A convergence of Light Use Efficiency

A convergence on a narrow range of light use efficiency in C3 and C4 crops:
Is it proof of the concept of an optimization of resource allocation and the functional convergence hypothesis in vegetation?

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Motivation

We argue that for accurate remote estimation of gross primary production (GPP), it is necessary to quantify the effect of *light use efficiency (LUE)* on GPP and understand how LUE variability affects accuracy of remote GPP estimation.

It is generally believed that

LUE is widely variable biophysical characteristic (*e.g. Turner et al., 2003, 2005, Kergoat et al., 2008*)

and just opposite

the concept of an optimization of limited resource allocation predicts the functional convergence of LUE in vegetation (*Field 1991, Field et al, 1995; Goetz and Prince, 1999; Ruimy et al., 1996*).

Gross primary production

$$GPP = fAPAR \times LUE \times PAR_{in}$$

fAPAR: fraction of absorbed photosynthetically active radiation

PAR_{in}: incident photosynthetically active radiation

LUE: light use efficiency

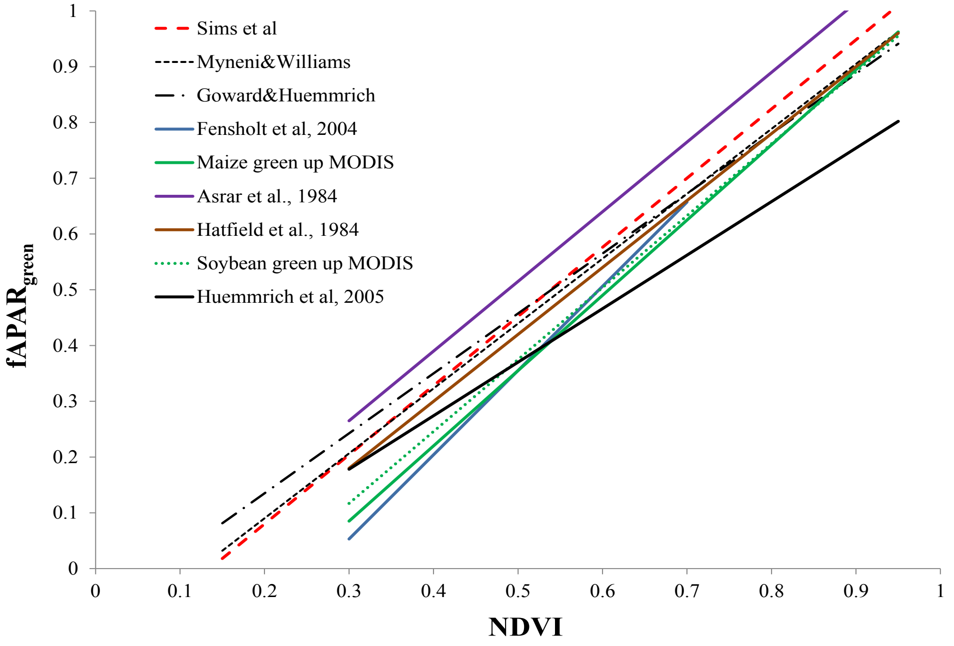
Monteith, Climate and the efficiency of crop production in Britain. Philosophical Transactions of the Royal society of London, 1977

So, to estimate GPP remotely, one should find a way to assess Fapar, PAR_{in} and LUE

Fapar estimation/measurement

- Direct measurement of total Fapar via canopy transmittance
  - Fapar = $(PAR_{inc} - PAR_{out} - PAR_{transm} + PAR_{soil})/PAR_{in}$
  - total Fapar vs. green/photosynthetic/chlorophyll Fapar issues
  - strict requirement for time of measurement
- Via green LAI
  - LAI is subjective characteristic
  - extinction coefficient (in Fapar vs. LAI relationship) is species-specific and affected by leaf structure and canopy architecture
  - the result is dependent on ratio of direct to diffuse radiation
- Via vegetation indices: NDVI, EVI, red edge NDVI, MTCI among others

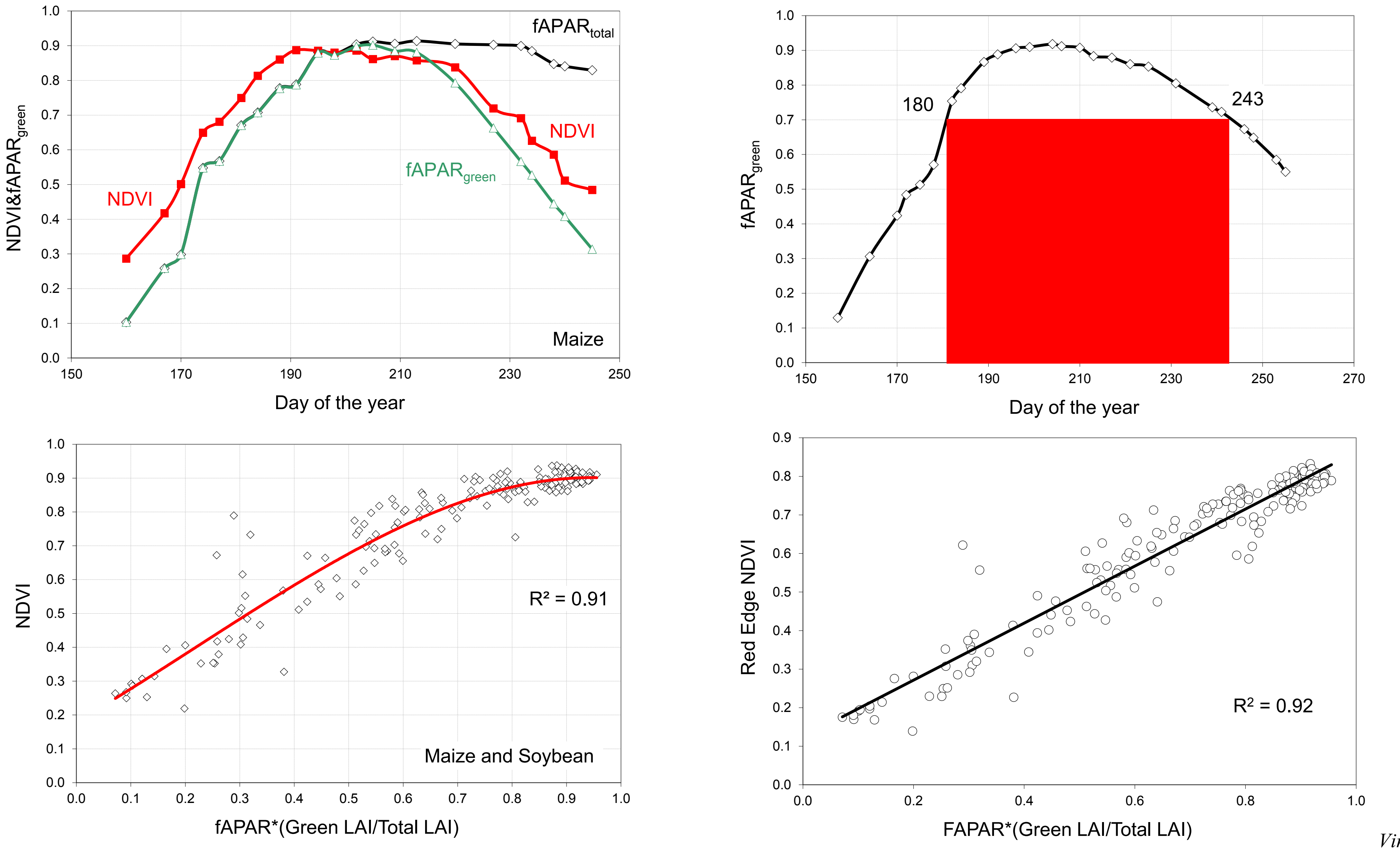
Fapar: remotely measured surrogates are either products of radiative transfer models or NDVI/other VIs



Best fit functions of $fAPAR_{green}$/NDVI relationships established using *in situ* measured NDVI (Asrar et al., 1984; Harfield et al., 1984; Fensholt et al., 2004; Sims et al., 2006), RTM (Myneni and Williams (1994); Goward and Huemmrich (1992), MODIS retrieved NDVI – Huemmrich et al., 2005) and this study (for green up stage only). The relationships $fAPAR_{green}$ vs. *in situ* NDVI established in this study was very close to that using MODIS retrieved NDVI.

