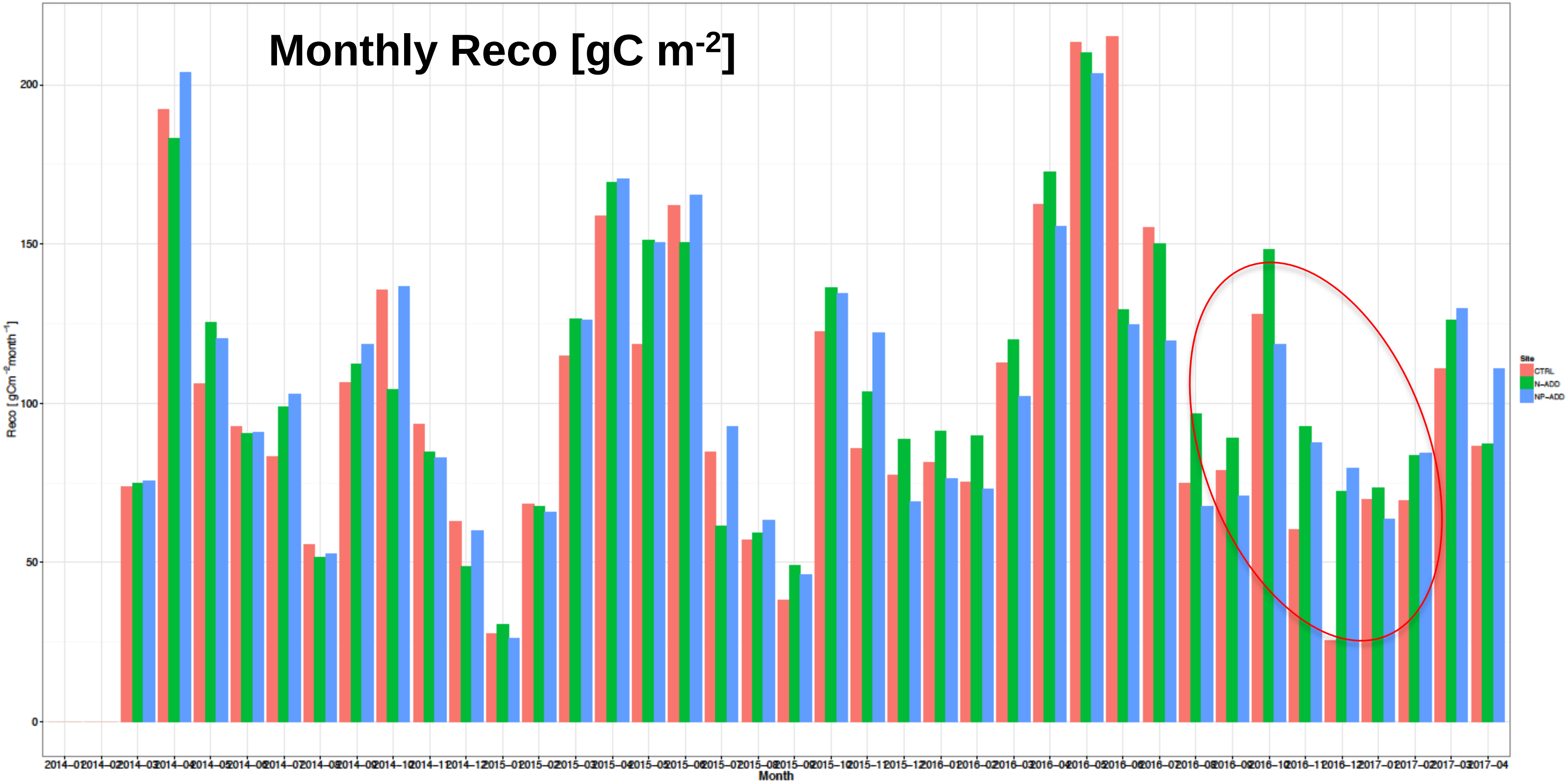


Results – Impact on C, H2O fluxes



Conclusions

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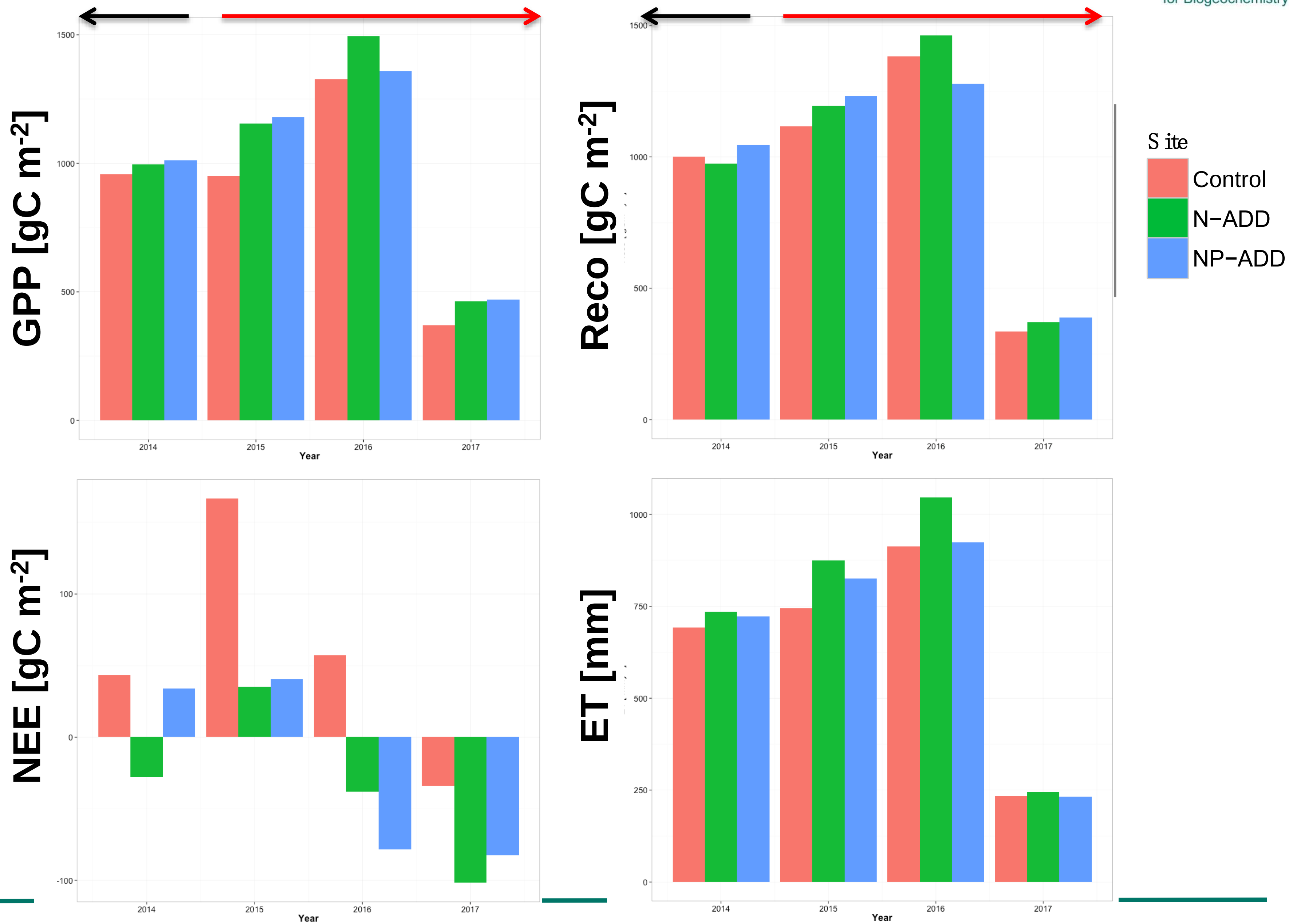
- **Barely significant** increase of the **water use efficiency** at annual time scale BUT…
  - Significant differences between treatments observed in specific periods (e.g. the **dry-down** and the **autumn season)**;
  - NP treatment higher iWUE in autumn

