Ph.D. thesis:
Comparison of Parsimonious Dynamic Vegetation Modelling Approaches in Semiarid Climates

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Grupo de Investigación de Modelación Hidrológica y Ambiental

UNIVERSITAT POLITÈCNICA DE VALÈNCIA

Contents

Context

Arid and semi arid climate

tight interconnection between vegetation and hydrological processes

Context

COUPLED MODELLING
hydrology - vegetation

LOW availability of
FIELD DATA

focus on
PARSIMONIOUS
MODELS

use REMOTE
SENSING data

not direct observations of
vegetation characteristics

need for INTERPRETATION

Leaf Area Index

VEGETATION MODELLING

SATELLITE INFORMATION

Leaf Area Index (LAI)

leaf area / ground area

- very important vegetation variable
- field measurements are complex

Research questions

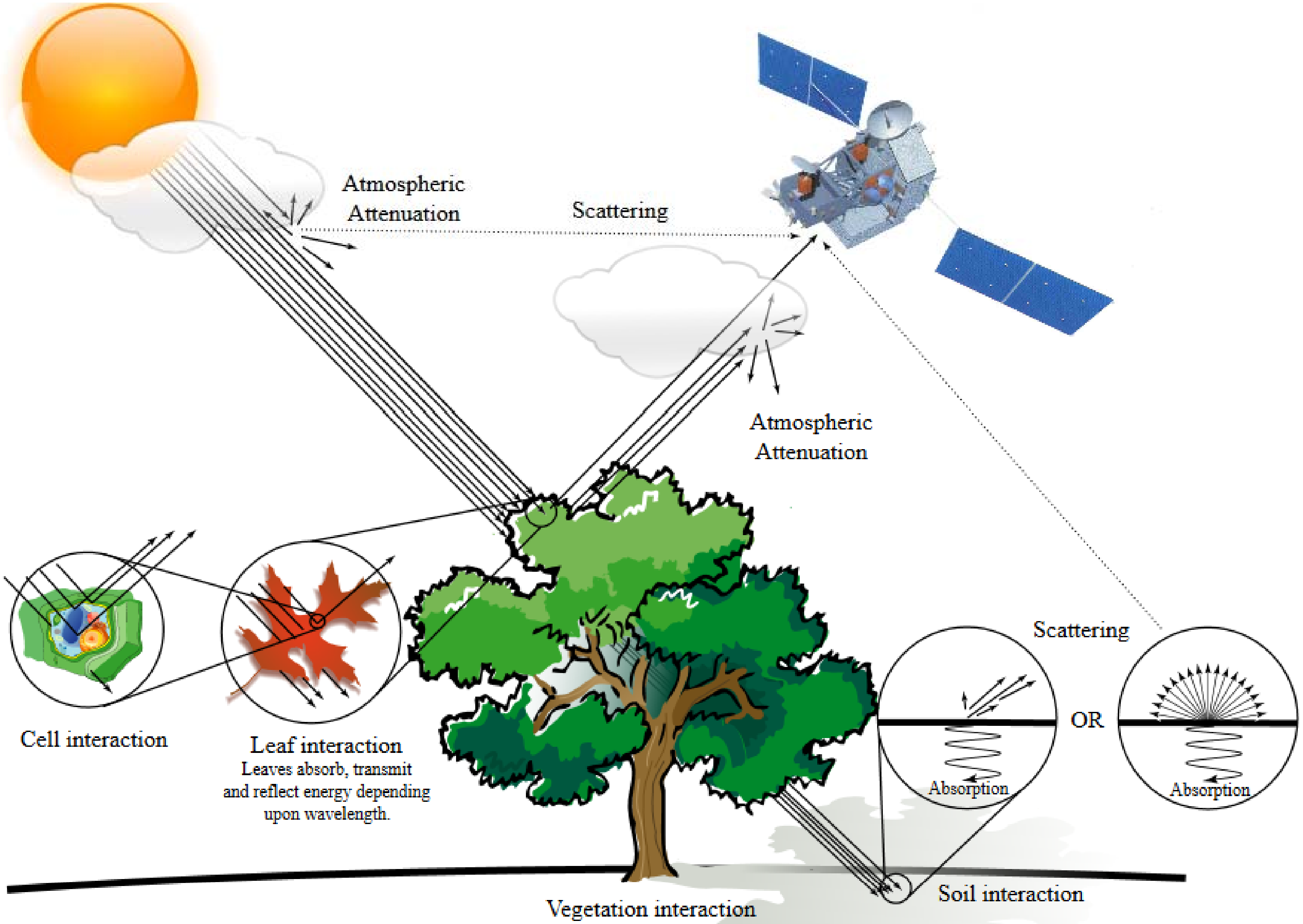
- which parsimonious vegetation model is most suitable to reproduce vegetation dynamics in semi arid environments?
  (need for reliable models!)

- which remote sensing vegetation indices provide information suitable to assess models' performance?
  (indirect observations)

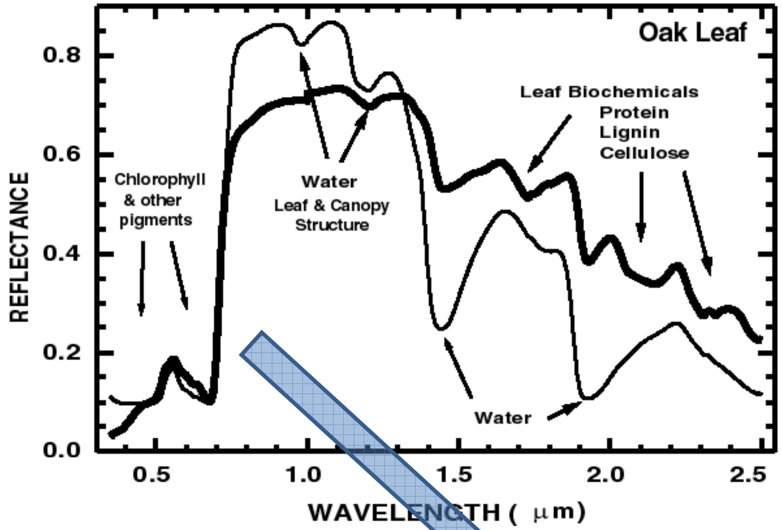
Methodology

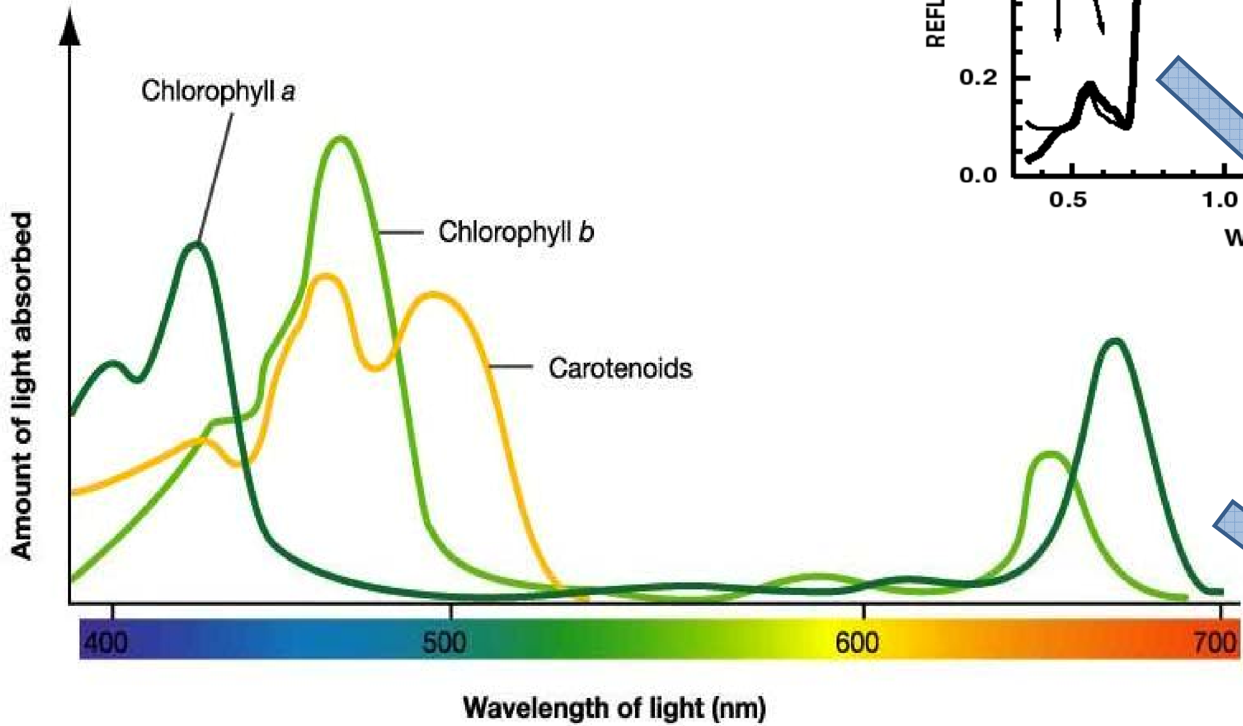
- identification of a study area: Aleppo pine forest in Valdeinfierno catchment (SE Spain)
- identification of suitable parsimonious vegetation models (for semi arid environments)
- analysis of vegetation-related satellite data
- modelling of vegetation dynamics
- analysis of results and conclusions

Remote sensing of vegetation



Remote sensing of vegetation





Reflection in the near infra-red

Absorption in the red

Vegetation Indices

NDWI

GNDVI

GARI

MSAVI

SAVI

SR

NDVI

PVI

EVI

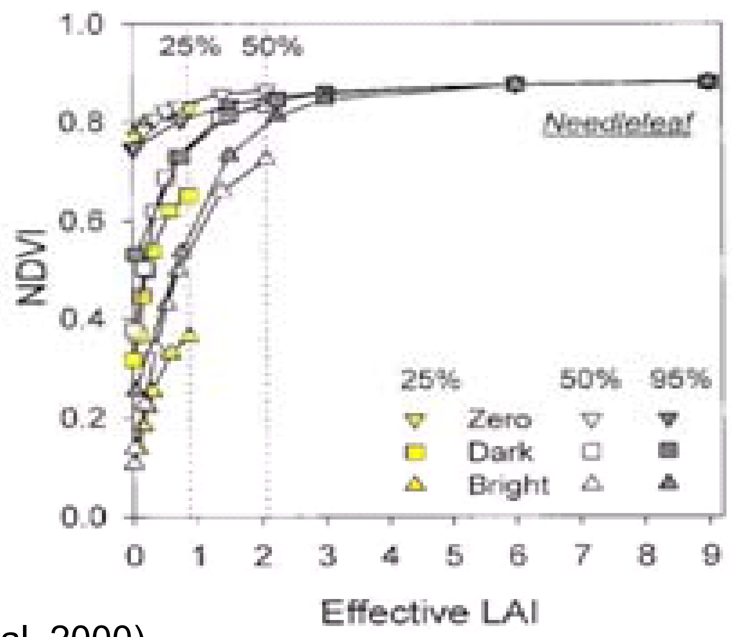
GVMI

TSAVI

NDVI

$$NDVI = \frac{NIR - red}{NIR + red}$$

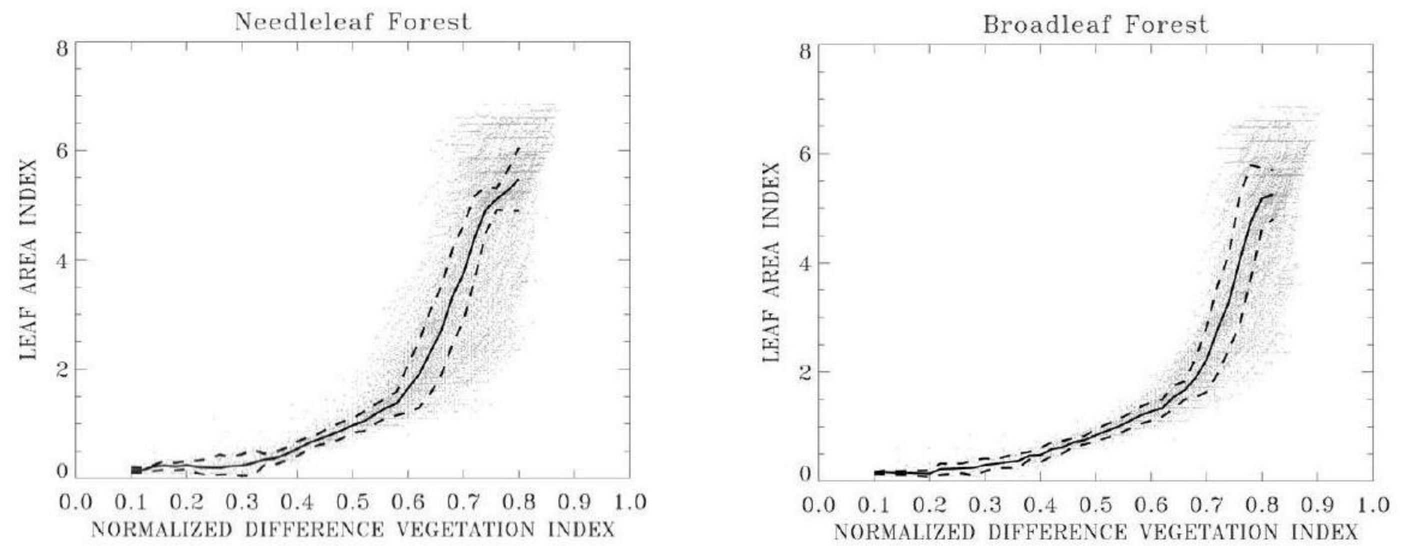
(Rouse et al, 1973)