Gitelson et al., 2016

Total Fapar, green Fapar and NDVIs



Vina and Gitelson, 2005

How to measure LUE remotely?

Photochemical reflectance index (Gamon et al., 1992)

$$PRI = (\rho 530 - \rho 570)/(\rho 530 + \rho 570)$$

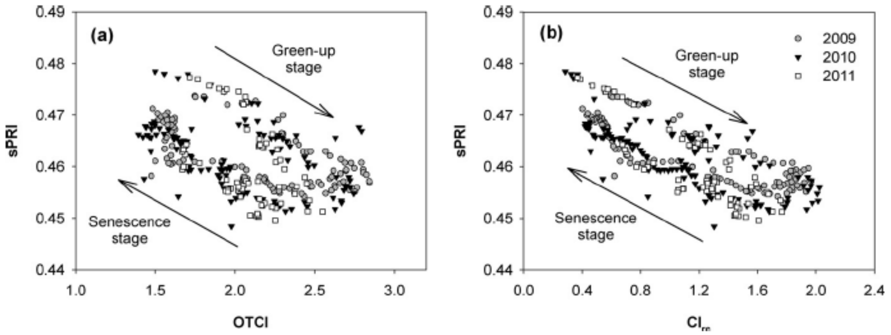
- Solar induced fluorescence?
- Detecting chloroplast avoidance movement

Zygielbaum et al, 2009

- Other photoprotective mechanisms?

PRI and canopy chlorophyll content
Plant/canopy level – seasonal and ontogenetic time spans

M. Rossini et al. / International Journal of Applied Earth Observation and Geoinformation 29 (2014) 1–10



Rossini et al., 2014

A.A. Gitelson et al. / Remote Sensing of Environment 190 (2017) 198–206

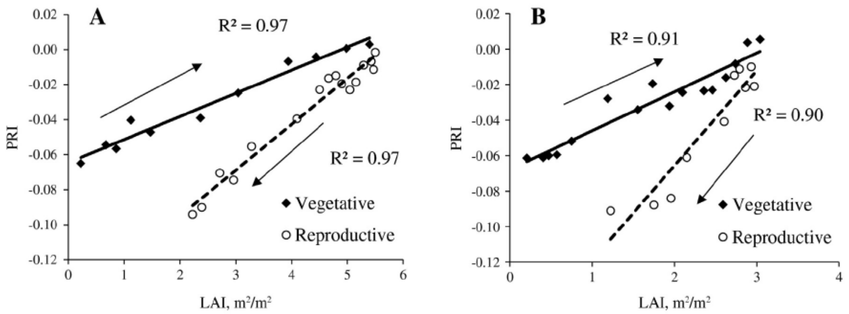


Fig. 4. Relationship between PRI and green LAI in maize (A) and soybean (B).

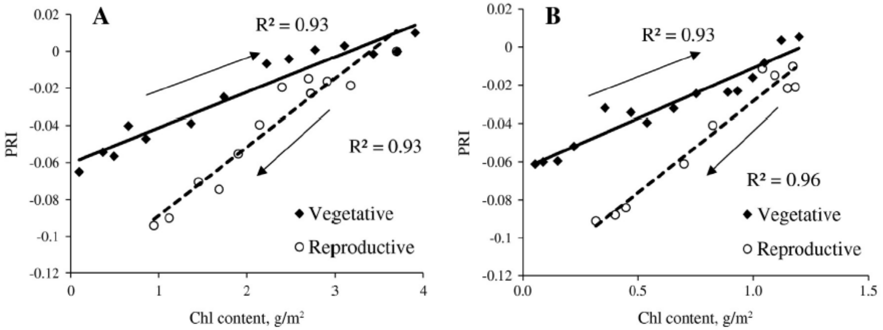


Fig. 5. Relationship between PRI and stand chlorophyll content in maize (A) and soybean (B).