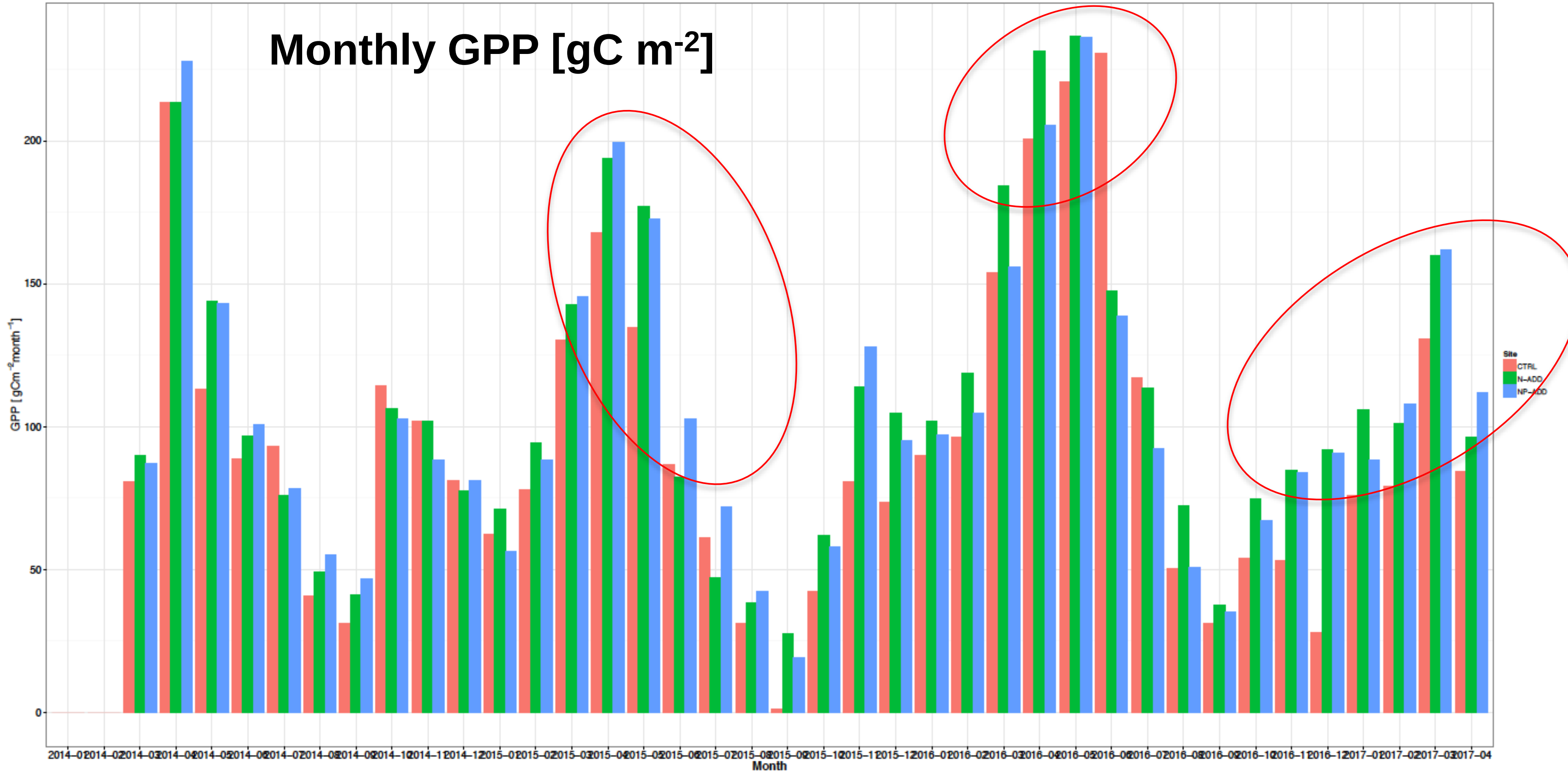
- The NP-ADD treatment is more dynamic in particular in Autumn after the first rainfall.

- After fertilization the different treatments show changes in sensitivities of processes to climate drivers and efficiencies in specific moment of the year:
  - N and NP → higher light use efficiency in spring
  - NP more responsive and more respiration in particular in fall
  - NP with WUE