(Gao et al, 2000)

- Sensitive to green biomass
- Useful to monitor photosynthetically active biomass
- Influenced by background brightness
- NDVI vs. LAI: non-linear and saturation for dense canopies

NDVI vs. LAI



(Buermann et al, 2002)

$$LAI_{NDVI} = -\frac{1}{k}\ln\frac{NDVI_{can} - NDVI}{NDVI_{can} - NDVI_{back}}$$

(Gigante et al, 2009)

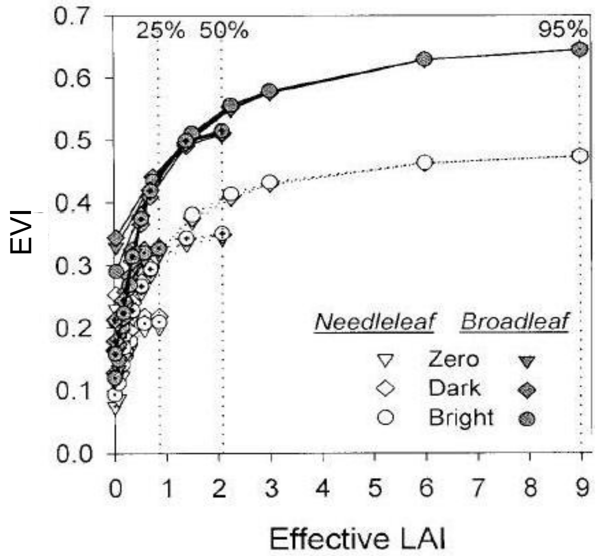
$NDVI_{can}$: value to which NDVI tends at high vegetation density
$NDVI_{back}$: NDVI value corresponding to very low vegetated soil
k: extinction coefficient

EVI

$$EVI = G \cdot \frac{(NIR - red)}{(NIR + C1 \cdot red - C2 \cdot blue + L)}$$

(Huete et al, 2002)

- Enhancement of vegetation signal:
  - correction for soil background
  - reduction in atmospheric influence
- Highly responsive to LAI



(Gao et al, 2000)

MODERATE-RESOLUTION IMAGING SPECTRORADIOMETER

- onboard Terra and Aqua satellites
- data every 1 - 2 days
- 36 spectral bands
- spectral range 0.4 - 14.4 µm
- spatial resolution depending on the bands (250, 500, 1000 m)

Good resolution in time and space for this research objectives.

Other MODIS products

LEAF AREA INDEX
(Myneni et al, 2003)

Algorithm needing:

- spectral information
- land cover classification

Observed vs. modelled BRDFs for different canopy structures and soil patterns.

If modelled and observed BRDFs ≈, correspondent LAI is accepted.

ACTUAL EVAPOTRANSPIRATION
(Mu et al, 2011)

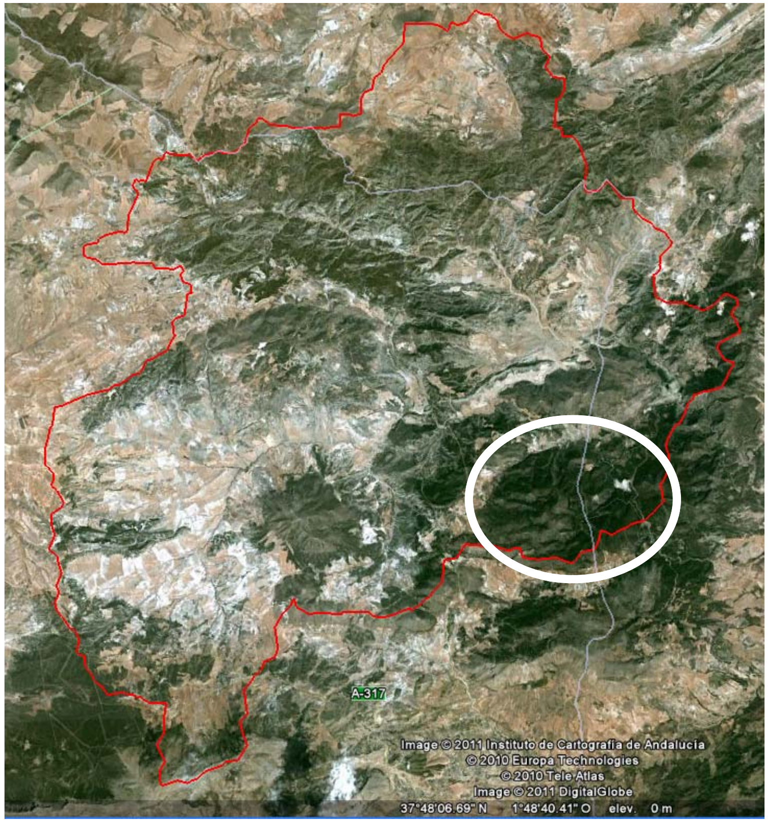
Algorithm needing:

- remote sensing inputs
  (land cover, LAI, albedo, FPAR)
- meteorological inputs
  (air pressure, air temperature, humidity, radiation)

BRDFs: Bidirectional Reflectance Distribution Functions

Study site - characteristics

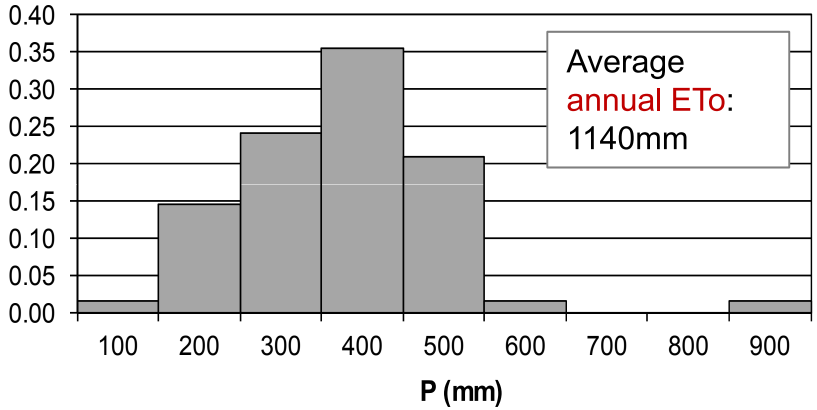
SE of Spain – Province of Almeria



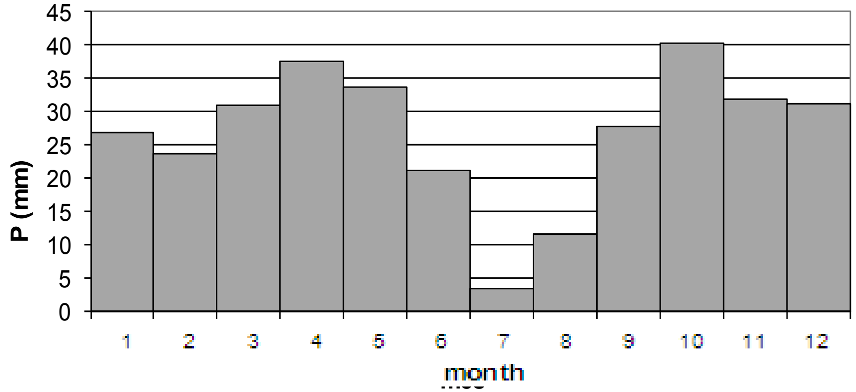
20 km^2 Aleppo pine forest

Study site – climate

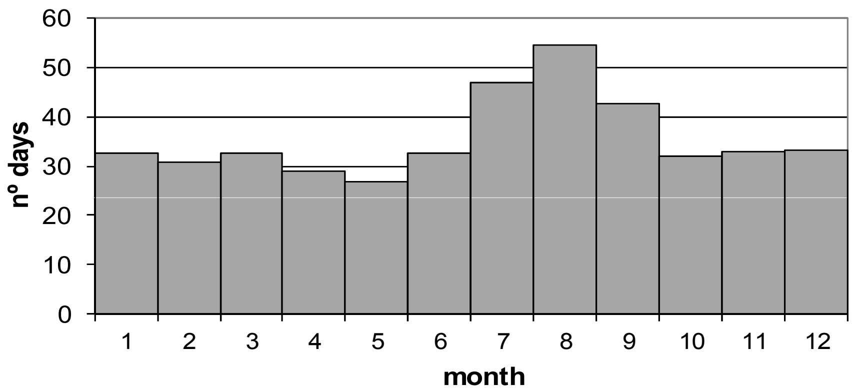
Relative frequency of annual precipitation. Average: 327 mm