Gitelson et al., 2017

There is a strong link between stand-level PRI and green LAI/Chl content

Is PRI a surrogate of LUE?
Plant/canopy level

A.A. Gitelson et al. / Remote Sensing of Environment 190 (2017) 198–206

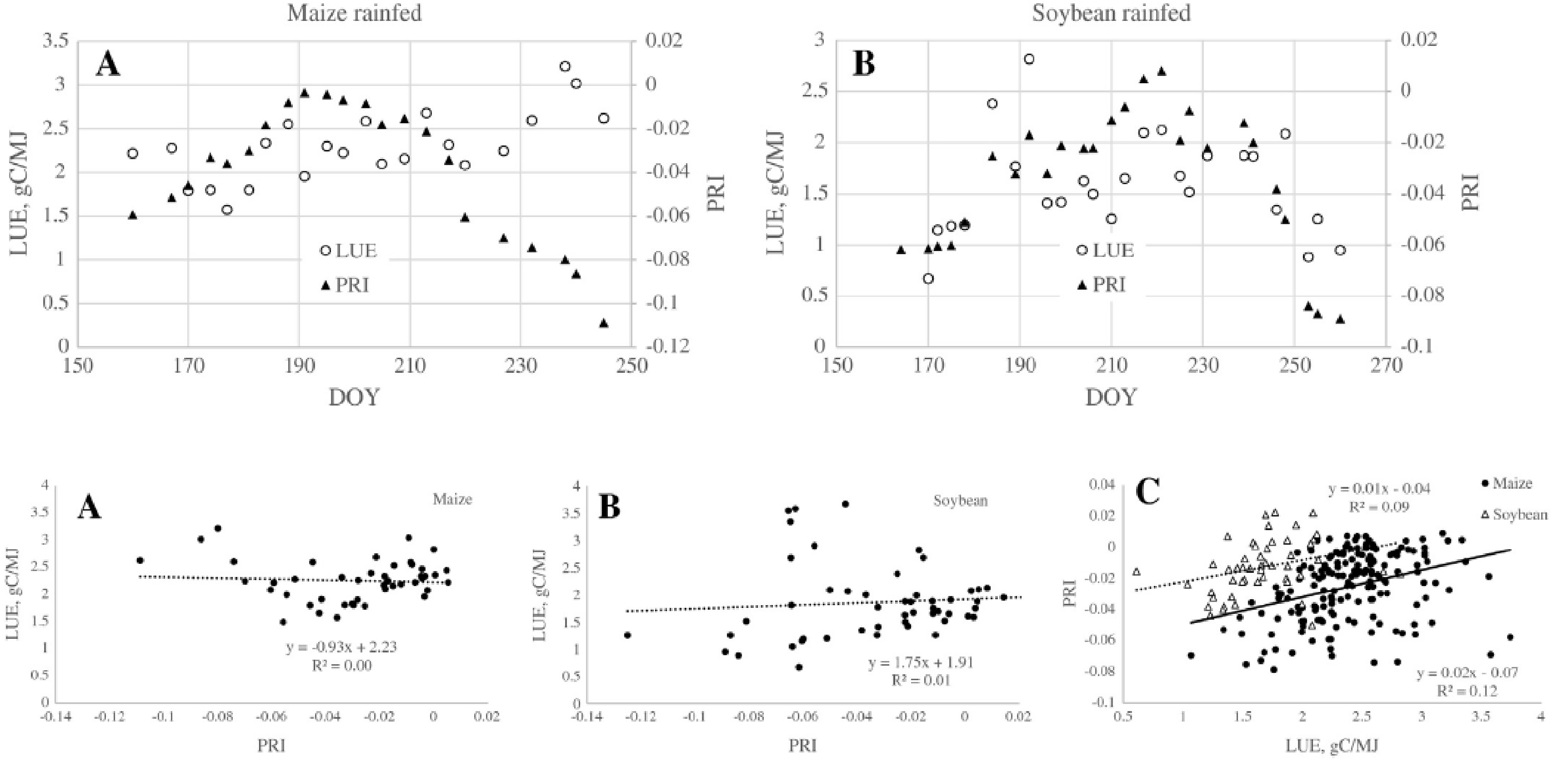


Fig. 7. LUE vs. PRI for maize and soybean irrigated and rainfed sites during growing season 2003 for maize (A), 2002 for soybean (B). PRI vs. LUE for irrigated and rainfed maize and soybean sites in 2001–2005 (C).

There is the lack of a clear relationship between PRI and LUE.

PRI cannot to be used for LUE estimation <u>over seasonal and ontogenetic time spans</u>

Gitelson et al., 2017

To reveal facultative changes in PRI, subtraction of the background of seasonal change in PRI due to changing canopy structure and constitutive pigment effects was suggested.

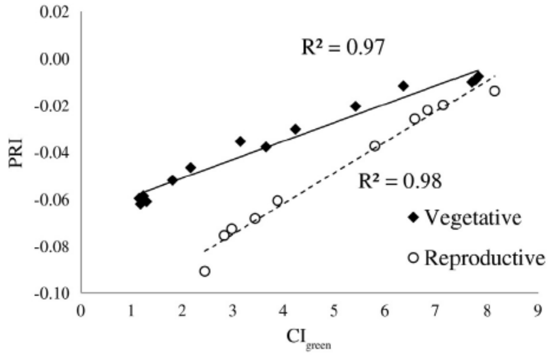


Fig. 10. Relationship between PRI and green chlorophyll index, $CI_{green} = (\rho_{NIR} / \rho_{570}) - 1$ (Gitelson et al., 2006), in maize.

Canopy Chl = Leaf Chl*LAI is a surrogate of canopy structure and pigment pool

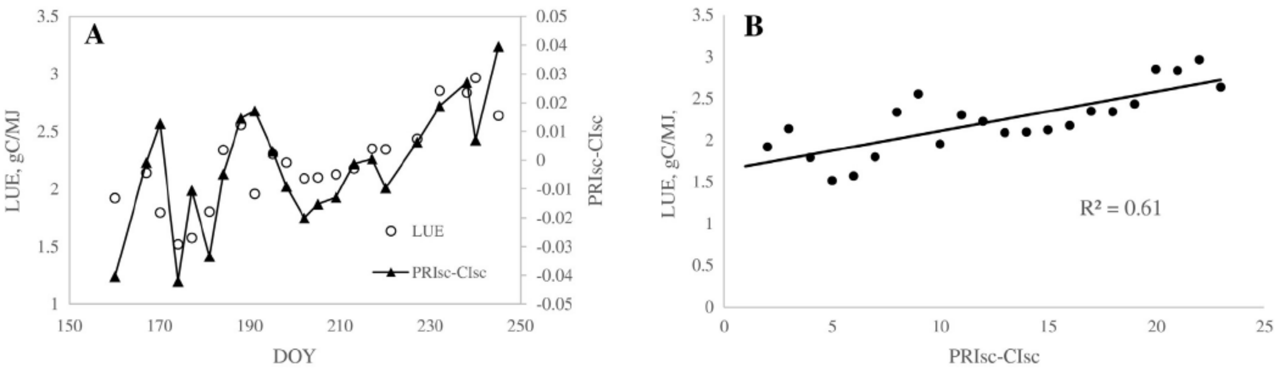


Fig. 11. Temporal behavior of light use efficiency (LUE) and difference between scaled PRI and red edge vegetation index, $CI_{red\ edge}$ (Gitelson et al. 2003, 2006) in rainfed maize (A) and (B) relationship LUE vs. PRIsc-CIsc.

Subtraction of the stand Chl content effect from PRI revealed apparent facultative change in PRI

Gitelson et al., 2017

How to measure LUE remotely?

What else?

Solar induced fluorescence?

$$GPP \approx F_{760} \cdot \frac{LUE_p}{f_{esc} \cdot LUE_f}$$

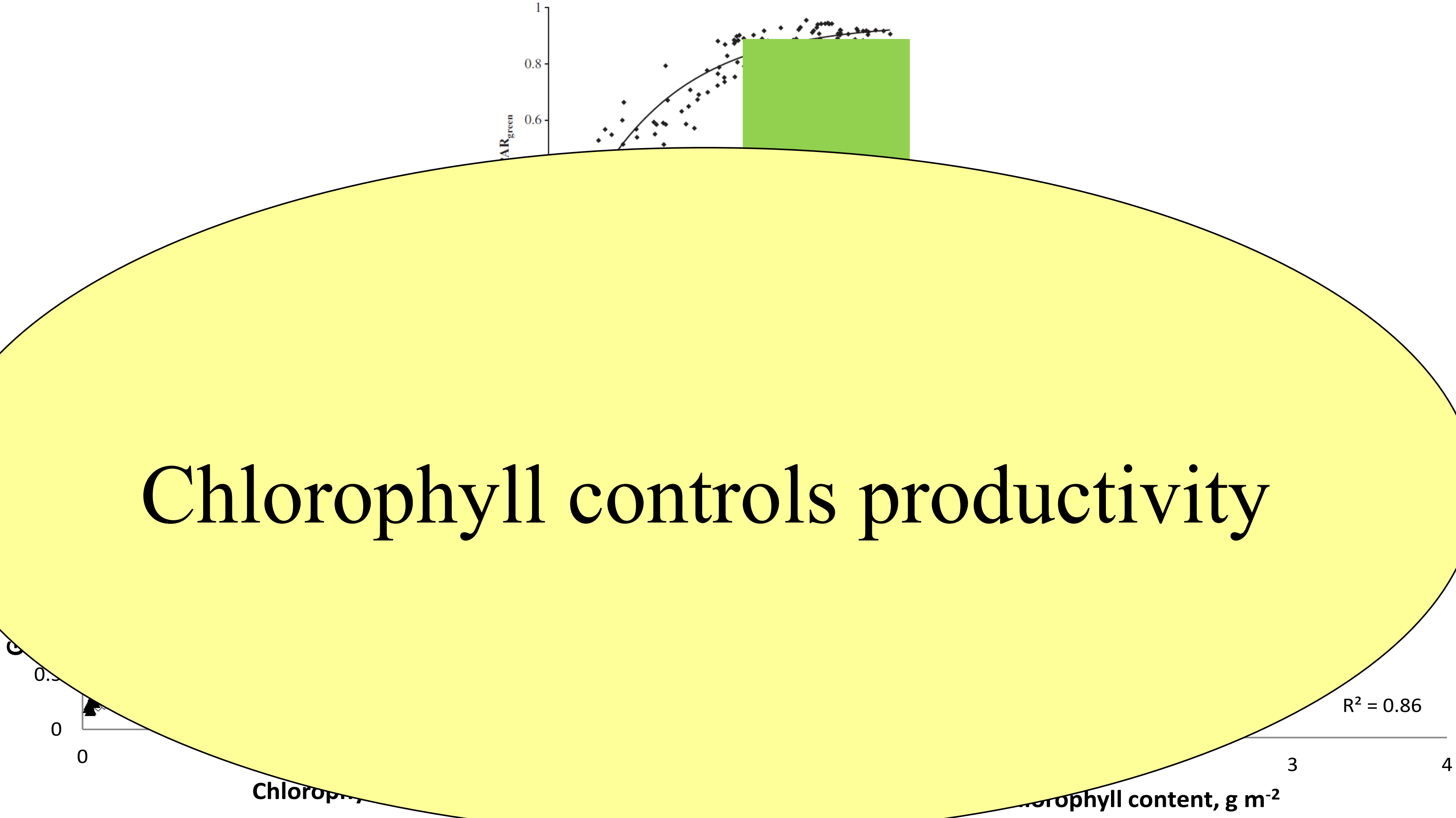
LUE_p, light use efficiency for photosynthesis
LUE_f, light use efficiency of fluorescence (i.e. fluorescence yield)
f_{esc}, a parameter accounting for the structural interference determining the fraction of F760 photons that are escaping the canopy