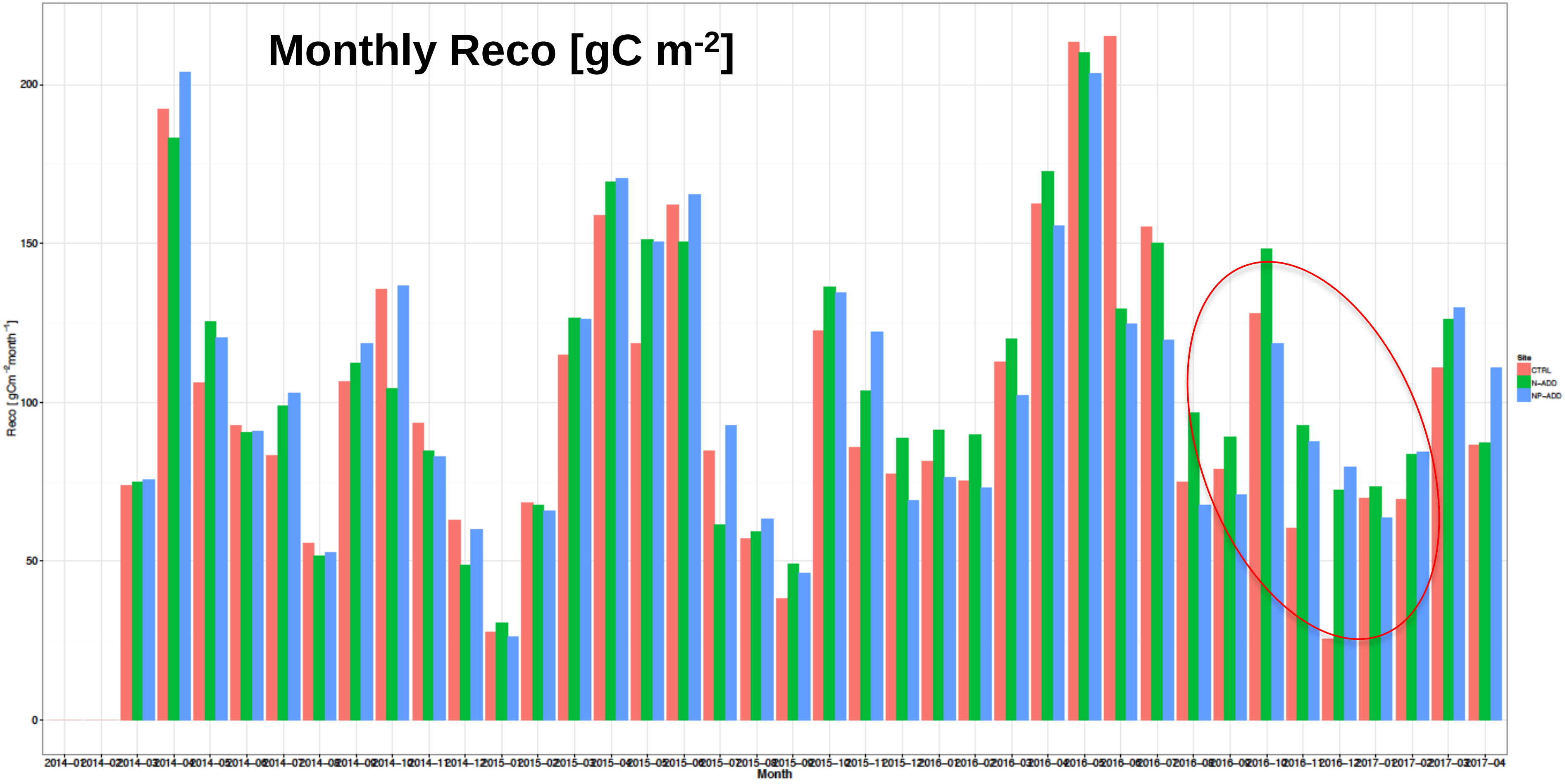
Results – Impact on C, H2O fluxes



Results – Impact on C, H2O fluxes



Results – Impact on C, H2O fluxes



Response of Soil processes

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Faster phosphate turnover in plot fertilized with nitrogen or phosphorus implying co-limitation

Site	Treatment	$\delta^{18}O_P$ (‰)	Bioavailable P concentration (μg/g soil)	Organic P concentration (μg/g soil)	C concentration (mg/g soil)	N concentration (mg/g soil)
MANIP	Control	23.8 ± 0.8	4.6 ± 0.3	15.9 ± 0.5	10.1 ± 1.8	0.9 ± 0.2
	Control - Tree	24 ± 0.8	9.4 ± 0.3	19.2 ± 3.1	20.8 ± 5.6	1.8 ± 0.5
	N	23.1 ± 0.2	5.3 ± 1.1	10.7 ± 1.6	11.1 ± 0.6	1.0 ± 0.1
	N - Tree	23.6 ± 1.1	4.4 ± 2.8	19.6 ± 2.6	17.9 ± 4.3	1.7 ± 0.3
	P	25.1 ± 2.2	10.8 ± 9.9	10.0 ± 1.6	8.0 ± 3.1	0.7 ± 0.3
	P - Tree	25.8 ± 0.7	12.7 ± 2.3	20.7 ± 5.2	22.9 ± 7.6	2.0 ± 0.5
	NP	23.6 ± 0	9.1 ± 0.1	16.7 ± 0.5	11.8 ± 1.7	1.1 ± 0.1
	NP - Tree	25.1 ± 0.1	10.6 ± 1.3	22.9 ± 6.3	19.4 ± 2.0	1.8 ± 0.2
SMANIE	Control	23.1 ± 0.4	4.1 ± 0.4			
	N	23.2 ± 0.8	4.9 ± 0.8			
	P	25.2 ± 0.6	21.2 ± 4			
	NP	24.4 ± 0.4	16.2 ± 1.7			