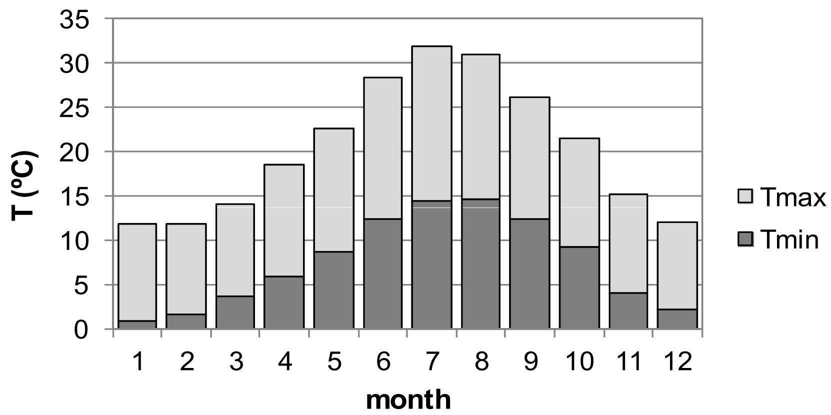
Mean monthly precipitation



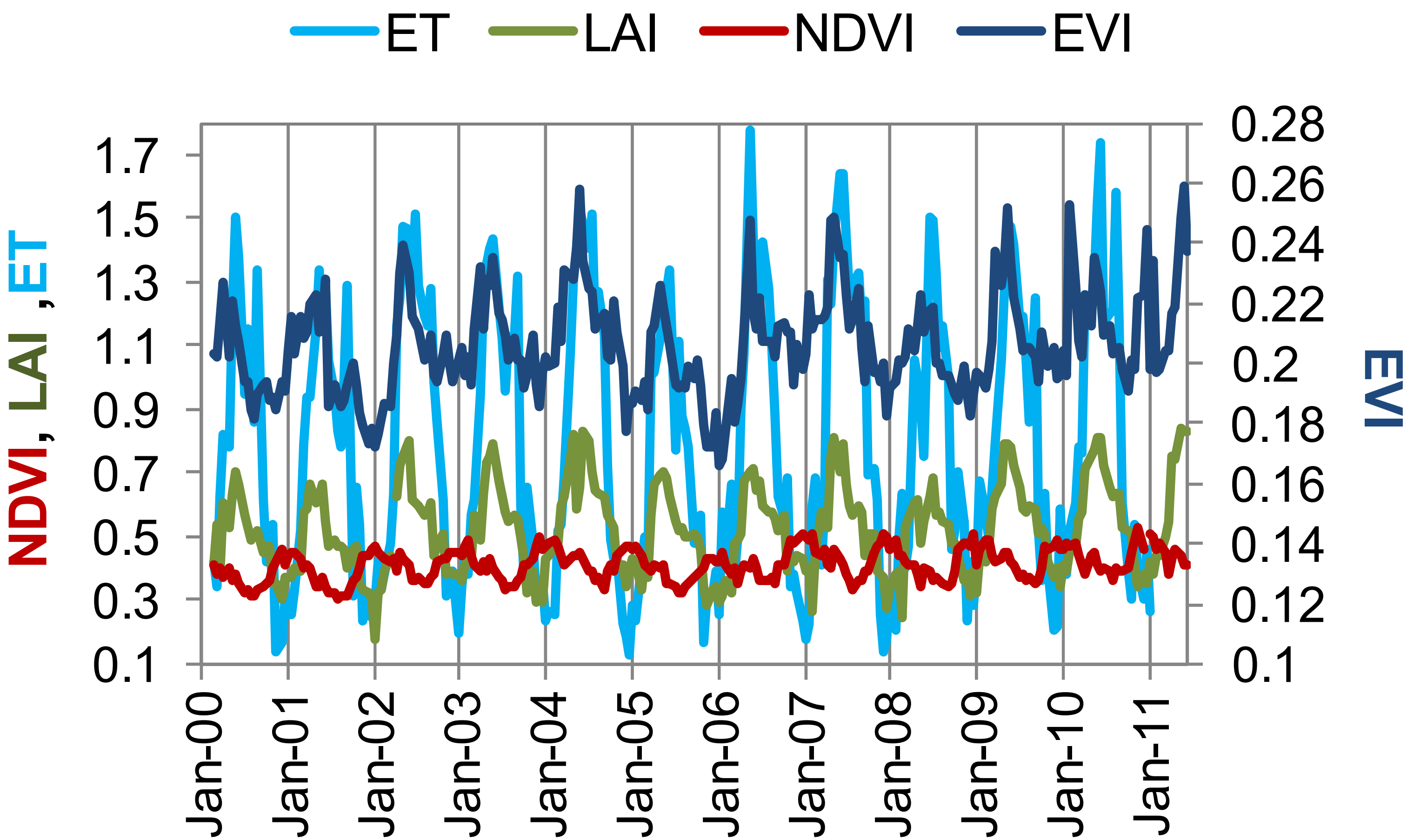
Average nº of consecutive dry days



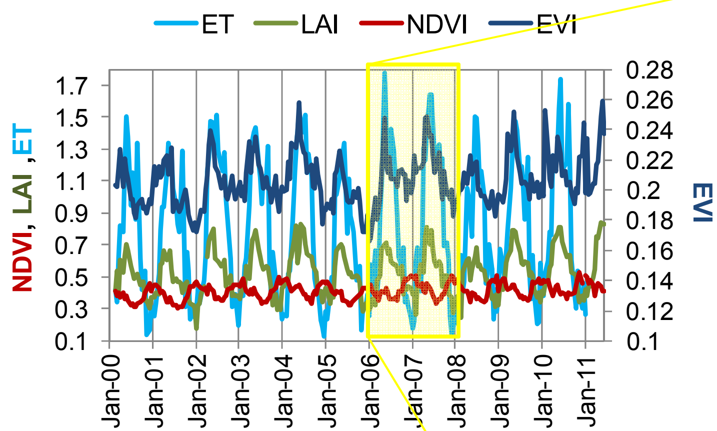
Max and min temperatures

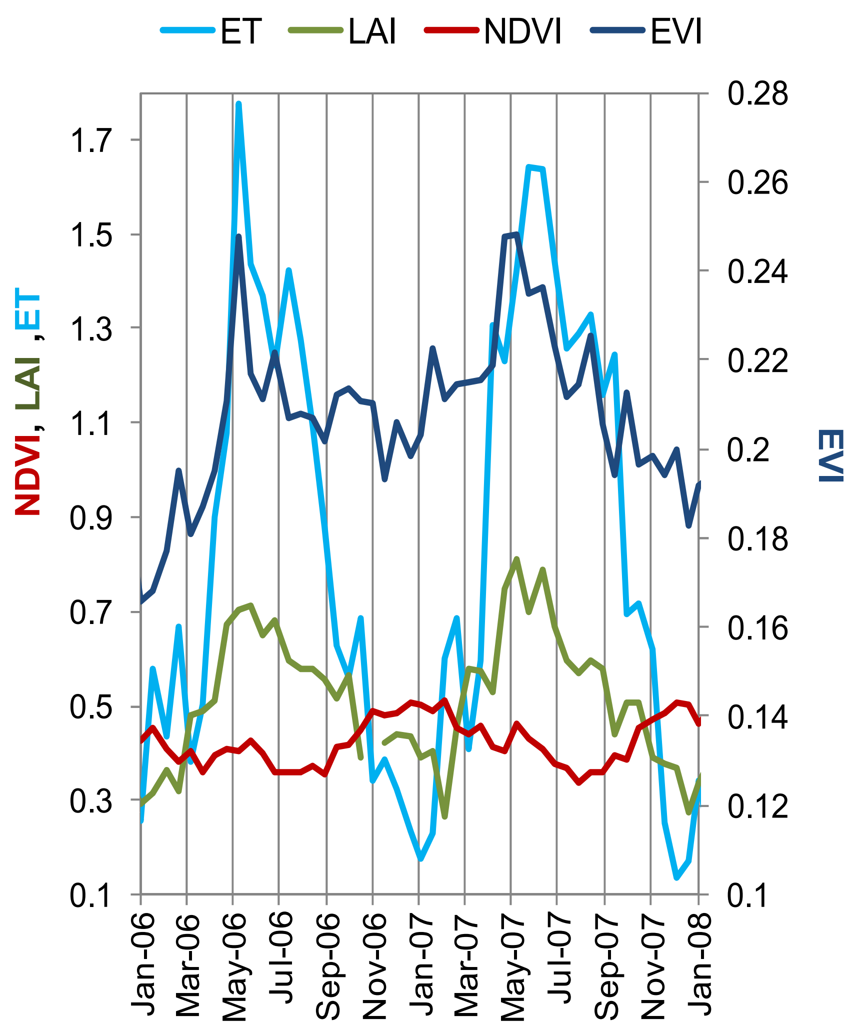


Satellite data

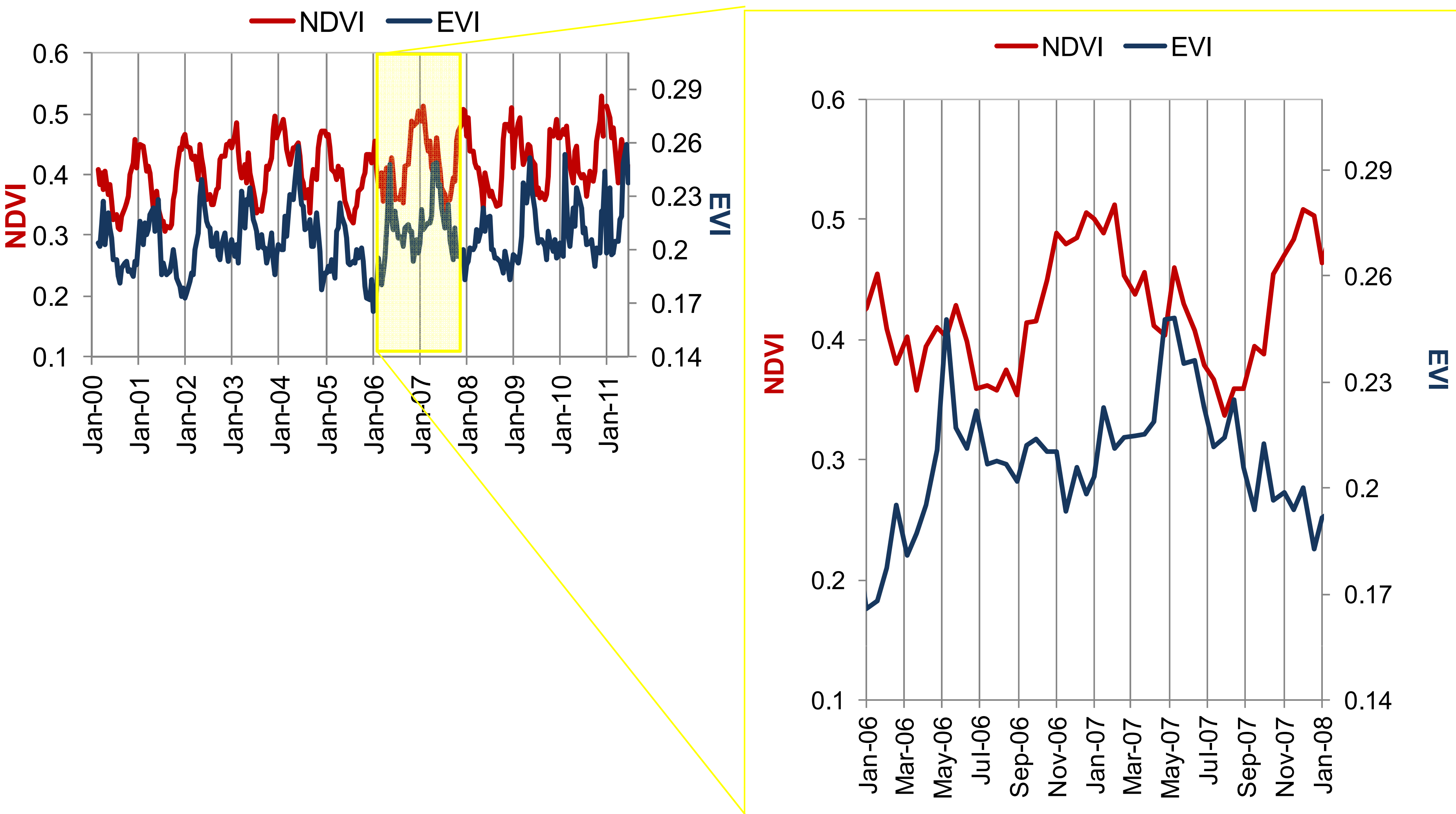


Satellite data





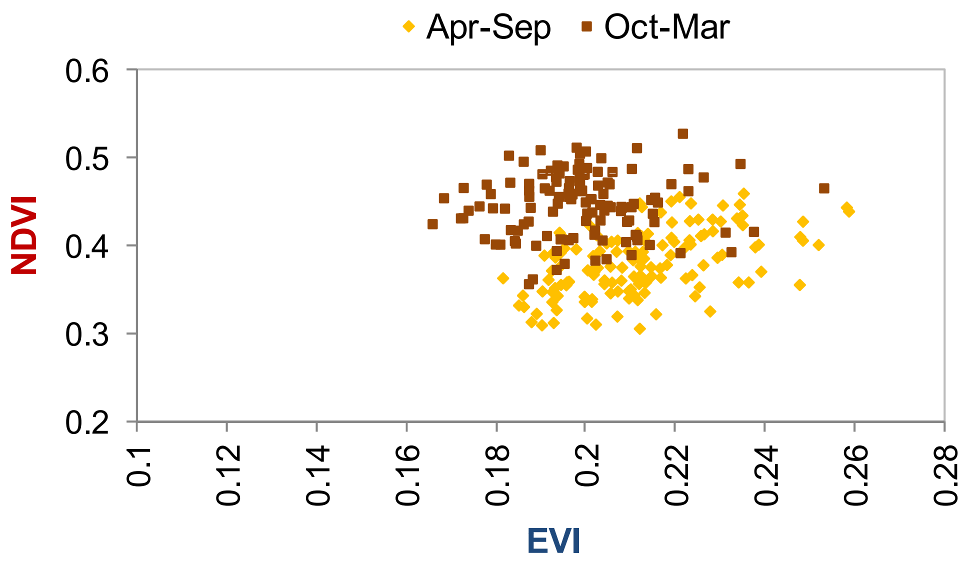
NDVI vs. EVI


NDVI
EVI
0.6
0.5
0.4
0.3
0.2
0.1
0.29
0.26
0.23
0.2
0.17
0.14
Jan-00
Jan-01
Jan-02
Jan-03
Jan-04
Jan-05
Jan-06
Jan-07
Jan-08
Jan-09
Jan-10
Jan-11
NDVI
EVI
0.6
0.5
0.4
0.3
0.2
0.1
0.29
0.26
0.23
0.2
0.17
0.14
Jan-06
Mar-06
May-06
Jul-06
Sep-06
Nov-06
Jan-07
Mar-07
May-07
Jul-07
Sep-07
Nov-07
Jan-08

NDVI vs. EVI

t-distribution test (95% confidence level)

NO correlation
but
data April – September: r = 0.66



EVI

⇕

Aleppo p. phenology

(Calatayud et al, 2000; Pardos et al, 2003)

NDVI

⇕

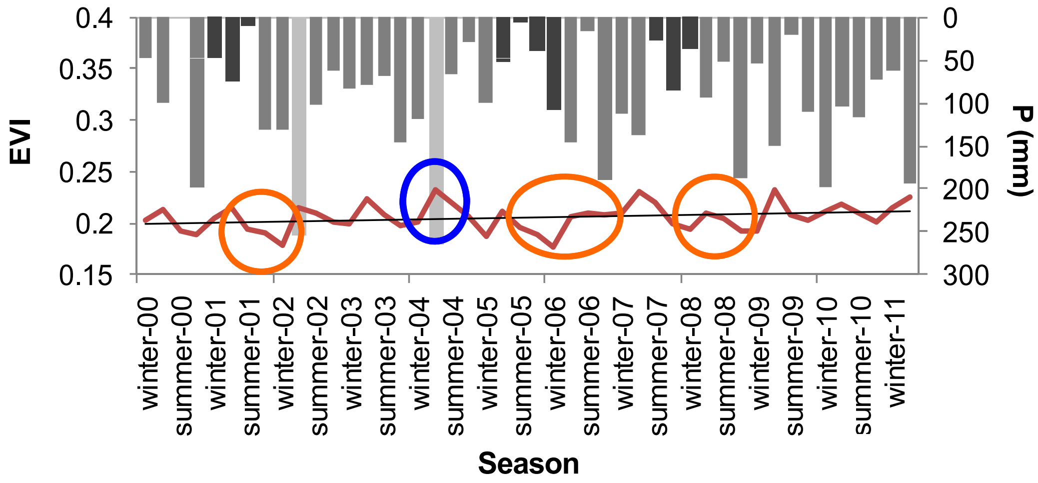
water stress

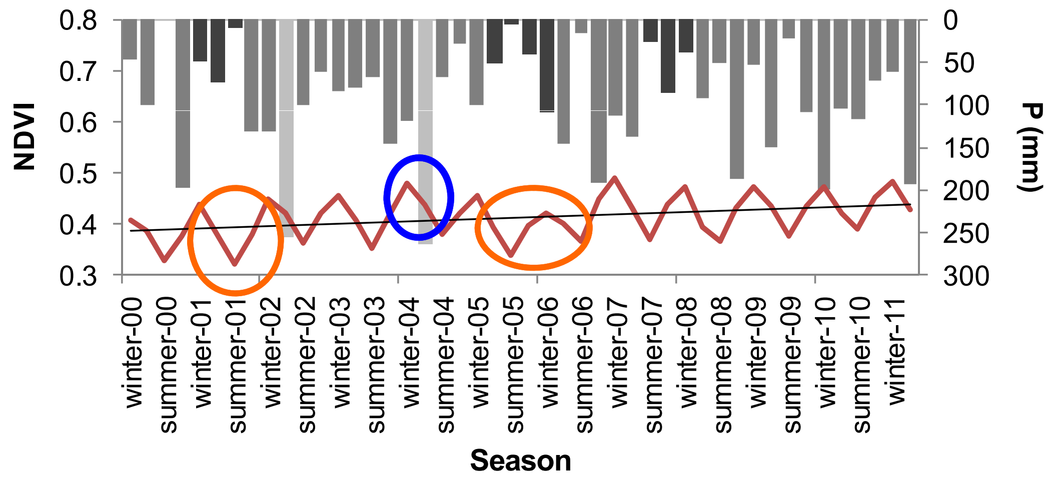
changes in chlorophyll content

(Baquedano, 2006)