To understand what is behind SIF - GPP, Fapar, and/or chlorophyll and nitrogen content - <u>one needs to accurately estimate LUE_{ph}</u>

Canopy chlorophyll content and primary production

Chlorophyll is one of the main components of the photosynthetic machinery. To understand the processes behind photosynthetic optimization patterns, rather than analyzing the individual and/or simultaneous efficiency of each of different resources, *we suggest firstly to evaluate the efficiency of chlorophyll*.

Gross primary production vs. canopy chlorophyll content



Chlorophyll controls productivity

Gitelson et al., 2015

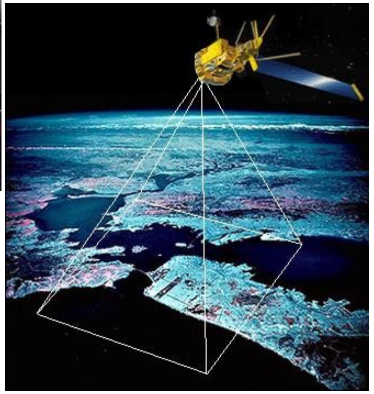
In two contrasting crops (C3 and C4) having different physiologies, leaf structures and canopy architectures the Chl content explains more than 86% of GPP/PAR variation

Is LUE is widely variable or conservative?
Does LUE strongly modulate GPP?

To answer these questions we investigated relationships between GPP and biophysical properties as Fapar, green LAI, reflectance, leaf and canopy chlorophyll contents during eight years in rainfed and irrigated C3 and C4 crops, maize and soybean, – 24 site*years altogether.

We estimated biophysical parameters of crops using hyperspectral data at leaf and canopy levels, as well as airborne and satellite data.

Carbon Sequestration Project at University of Nebraska-Lincoln: http://csp.unl.edu/Public/G_rs-exchange.htm



$$GPP = Chl \times PAR_{in}$$

Chl: stand chlorophyll content (leaf Chl × green LAI)

PAR_{in}: incident photosynthetically active radiation

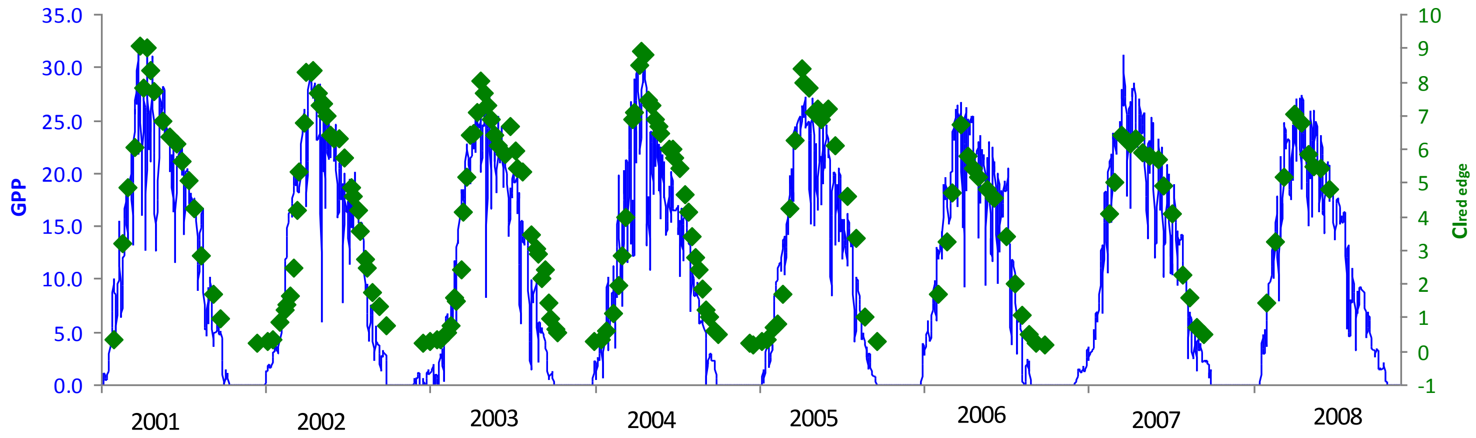
Gitelson et al., 2003; 2006

GPP determined in such way is ***potential GPP*** because *LUE was assumed constant*

Stand Chl may be estimated by NDVI, green and red edge chlorophyll indices, MTCI, WDRVI or other Chl-related vegetation indices

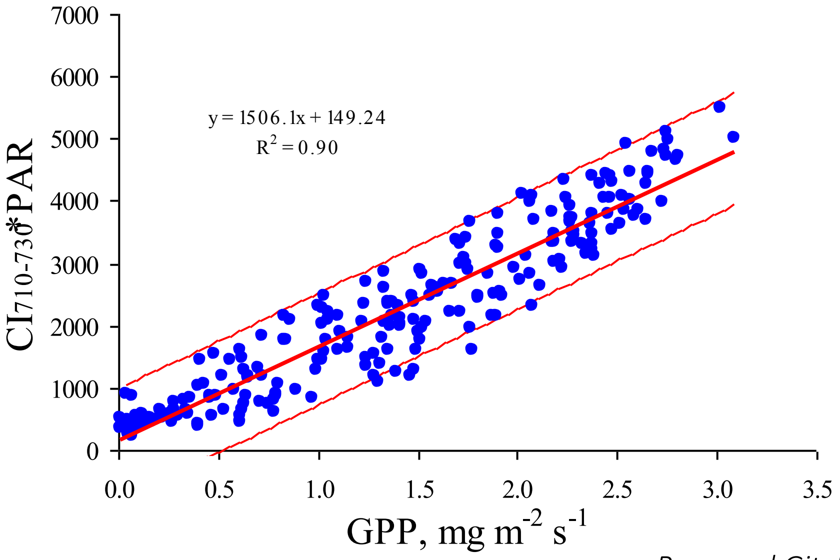
$$NDVI = (\rho_{NIR} - \rho_{red})/(\rho_{NIR} + \rho_{red})$$
$$WDRVI = (0.1 \times \rho_{NIR} - \rho_{red})/(0.1 \times \rho_{NIR} + \rho_{red})$$
$$MTCI = (\rho_{NIR} - \rho_{red\ edge})/(\rho_{red\ edge} - \rho_{red})$$
$$CI_{red\ edge} = (\rho_{NIR}/\rho_{red\ edge}) - 1$$
$$CI_{green} = (\rho_{NIR}/\rho_{greren}) - 1$$

What did we find?