Weiner et al., (JGR Submitted)

Response of Soil processes

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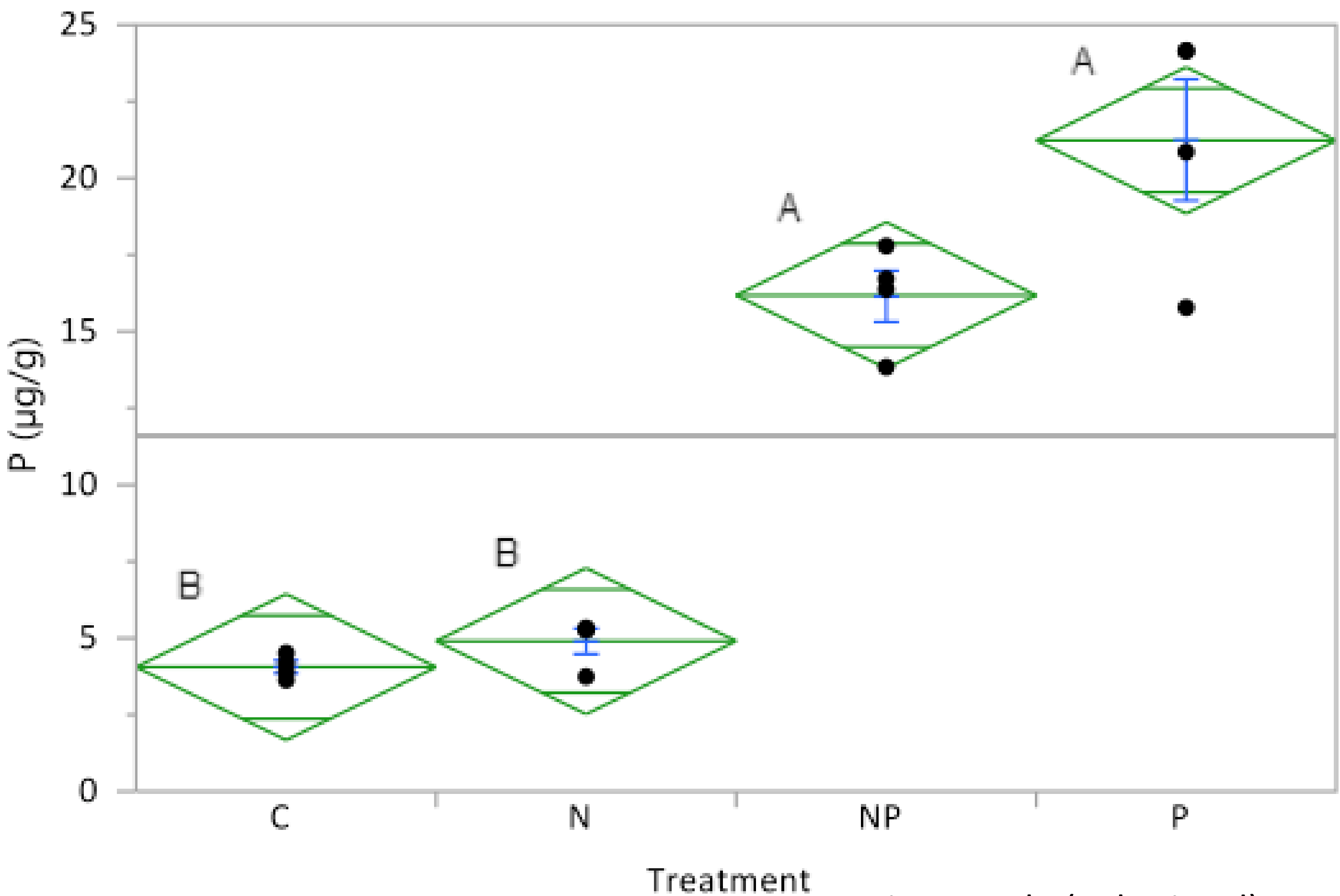