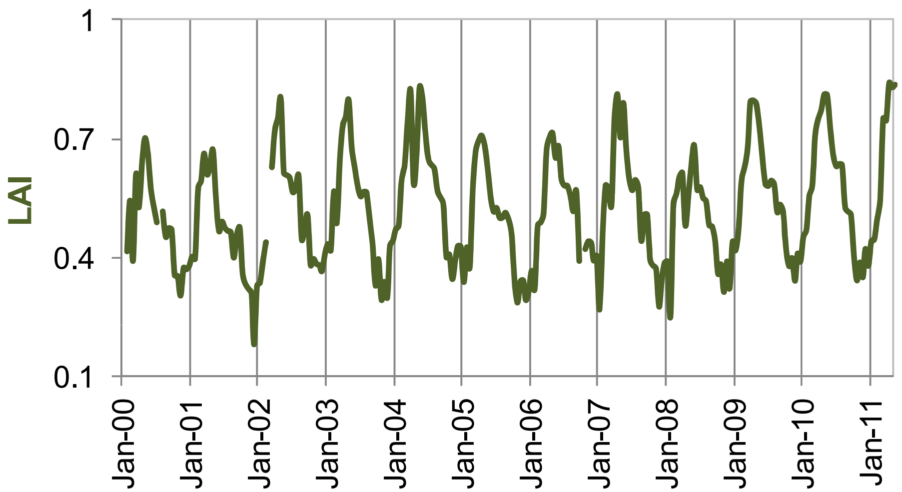
BREAKTROUGH

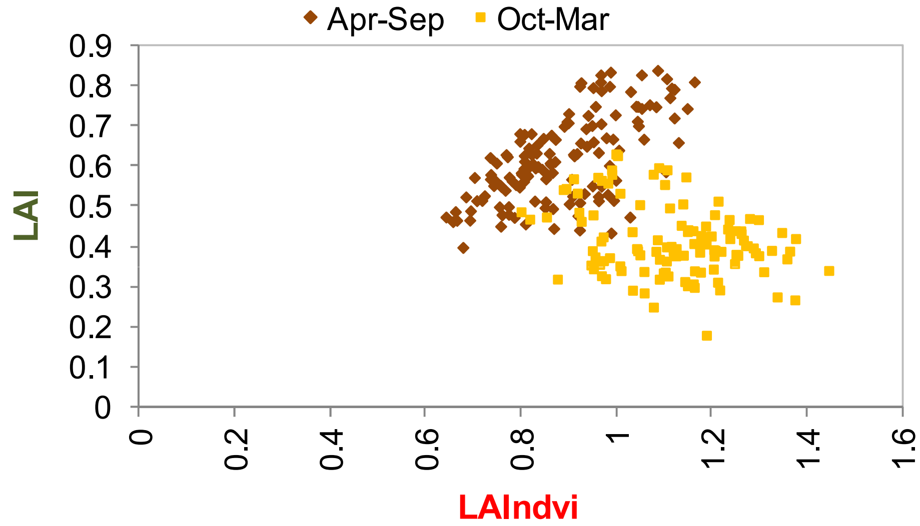
NDVI, EVI vs. P


EVI
0.4
0.35
0.3
0.25
0.2
0.15
P (mm)
0
50
100
150
200
250
300
winter-00
summer-00
winter-01
summer-01
winter-02
summer-02
winter-03
summer-03
winter-04
summer-04
winter-05
summer-05
winter-06
summer-06
winter-07
summer-07
winter-08
summer-08
winter-09
summer-09
winter-10
summer-10
winter-11
Season


NDVI
0.8
0.7
0.6
0.5
0.4
0.3
P (mm)
0
50
100
150
200
250
300
winter-00
summer-00
winter-01
summer-01
winter-02
summer-02
winter-03
summer-03
winter-04
summer-04
winter-05
summer-05
winter-06
summer-06
winter-07
summer-07
winter-08
summer-08
winter-09
summer-09
winter-10
summer-10
winter-11
Season

LAI vs. LAI_{NDVI}





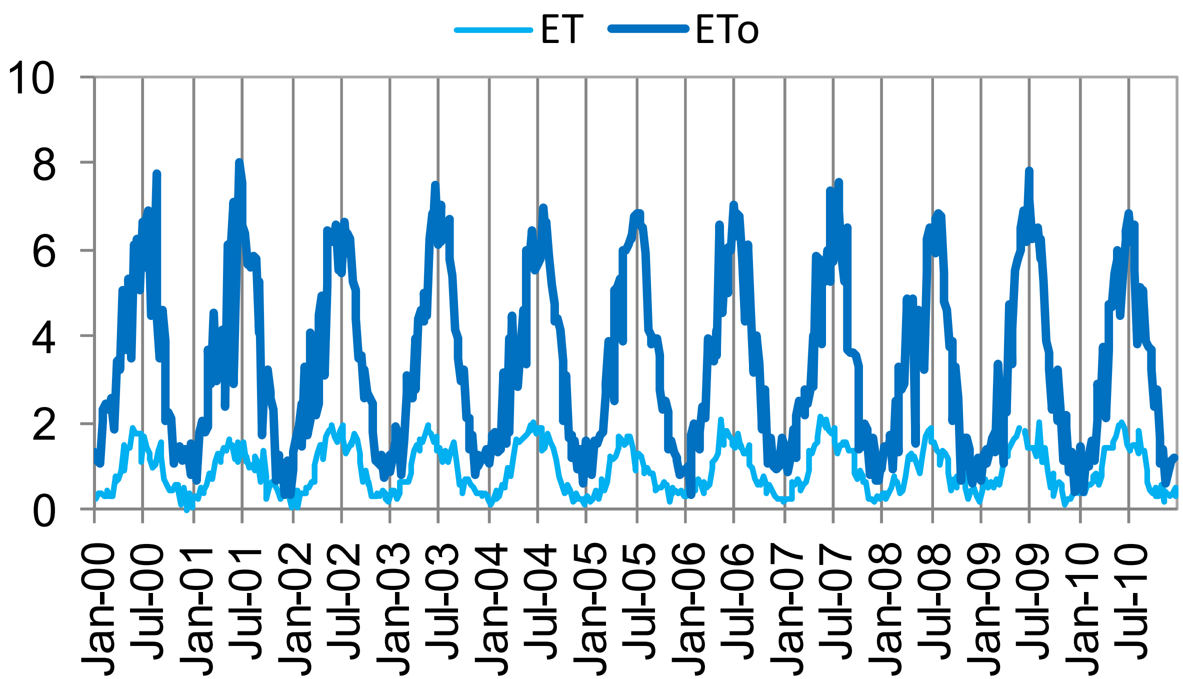
WRONG land cover classification

LAI values: 0.2 – 0.8

…DOUBTS…field campaign (August '12) ➡ values 1 - 2

0.5 corresponds to just 16% forest cover (Molina & Del Campo, 2012)

ET vs. ET$_o$



HIGH CORRELATION (r = 0.79)

Obtained from satellite LAI

Vegetation models

Which characteristics do we seek?

- focused on semiarid environments
- requiring information commonly available
- simple models

Simple vs. complex models

COMPLEX MODELS:

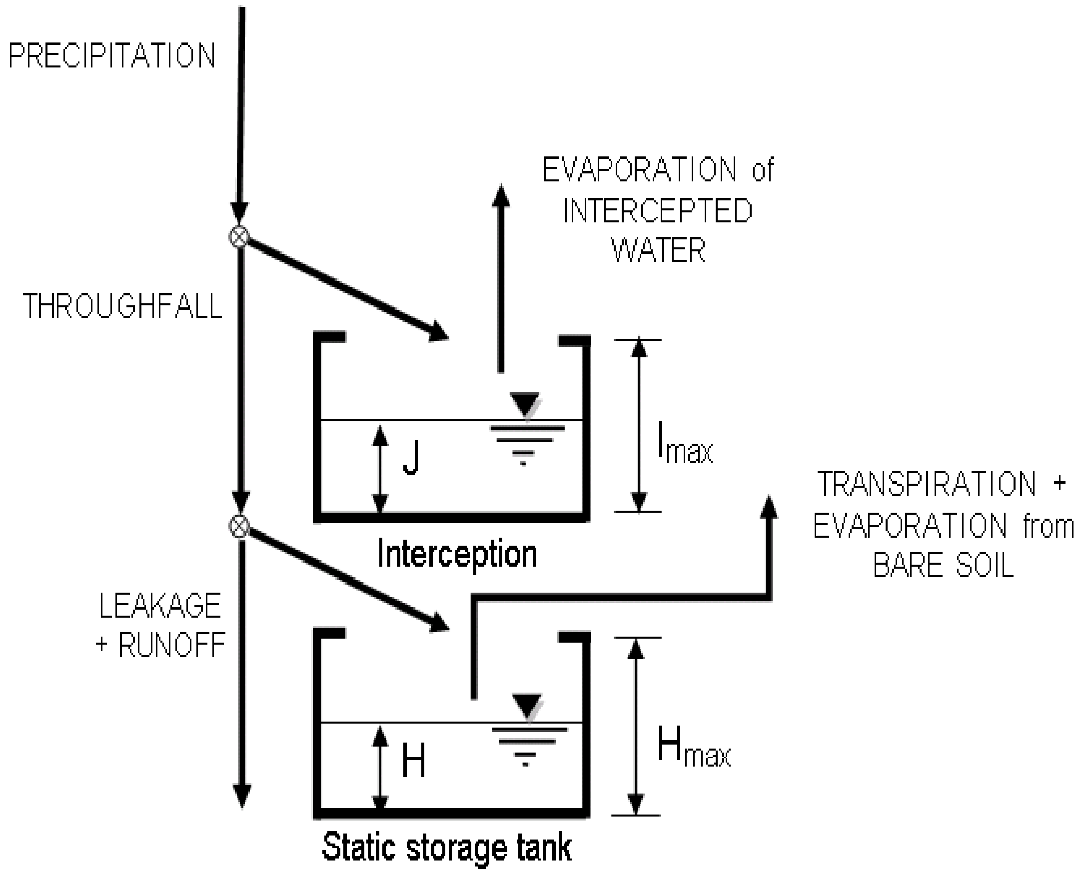
- accurate description of the processes
- high n° of parameters (and data required)
- computational burden
- sensation of total reliability

SIMPLE MODELS:

- processes are schematised
- low n° of parameters
- the most important processes need to be correctly reproduced

It depends on the OBJECTIVES of the research

HORAS model



WATER BALANCE EQ.

$$\frac{dH}{dt} = (P - I) - L - E - T$$

INTERCEPTION

$$I = P \cdot R$$

INTERCEPTION STORAGE

$$\frac{dJ}{dt} = I - \min\left(ET_o \cdot R, J\right)$$

HORAS model

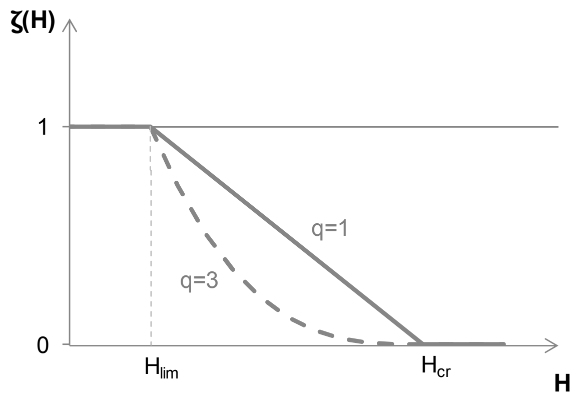
$$\frac{dR}{dt} = \frac{A_{n,mx}}{B_{pot}} \left(\frac{T}{T_{mx}} \right)^c - k_{ws} \cdot R \cdot \zeta$$

(Quevedo and Francés, 2008)

$$\zeta(H) = \begin{cases} 0 & \text{for } H \geq H_{cr} \\ \left(\frac{H_{cr} - H}{H_{cr} - H_{\lim}} \right)^q & \text{for } H_{\lim} < H < H_{cr} \\ 1 & \text{for } H \leq H_{\lim} \end{cases}$$

State variable: **R (relative leaf biomass)**

5 parameters:
- **$A_{n,mx}$ (maximum net carbon assimilation)**
- **B_{pot} (potential foliar biomass)**
- **T_{mx} (maximum transpiration)**
- **c (shape exponent)**
- **k_{ws} (water stress leaf shedding coefficient)**



HORAS model

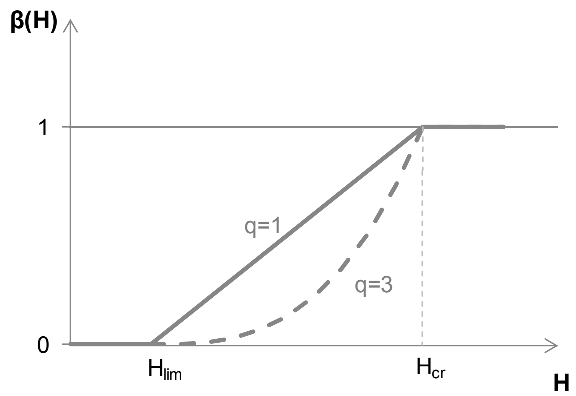
$$T = ET_o \cdot R \cdot \beta_t$$

$$T = ET_o \cdot \lambda_v \cdot \lambda_s$$

TRANSPIRATION

FAO EQUATION
(Allen et al, 1998)

$$\beta(H) = \begin{cases} 1 & \text{for } H \geq H_{cr} \\ \left(\dfrac{H - H_{\lim}}{H_{cr} - H_{\lim}} \right)^q & \text{for } H_{\lim} < H < H_{cr} \\ 0 & \text{for } H \leq H_{\lim} \end{cases}$$