Peng et al., 2011; Peng and Gitelson, 2011

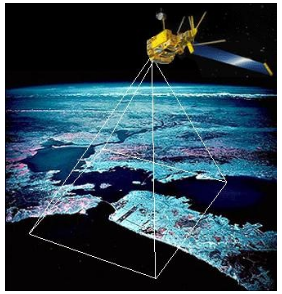
Proximal sensing: GPP and red edge CI



Peng and Gitelson, 2011

Generic algorithm for maize and soybean

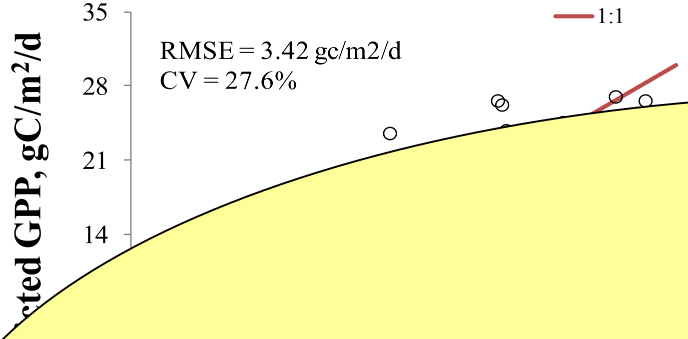
At close range, GPP was accurately estimated via crop chlorophyll content
assuming LUE is constant

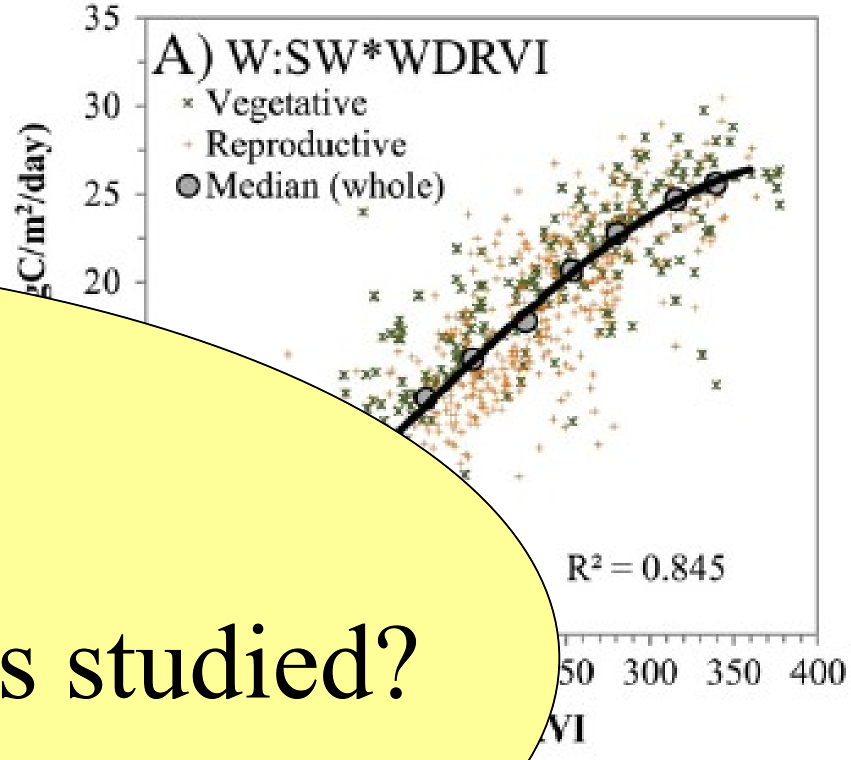


Satellite level

TM/ETM+: US Corn Belt IL, MN, IA and NE

MODIS 250 m resolution

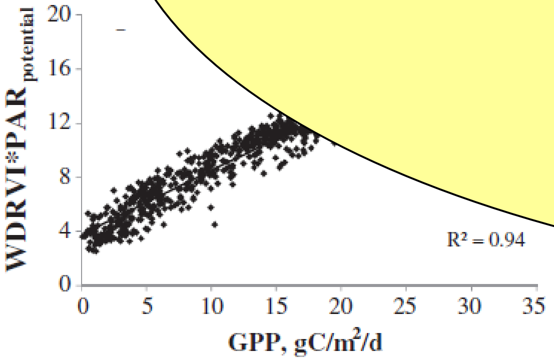


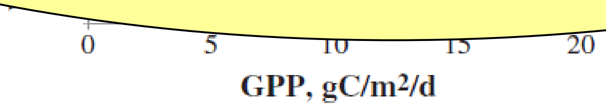


Is LUE conservative for crops studied?

W*WDRVI) = 0.98

Sakamoto et al., 2011





Peng et al., 2013

At all levels of observation - close range, aircraft, satellites (MODIS, TM/ETM and MERIS) - assuming LUE is constant GPP was accurately estimated via crop chlorophyll content