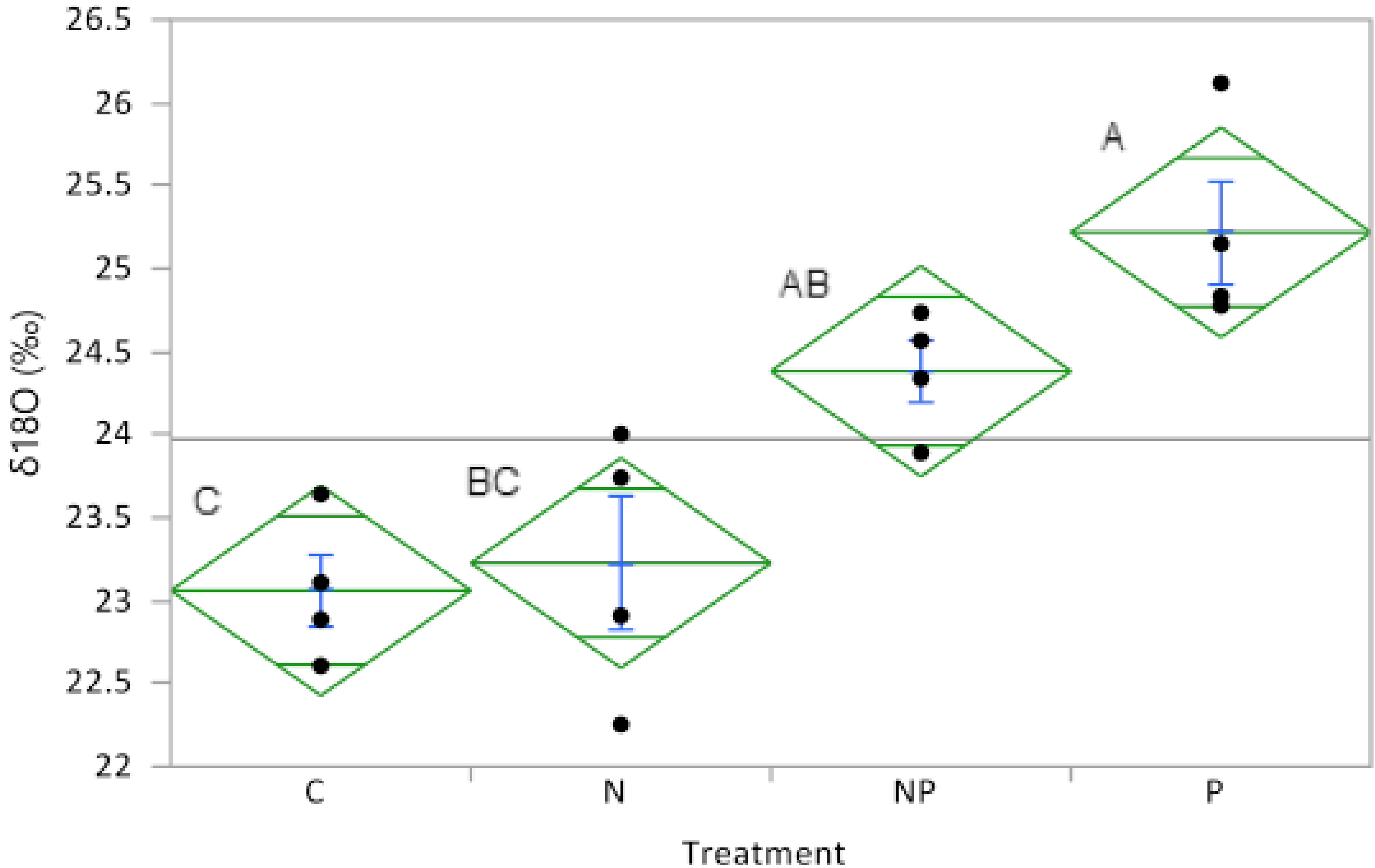
Grassland layer



Weiner et al., (Submitted)



Weiner et al., (Submitted)