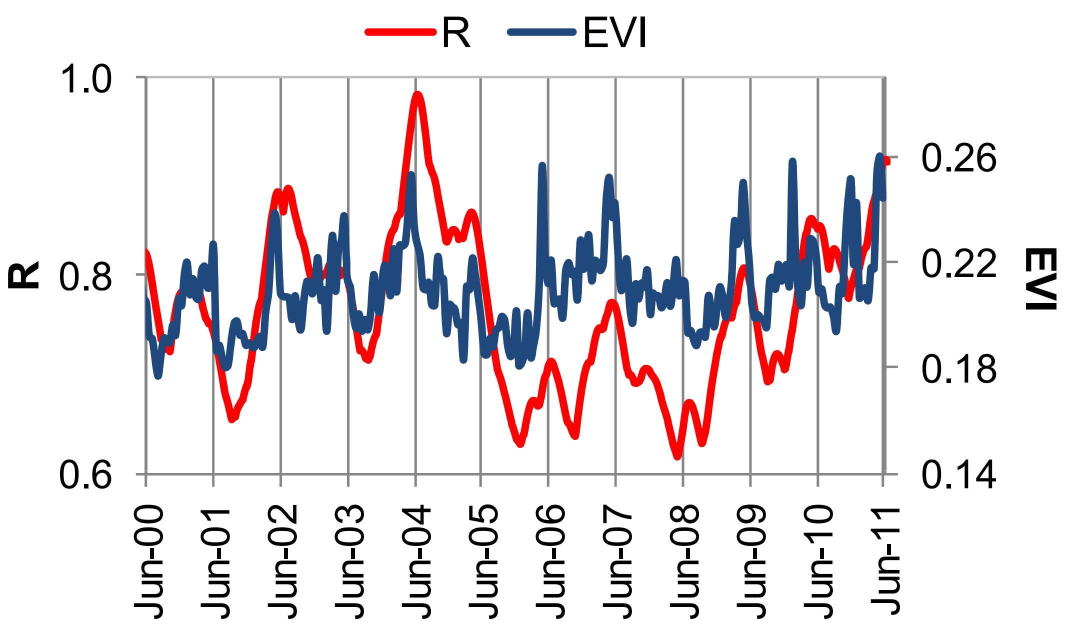
$$E = H \cdot \left(\frac{Z_{SS}}{Z_e} \right) \cdot (1 - R)$$

BARE SOIL
EVAPORATION

Modelling - HORAS

CALIBRATION
max Pearson correlation coefficient (r) between R and EVI

Parameters	Description	Calibrated value
α	Ratio between maximum net carbon assimilation and potential foliar biomass [d^{-1}]]	0.0018
T_{mx}	Maximum transpiration ratio [mm d^{-1}]	5.5
c	Shape exponent	0.054
k_{ws}	Water stress-dependent leaf shedding coefficient	0.0035



FINAL RESULT
r = 0.39

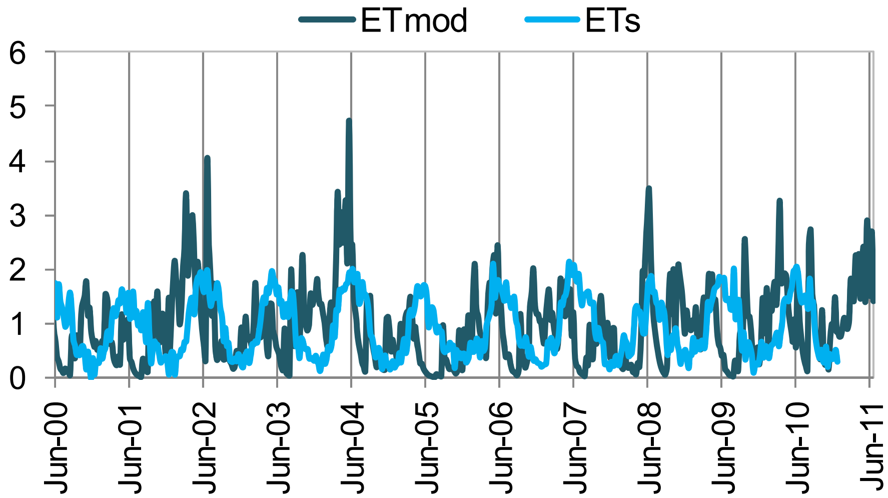
PROBLEMS
Annual cycle not clear (2002-2003; 2004-2005)

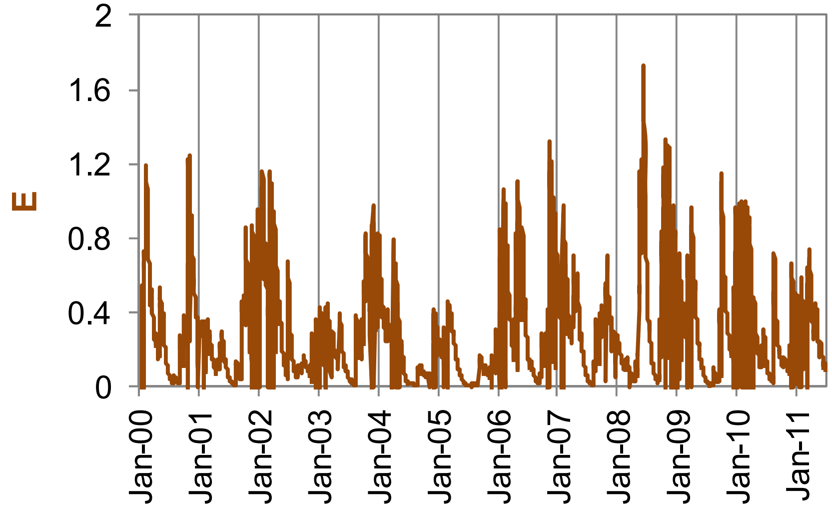
Marked drop (2005)

→ WUE-model
LUE-model

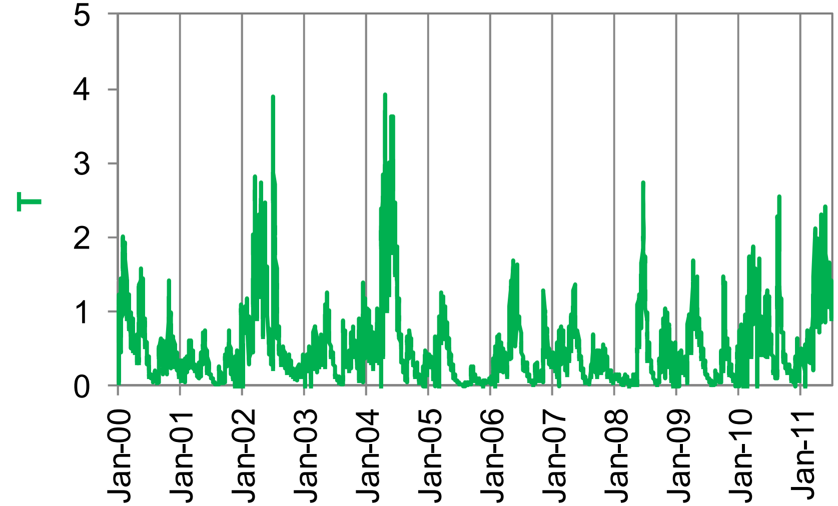
Modelling - HORAS

ET_{mod} → prolonged periods value ≈ 0





E → average: 0.3 mm d^{-1}
max: 1.7 mm d^{-1}



T → average 0.5 mm d^{-1}
max: 3.9 mm d^{-1}

Modelling - HORAS

E → 31% of ET vs. 23% simulated bare soil

T → 56% of ET vs. 77% simulated veg. cover

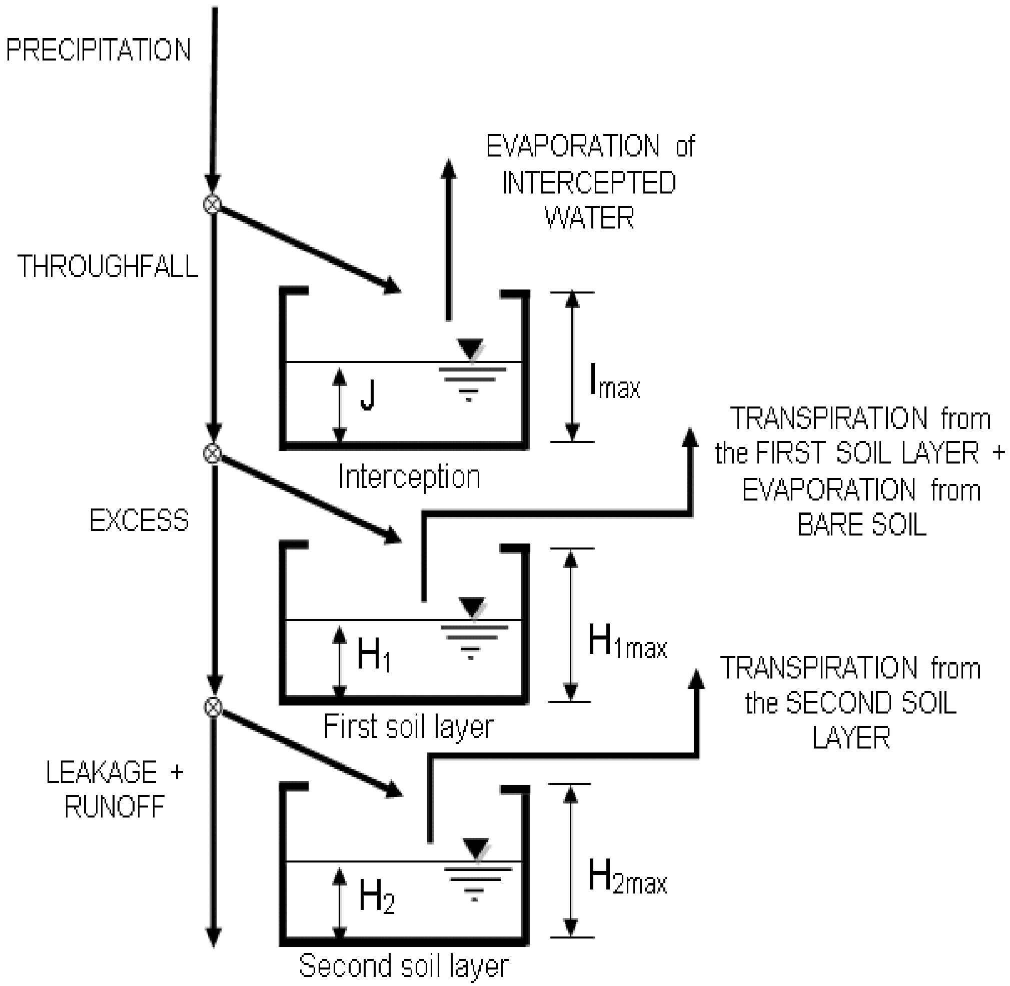
WHY?

Not correct to assume superficial soil layer (→ E) with same moisture content of the entire root soil depth

→

For WUE- and LUE-models: 2 soil layers (1° → E+T; 2° → T)

WUE and LUE models



WATER BALANCE EQ.

$$\frac{dH_1}{dt} = (P - I) - D - E - T_1$$

$$\frac{dH_2}{dt} = D - L - T_2$$

INTERCEPTION

$$I = P \cdot f_t$$

INTERCEPTION STORAGE

$$\frac{dJ}{dt} = I - \min\left(ET_o \cdot f_t, J\right)$$

WUE and LUE models

$$\frac{dB_l}{dt} = \left(T \cdot WUE \cdot \rho_v \cdot \omega - \mathrm{Re}\right) \cdot \varphi_l - k_l \cdot B_l$$

WATER USE EFFICIENCY

WUE ➡ [kg DM kg^{-1} H_2O]

(Williams and Albertson, 2005)

$$\frac{dB_l}{dt} = \left(APAR \cdot LUE \cdot \varepsilon - \mathrm{Re}\right) \cdot \varphi_l - k_l \cdot B_l$$

LIGHT USE EFFICIENCY

LUE ➡ [kg DM m^{-2} MJ^{-1}]

(Monteith, 1972)

State variable: **B_l** - leaf biomass [kg DM m^{-2} veg cover]

4 parameters:

WUE – water use efficiency
ω – conversion CO_2→DM
φ_l – allocation term
k_l – turnover coefficient

LUE – light use efficiency
ε – stress coefficient
φ_l – allocation term
k_l – turnover coefficient

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WUE and LUE models

$$T_1 = ET_o \cdot f_t \cdot \min\left(LAI_{mod}, 1\right) \cdot \beta_t\left(H_1\right) \cdot r_1$$

$$T_2 = ET_o \cdot f_t \cdot \min\left(LAI_{mod}, 1\right) \cdot \beta_t\left(H_2\right) \cdot \left(1 - r_1\right)$$

TRANSPIRATION
(Williams and Albertson, 2005)

$$T = ET_o \cdot \lambda_v \cdot \lambda_s$$

FAO EQUATION
(Allen et al, 1998)

$$E = ET_o \cdot f_b \cdot \beta_b\left(H_1\right)$$

BARE SOIL EVAPORATION

WUE and LUE models

$$\varphi = 1 - \frac{LAI}{LAI_{\max}}$$

ALLOCATION FACTOR
(Williams and Albertson, 2005)

$$LAI_{\text{mod}} = B_l \cdot SLA \cdot f_t$$

GROUND BASED LAI
(Williams and Albertson, 2005)

$$LAI^*_{\text{mod}} = LAI_{\text{mod}} \cdot \left(1 - \overline{\zeta}_{10}\right)$$

CORRECTED LAI
(Williams and Albertson, 2005)

$$\zeta(H) = \begin{cases} 0 & \text{for } H \geq H_{cr} \\ \left(\dfrac{H_{cr} - H}{H_{cr} - H_{\lim}}\right)^3 & \text{for } H_{\lim} < H < H_{cr} \\ 1 & \text{for } H \leq H_{\lim} \end{cases}$$

WATER STRESS
(Porporato et al, 2001)

$$\zeta_{tot} = \zeta(H_1) \cdot r_1 + \zeta(H_2) \cdot (1 - r_1)$$

TOTAL WATER STRESS
(Williams and Albertson, 2005)

Sensitivity analysis

Which parameters mostly affect models' performance?