GPP vs. $aPAR_{green}$

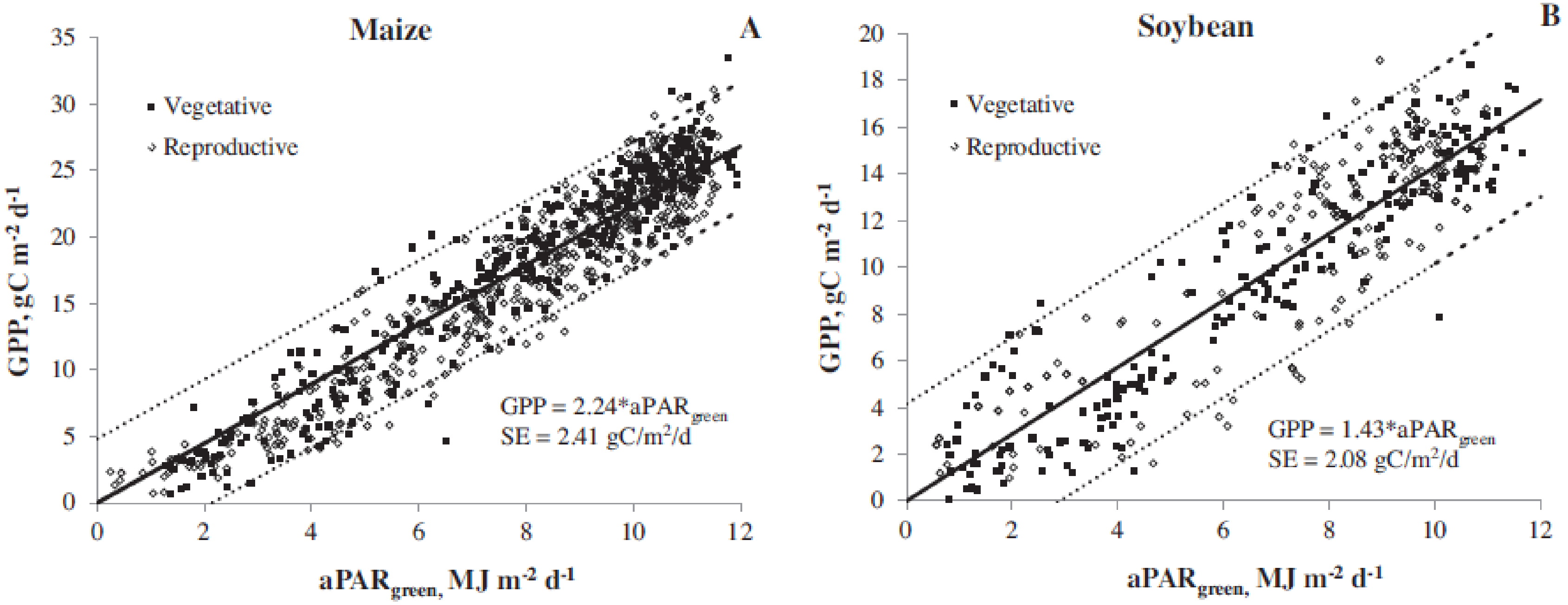


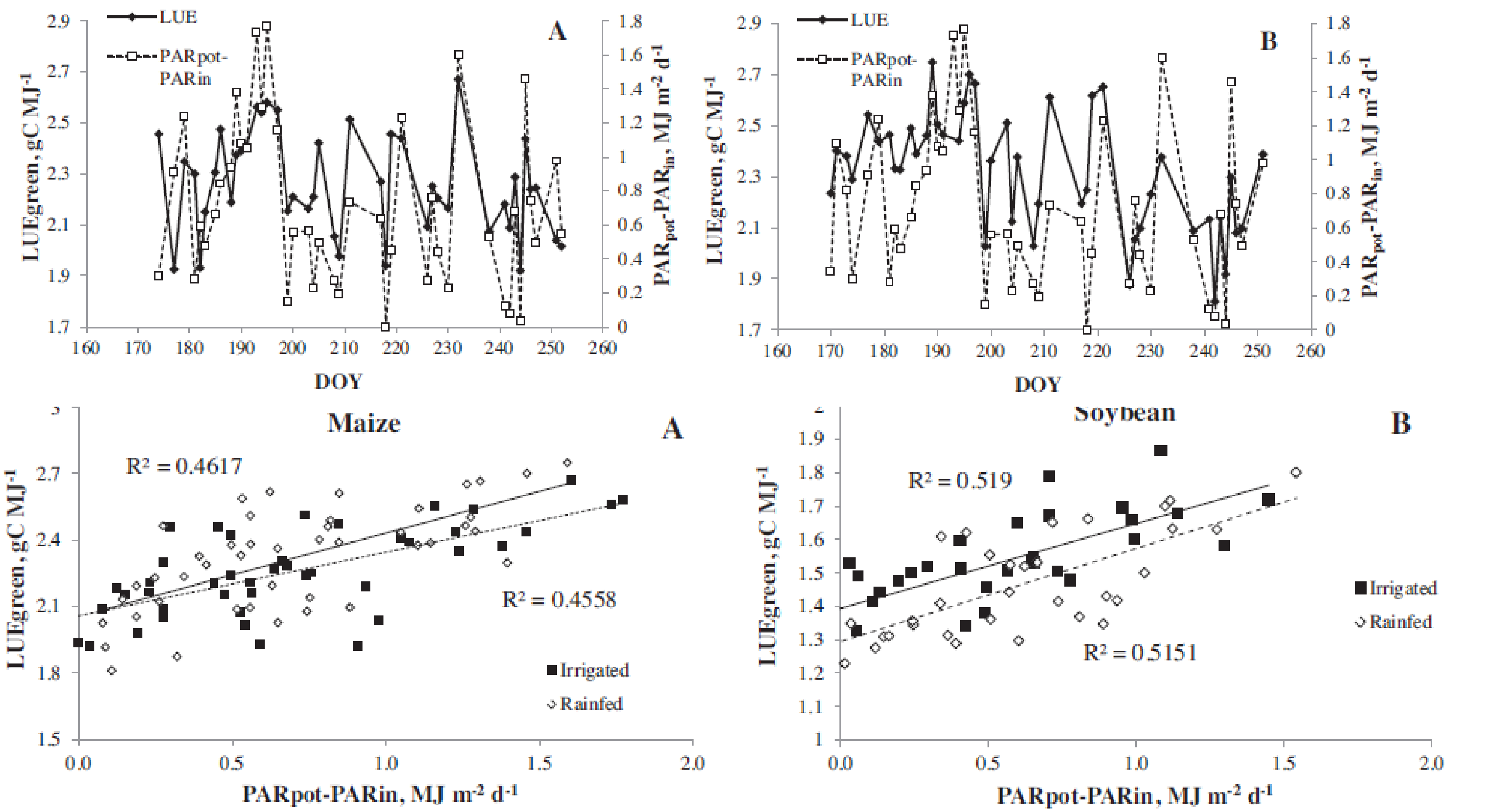
Fig. 11. Relationships between gross primary production (GPP) and PAR absorbed by photosynthetically active vegetation ($aPAR_{green}$) for maize in 2001–2008 (A), and soybean in 2002, 2004, 2006, 2008 (B) in vegetative and reproductive stages.

Gitelson et al., 2015

Maize: LUE ≈ **2.25** gC MJ^{-1} STE = 0.22 gC MJ^{-1}, CV = 10%

Soybean: LUE ≈ **1.46** gC MJ^{-1} STE = 0.18 gC MJ^{-1}, CV = 11%.