WUE- model
LUE-model

GSA (general sensitivity analysis)
8 parameters
(Hornberger and Spear, 1980)

Montecarlo technique:

60,000 independent sets of parameters (random from uniform distributions)

Objective function: RMSE (LAI_{NDVI} vs. LAI*mod)

Threshold RMSE = 0.2

Sets of parameters divided into behavioural / non-behavioural ones

3958 behaviours and 56042 non-behaviours for the WUE-model

16893 behaviours and 43107 non-behaviours for the LUE-model.

Kolmogorov-Smirnov

Kolmogorov-Smirnov two-sample test

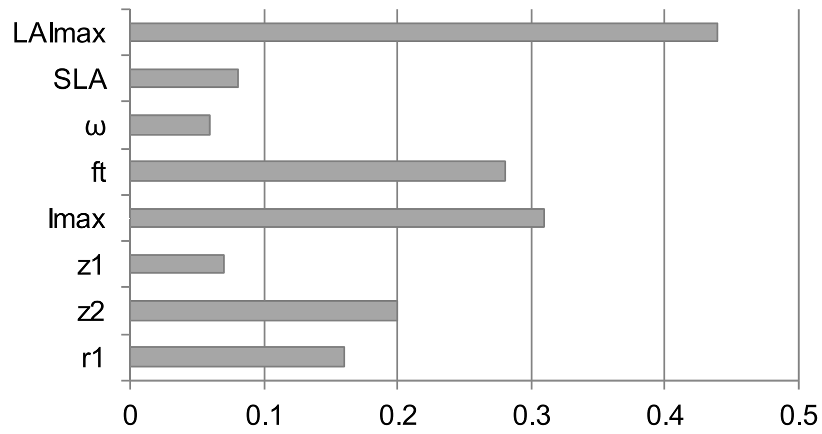
(Kolmogorov, 1933; Smirnov, 1948)

Cumulative probability distribution curves for the behaviours and non-behaviours

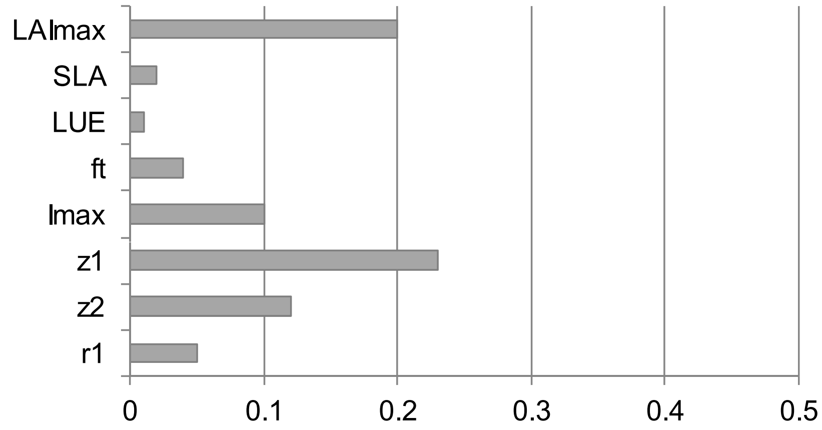
Measure of the maximum vertical distance between the curves (KS)

The larger the value of the KS index, the higher the importance of the considered parameter in determining the simulation result.

WUE-model



LUE-model



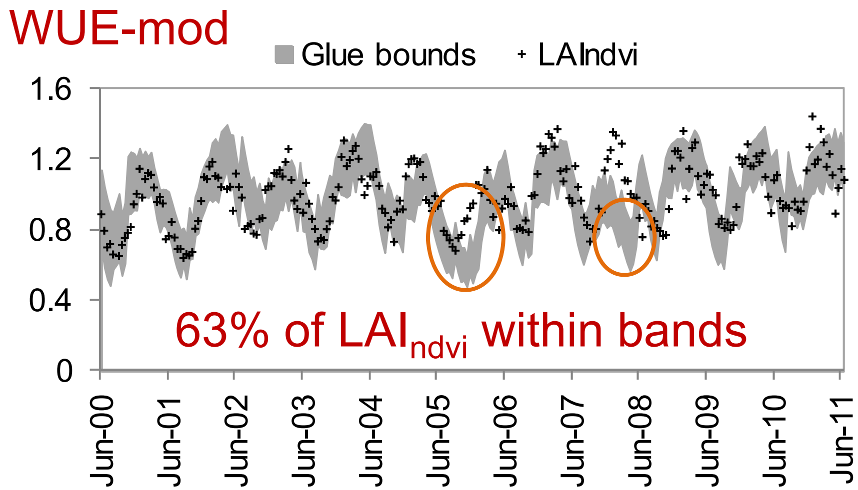
GLUE

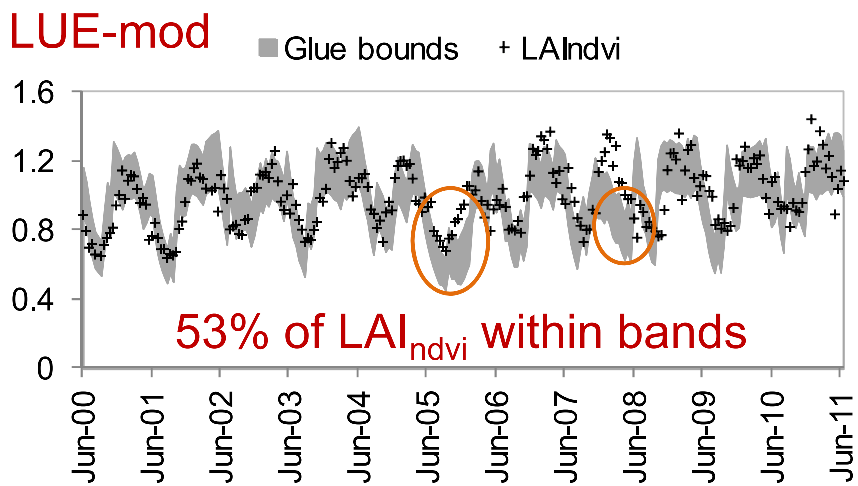
GLUE: General Likelihood Uncertainty Estimation
(Beven and Binley, 1992)

To test the models' capability in reproducing vegetation dynamics, and their robustness

Calculating the likelihood-weighted distribution of the outputs corresponding to the accepted sets of parameters

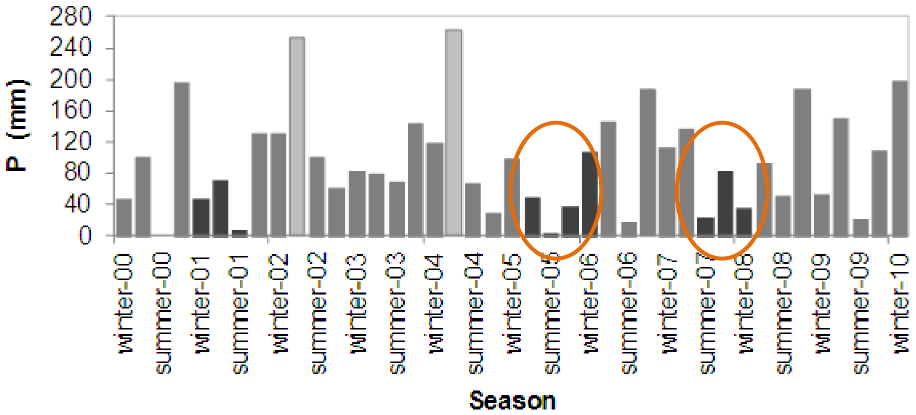
Computing the 90% GLUE band (5% and 95% percentiles as bounds)

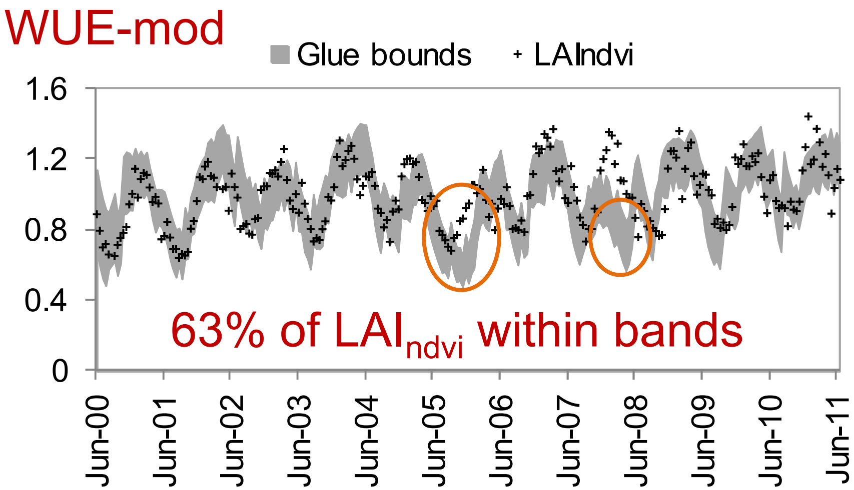


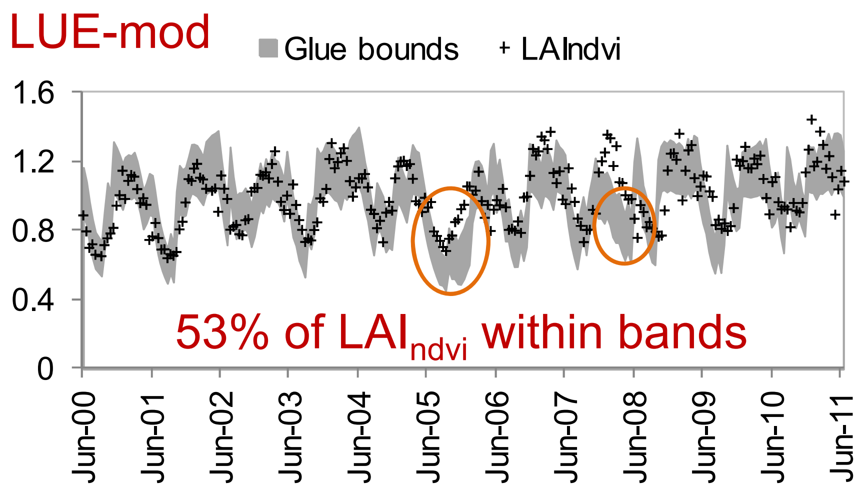


GLUE: General Likelihood Uncertainty Estimation

(Beven and Binley, 1992)







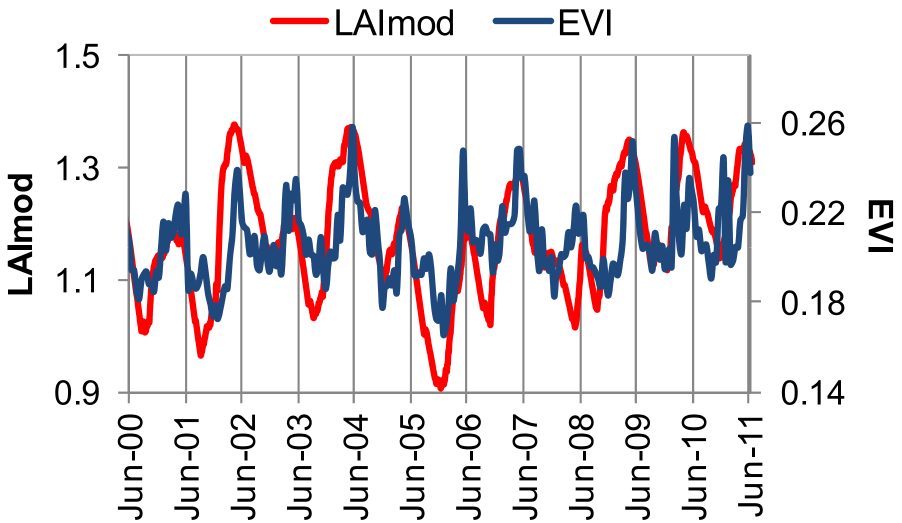
Calibration

Genetic algorithm → minimize RMSE (LAI^*_{mod} vs. LAI_{NDVI})

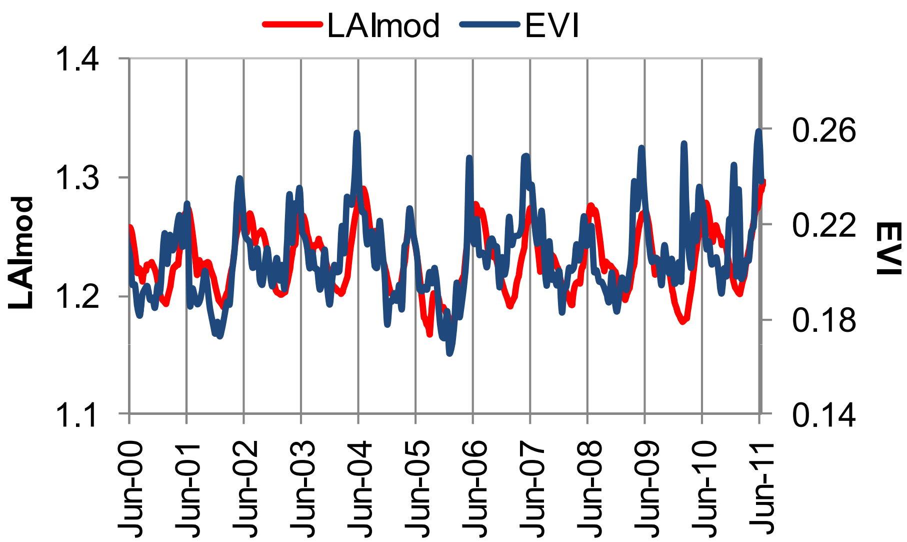
Parameter	Description	Value	Sources*
LAI_{max}	Maximum LAI [m^2 leaf m^{-2} vegetation]	1.4	calib.
k_l	Leaf natural decay factor [d^{-1}]	0.00137	1, 2
SLA	Specific leaf area [m^2 leaf kg^{-1} DM]	1.6	calib.
I_{max}	Maximum interception [mm d^{-1}]	1	calib.
θ_{lim},θ_{cr}	Limit (lim), critical (cr) soil moisture [m^3 H_2O m^{-3} soil]	0.109, 0.256	calc.(3)
r_1	Fraction of roots in upper soil layer [-]	0.1	calib.
d_1,d_2	Thickness of soil layers [mm]	50, 950	calib.
Ψ_{ae}	Air entry matric potential for loam [MPa]	1.43E-03	3
Ψ_{lim}, Ψ_{cr}	Matric potential at limit (lim), critical (cr) points [MPa]	3, 0.03	4
n	Porosity [m^3 void m^{-3} soil]	0.451	3
b	Soil parameter for loam [-]	5.39	3
ω	Conversion of CO_2 to DM [kg DM kg^{-1} CO_2]	0.54	calib.
LUE	Light use efficiency [kg C m^{-2} MJ^{-1}]	2.1	calib.
f_t	Vegetation fractional cover	0.89	calib.

*: 1. *Ceballos and Ruiz de la Torre* (1979); 2. *Calatayud et al.*(2000); 3. *Clapp and Hornberger* (1978); 4. *Laio et al.* (2001).

LAI_{mod} vs. EVI



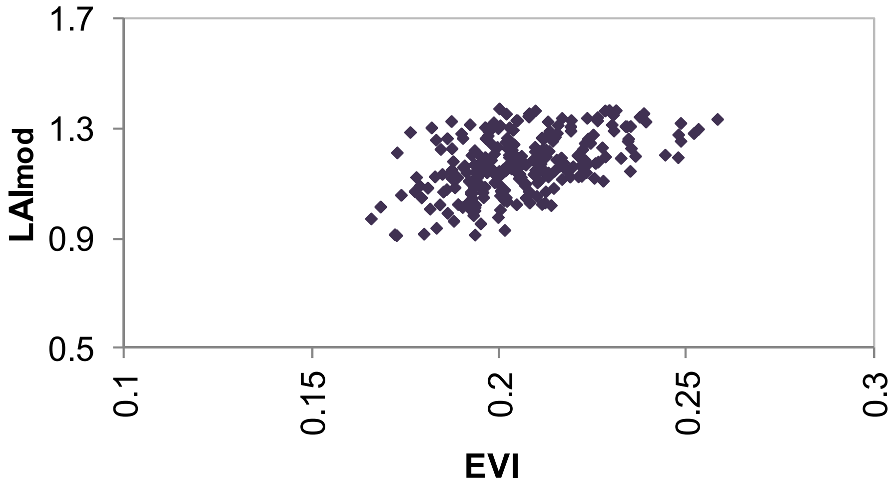
WUE-model
r = 0.45

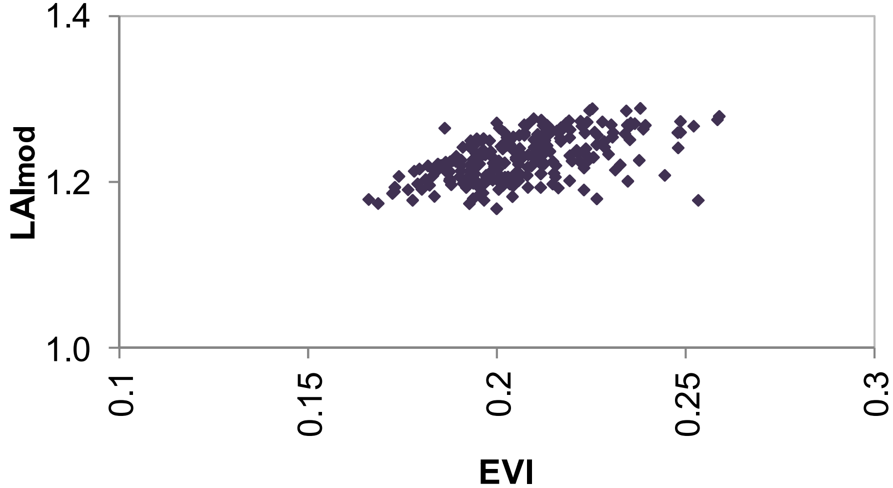


LUE-model
r = 0.57

LAI_{mod} vs. EVI

WUE-model
r = 0.45





LUE-model
r = 0.57

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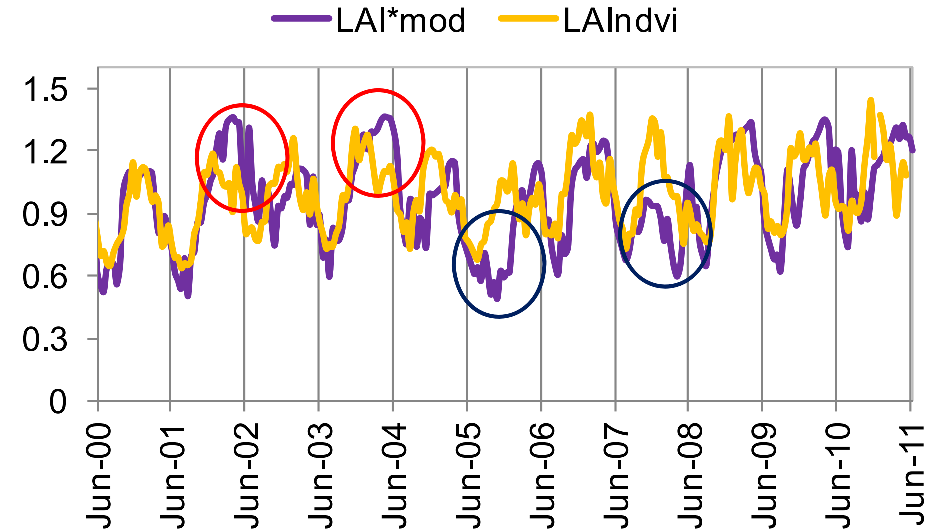
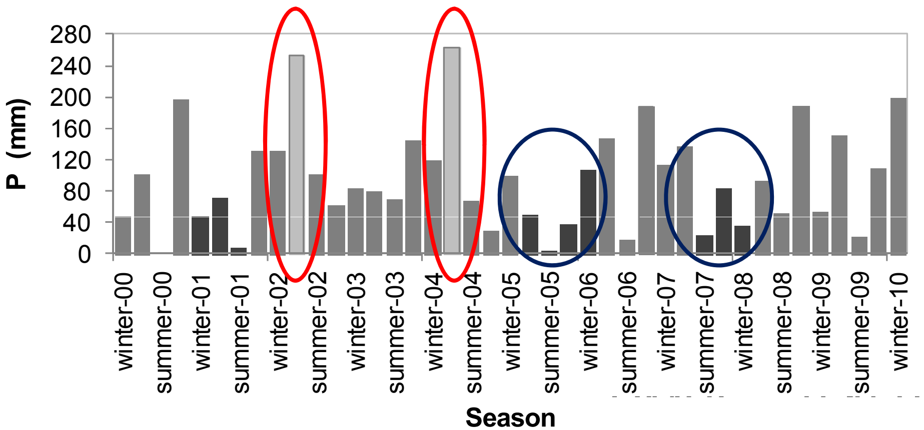
LAI^*_{mod} vs. LAI_{ndvi}