Day-to-day facultative change of LUE

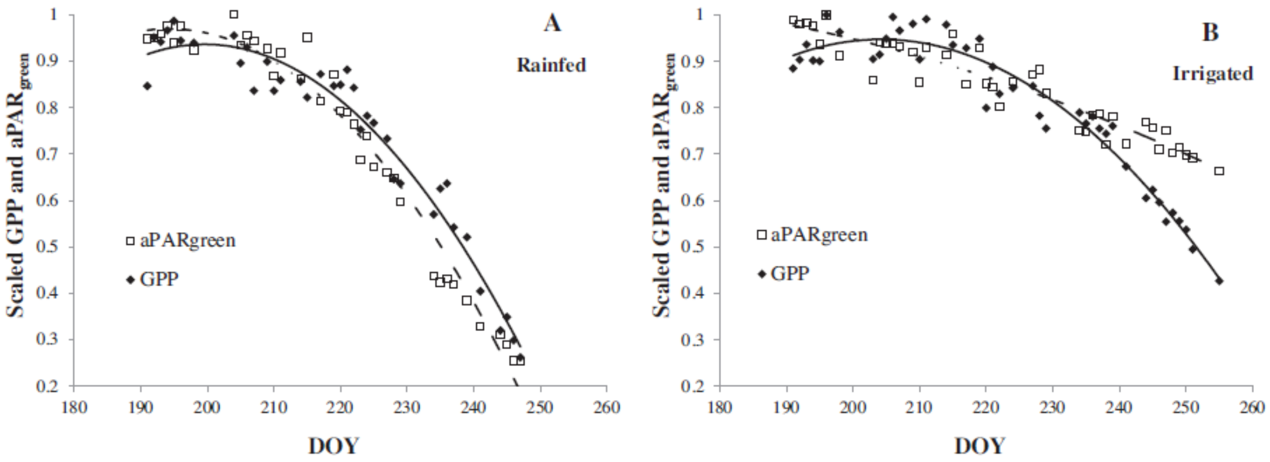


Gitelson et al., 2015

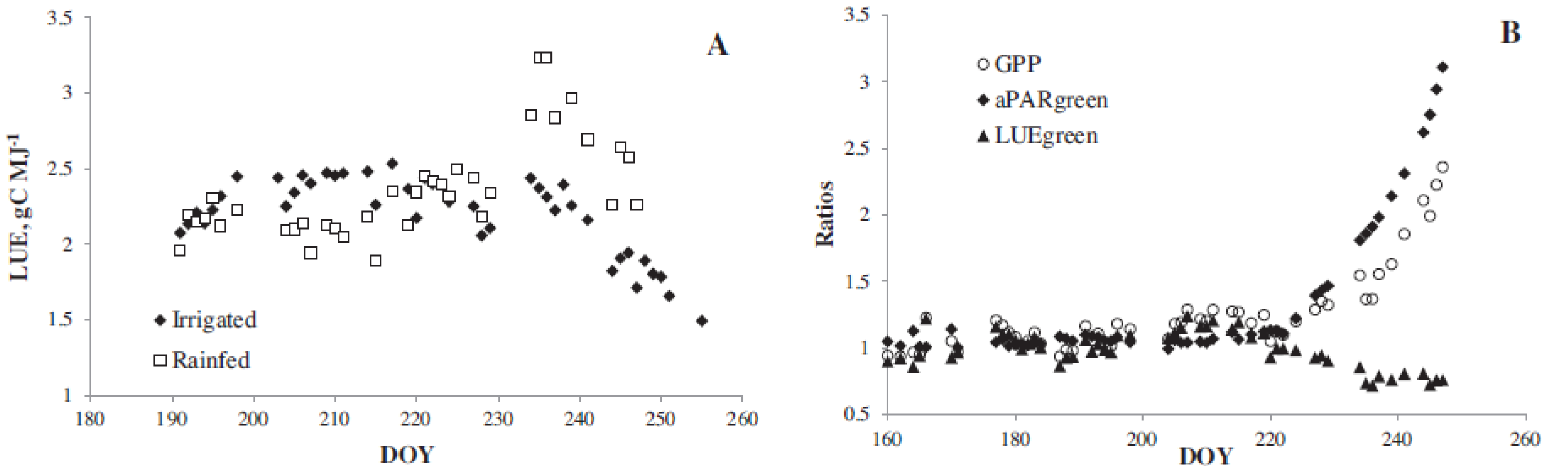
The main (not only) reason for the day-to-day LUE_{green} oscillation was the *daily variability of incident PAR*

Increase of incident irradiation caused decrease of LUE_{green}

Seasonal constitutive change of GPP, Fapar and LUE



Irrigated to rainfed BPC ratios



In both crops, the higher amount of Chl ***produced*** at irrigated sites was ***less effective as a driver*** of photosynthesis than Chl *produced* at the rainfed sites with limited water resources.

Canopy with smaller Chl content may absorb the same or almost the same amount of radiation as canopy with higher Chl content/density

In maize, a 3-fold higher Chl content does not bring any difference in LUE
In soybean, 2.6-fold higher Chl content does not bring any difference in LUE

As **a *driver*** of photosynthesis, <u>decreased canopy Chl content</u> is effective in

- ✓ capturing light, facilitating deeper light penetration inside the canopy
- ✓ maximizing photosynthetic rate under conditions of limited water availability

Is limited resource availability and high resource acquisition cost at rainfed sites is a reason for efficient resource use?

If so, it results in an optimization of resource allocation, which then results in a maximization of carbon gains and a convergence on a narrow range of LUE (Field, 1991; Goetz and Prince, 1999) and

the response is a change in aPAR such that LUE remains relatively invariant

$$LUE = GPP/aPAR$$

Variability of LUE

Table 2. Optimum Daily Light-Use Efficiency (LUE, mol/mol) and Canopy Normalized Photosynthesis (GEE*, μmol m^{-2} s^{-1}): Average, Coefficient of Variation (CV) and Number of Data, Grouped by Plant Functional Types

Plant Types	LUE	CV	GEE*	CV
Deciduous broadleaved	0.0225	10 (n = 7)	34.5	14 (n = 13)
Evergreen broadleaved	0.0144	43 (n = 3)	22.5	24 (n = 4)
Mixed forests	0.0187	17 (n = 3)	27.2	10 (n = 4)
Evergreen needleleaved	0.0155	32 (n = 19)	23.6	24 (n = 25)
Deciduous needleleaved	-	-	21.7	71 (n = 2)
Tundra, wetlands	0.0116	41 (n = 3)	18.0	48 (n = 19)
C3 grasses and crops	0.0270	42 (n = 3)	35.8	51 (n = 5)
C4 grasses and crops	0.0245	28 (n = 4)	43.6	27 (n = 5)
All grasses and crops	0.0256	32 (n = 7)	39.7	38 (n = 10)
All plant types	0.0182	37 (n = 42)	26.2	42 (n = 77)

Deciduous broadleaved	0.0225
C3 grasses and crops	0.0270
C4 grasses and crops	0.0245

STE = 0.0014

CV, % =5.8

Kergoat et al., 2008

In our study Maize: LUE ≈ **2.25** gC MJ^{-1} STE = 0.22 gC MJ^{-1}, CV = 10%
Soybean: LUE ≈ **1.46** gC MJ^{-1} STE = 0.18 gC MJ^{-1}, CV = 11%.

Gitelson et al., 2015

Conclusions

- ✓ About 90% of GPP variation in crops is explained by total canopy/stand chlorophyll content
- ✓ Magnitude and composition of incident radiation affect the magnitude of the day-to-day *facultative* LUE behavior. Increase in incident PAR caused decrease of LUE
- ✓ Seasonal *constitutional* LUE change remained remarkably invariant (CV = 10-11%) over a wide range of water supply in rainfed and irrigated maize and soybean, crops with different photosynthetic pathways, leaf structures and canopy architectures
- ✓ Conservative LUE behavior *may be* a result of an *optimization of limited resource allocation*, which causes a maximization of carbon gains and a convergence on a narrow range of LUE (Field, 1991; Goetz and Prince, 1999)
- ✓ To make conclusion about facultative and constitutional LUE changes and to get to the bottom of this, *it is necessarily to assess LUE using identical consistent procedures*. With no that, goals of FLEX mission could not be accomplished
- ✓ The use of models based on the canopy/stand chlorophyll content may facilitate assessments of *potential primary production* and plant optimization patterns at multiple scales, from leaves to canopies and entire regions

Thanks

Questions/concerns?

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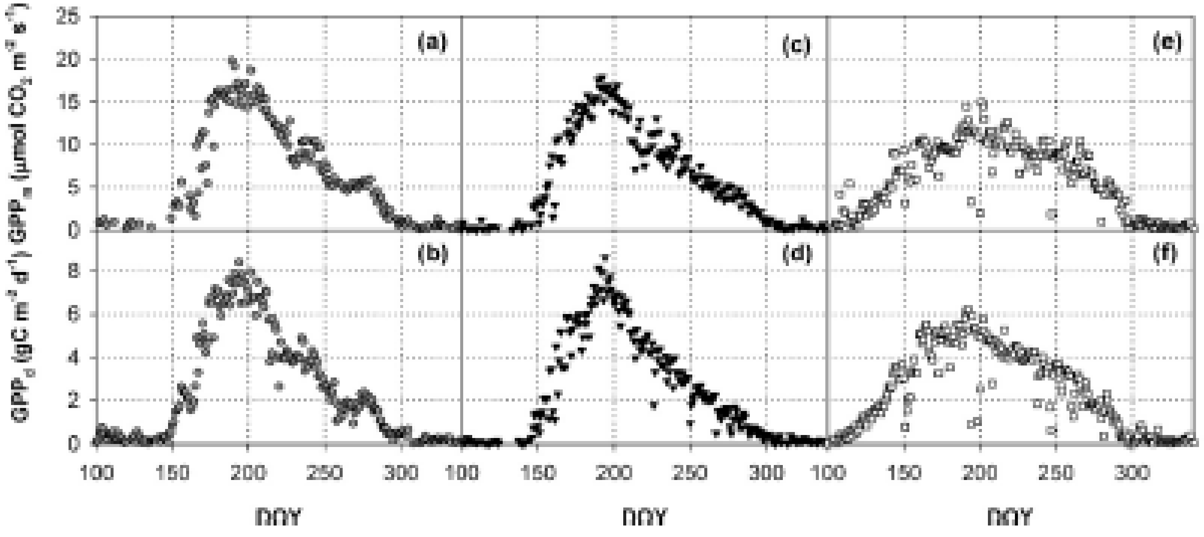
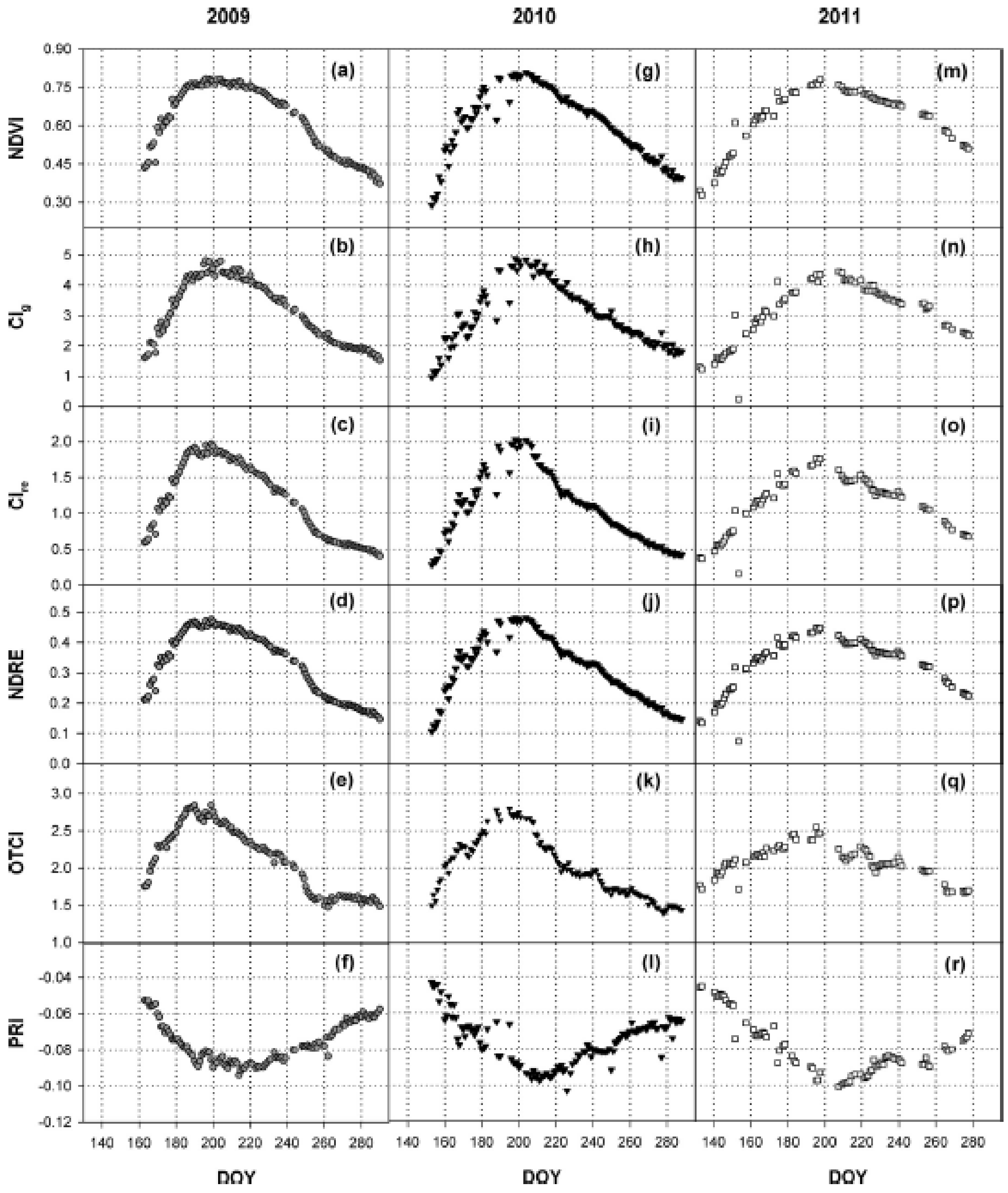
GPP and vegetation indices

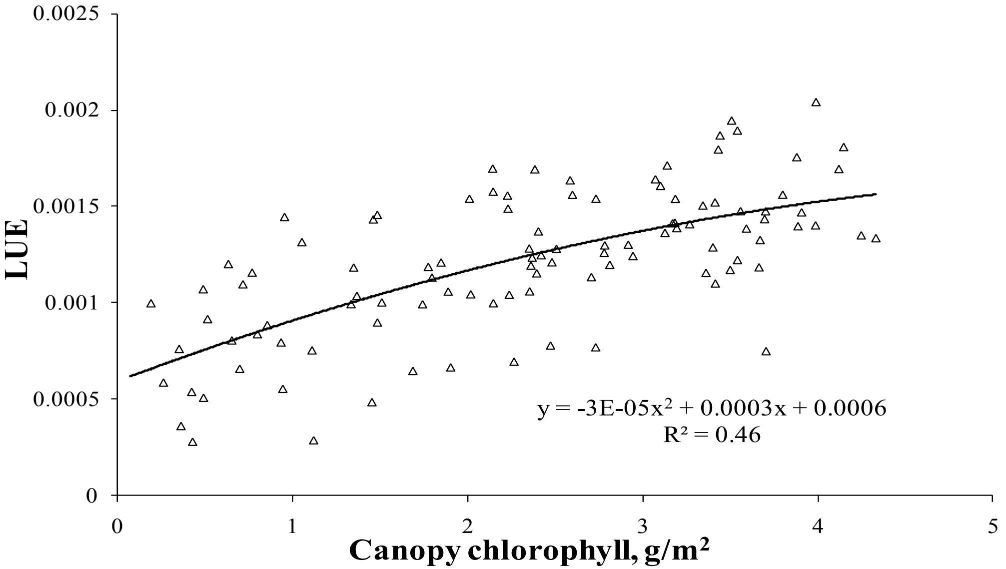


Rossini et al., 2014



VIs, <u>when used with PAR alone</u>, account for both the seasonal change in Chl content and the modulation of GPP due to changes in radiation conditions

LUE vs. canopy Chl content



Peng et al., 2011