WUE-model

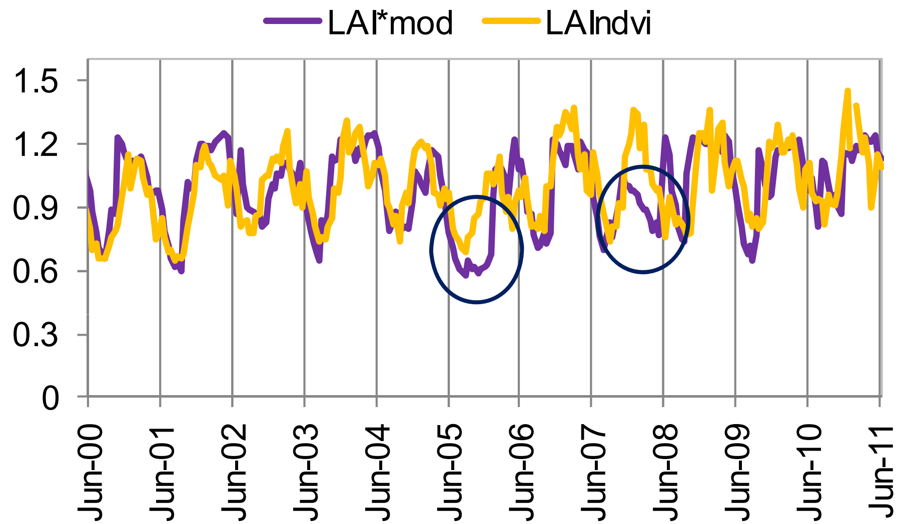
r = 0.61

RMSE = 0.181

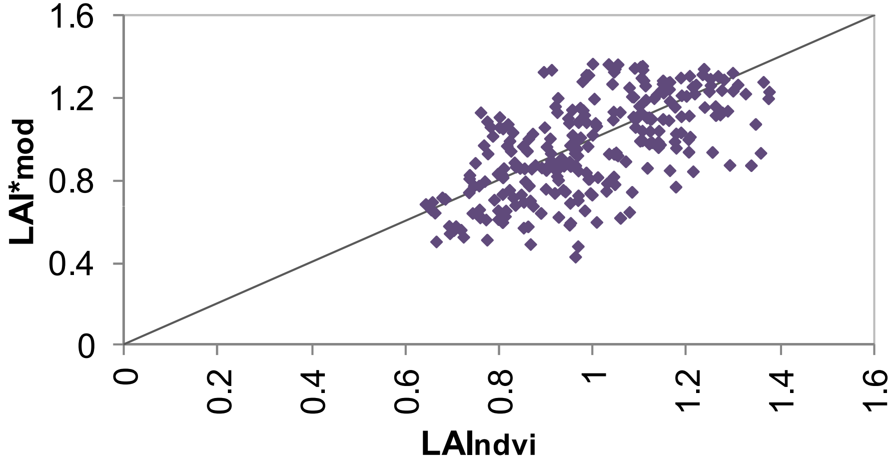
LUE-model

r = 0.60

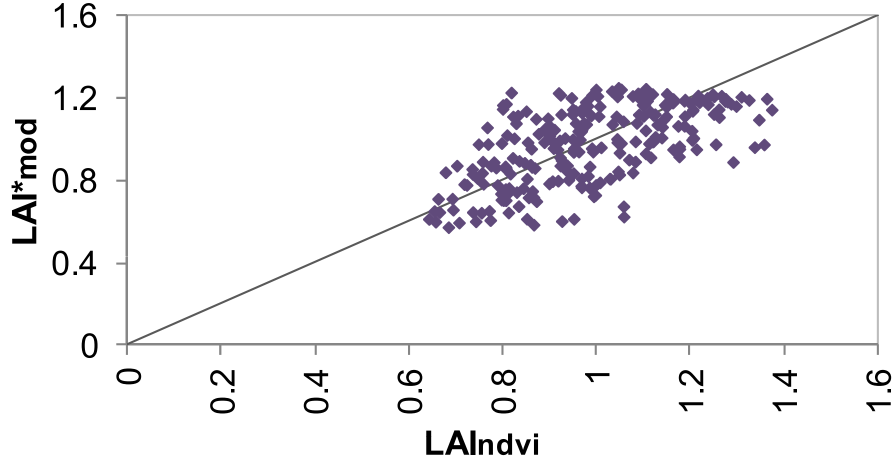
RMSE = 0.162



LAI^*_{mod} vs. LAI_{ndvi}

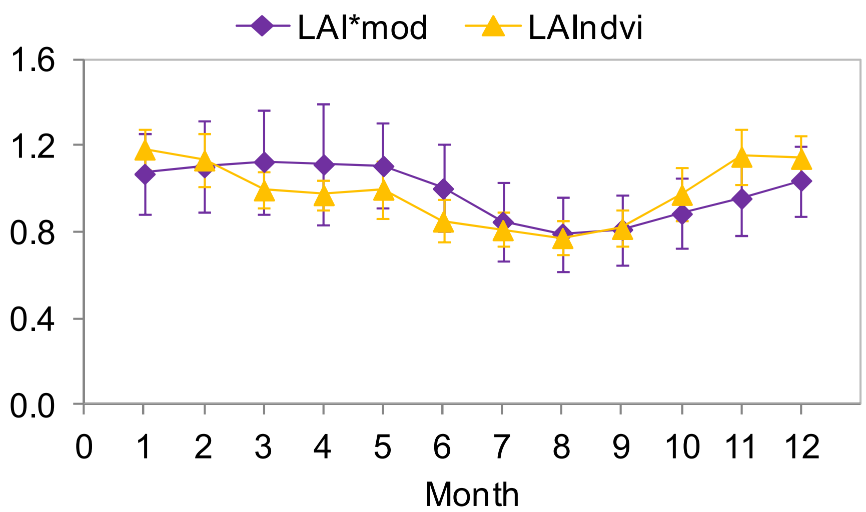


WUE-model
r = 0.45
RMSE = 0.181

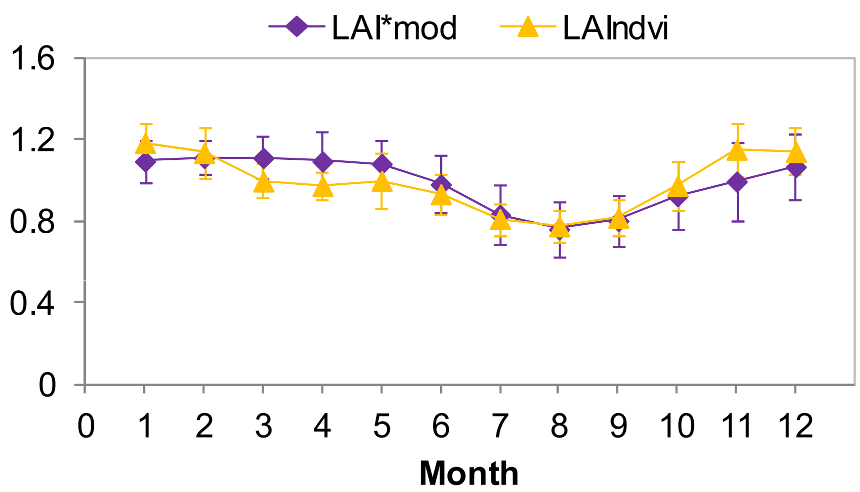


LUE-model
r = 0.57
RMSE = 0.162

LAI^*_{mod} vs. LAI_{ndvi}

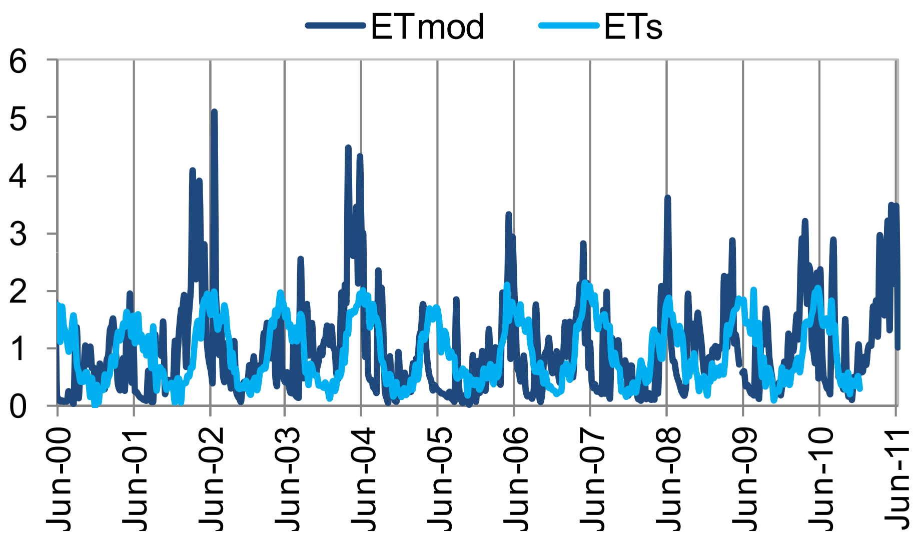


WUE-model
r = 0.65
RMSE = 0.11



LUE-model
r = 0.85
RMSE = 0.07

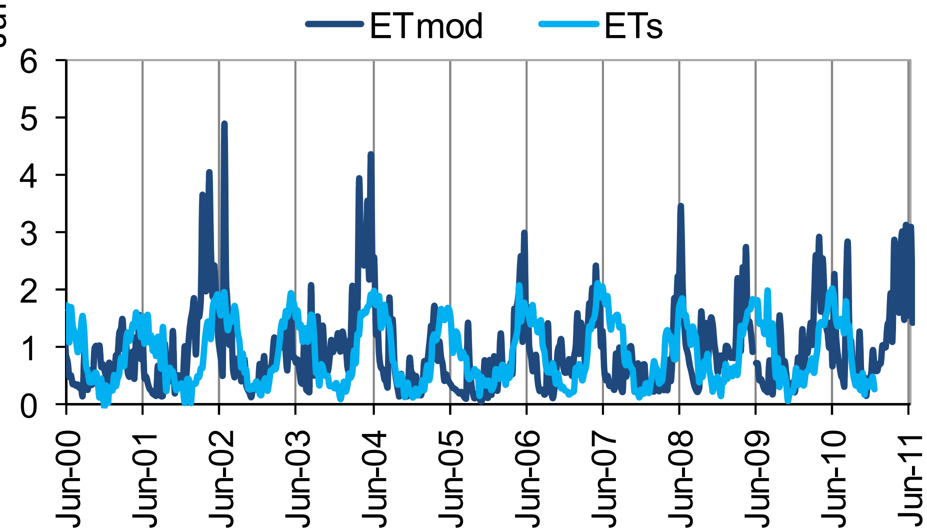
ET_{mod} vs. ET_s



WUE-model
r = 0.28
RMSE = 0.82

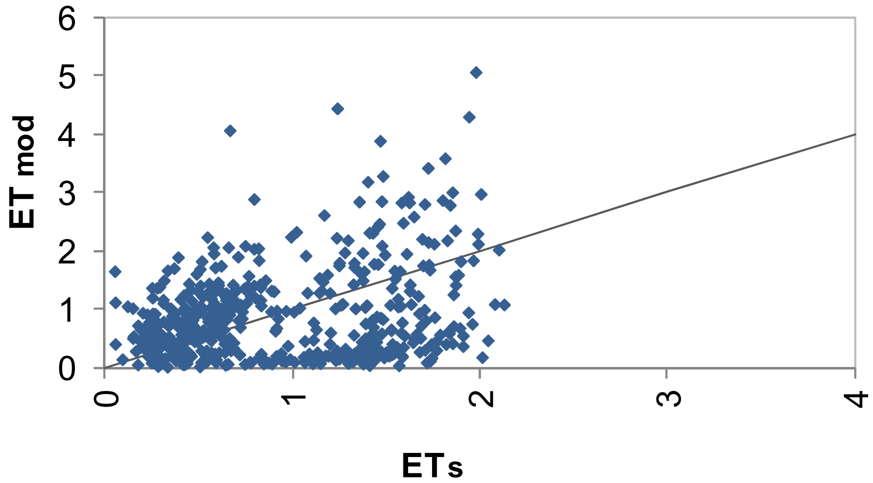
ET decline in July-August?

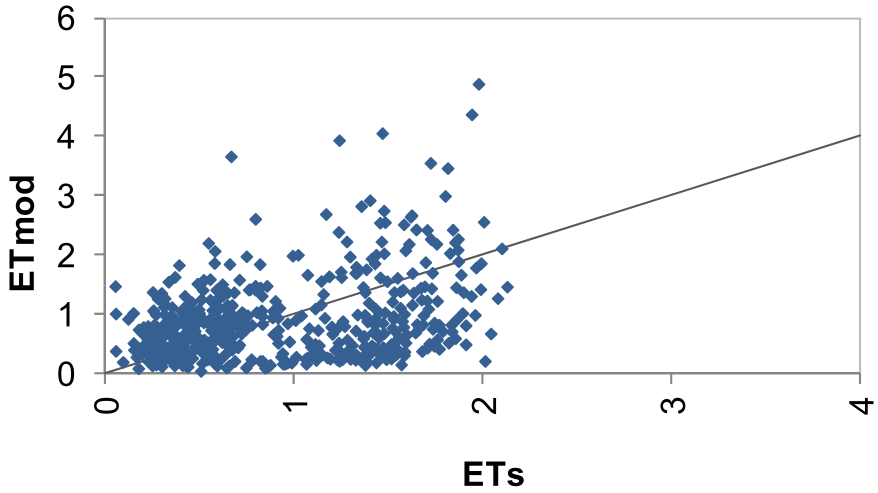
LUE-model
r = 0.35
RMSE = 0.72



ET_{mod} vs. ET_s

WUE-model
r = 0.28





LUE-model
r = 0.35

Discussion

From GSA and GLUE analysis ➡
- 2 models, similar behaviour
- poor performance linked to drought periods

After the calibration: same qualities and problems evidenced by the sensitivity analysis (problems WUE wet springs)

LUE-model performed best: agreement with EVI and LAI_{NDVI}

Conclusions – Issues

Role of vegetation in hydrological systems → important

Relationships soil-veg. → highly non-linear

↓

appropriate vegetation modelling → crucial
(water resources, flood risk…climate change?!)

Two basic issues:

1. Which model (how to choose?)
2. Careful interpretation of each remote-sensing product
   (vegetation indices supply indirect information)

Conclusions – Satellite data

EVI: well correlated with leaf biomass

NDVI: dependence on soil moisture

LAI: wrong classification veg. cover

ET: correlated with ETo, algorithm depends on LAI

BE CAREFUL

Conclusions - Modelling

VEGETATION MODELS:

- HORAS → failed to reproduce annual cycle
- WUE-model → specific for water limited climates (control on growth through T)
- LUE-model → widely applicable (change ε formulation) best results

Recommended LUE-model

Future research lines

- Implement the models at a distributed level and couple them with a distributed hydrological model
- Use of satellite soil moisture estimation (e.g. SMOS, ASCAT)
- Consider other environmental stresses in addition to water stress (temperature, nutrients)
- Competition and succession conceptualization (herbaceous vegetation and open canopy)

Research diffusion

Paper - will be submitted shortly:

Pasquato M, Medici C, Friend AD, Francés F. Comparing two approaches for parsimonious vegetation modelling in semiarid regions using satellite data. *Ecohydrology*

Participations in congresses:

Pasquato M, Medici C, Francés F. 2013. Assessing a parsimonious eco-hydrological model implementation to an Aleppo pine semiarid forest through available remote sensing data. *AGU Fall Meeting*. San Francisco, USA. (poster)

Pasquato M, Medici C, Friend AD, Francés F. 2013. Comparing modelled and remotely sensed leaf area dynamics in an Aleppo pine semiarid forest. *EGU General assembly.* Vienna, Austria. (poster)

Pasquato M, Medici C, Francés F. 2011. Aplicación de un modelo conceptual distribuido de vegetación dinámica a una cuenca semiárida del SE de España. *Symposium on Vadose Zone*. Salamanca, Spain. (poster and article in Book of Proceedings)

Pasquato M, Medici C, Francés F. 2011. Application of a conceptual distributed dynamic vegetation model to a semi-arid basin, SE of Spain. *EGU General assembly.* Vienna, Austria. (oral presentation)

Francés F, Medici C, Bussi G, García A, Barrios M, Pasquato M. 2010. Distributed hydrological modelling within SCARCE Project: integrating water, sediment, quality and vegetation. *SCARCE Annual Conference*. Girona, Spain. (oral presentation and article in Book of Proceedings)

THANK YOU
FOR YOUR ATTENTION

UNIVERSITAT POLITÈCNICA DE VALÈNCIA

Instituto de Ingeniería del Agua y Medio Ambiente

Programa de Doctorado de Ingeniería Hidráulica y Medio Ambiente

Grupo de Investigación de Modelación Hidrológica y Ambiental

HORAS

$$\frac{dH}{dt} = (P - I) - L - E - T$$

WATER BALANCE EQ.

$$I = \min\left(P \cdot R, I_{\max} \cdot R - J\right)$$

INTERCEPTION

$$\frac{dJ}{dt} = I - \min\left(ET_o \cdot R, J\right)$$

INTERCEPTION STORAGE

$$T = \min\left(ET_o \cdot R \cdot \beta_t, ET_o - E_i, H\right)$$

TRANSPIRATION

$$E = \min\left[H \cdot \left(\frac{z_{ss}}{z_e}\right) \cdot (1 - R), ET_o - E_i - T\right]$$

BARE SOIL EVAPORATION

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WUE-/LUE- MODEL

$$\frac{dH_1}{dt} = (P - I) - D - E - T_1$$

$$\frac{dH_2}{dt} = D - L - T_2$$

WATER BALANCE EQ.

$$I = \min\left(P \cdot f_t, I_{\max} \cdot f_t - J\right)$$

INTERCEPTION

$$\frac{dJ}{dt} = I - \min\left(ET_o \cdot f_t, J\right)$$

INTERCEPTION STORAGE

$$T_1 = \left[ET_o \cdot f_t - \min\left(ET_o \cdot f_t, J\right)\right] \cdot \min\left(LAI_{\text{mod}}, 1\right) \cdot \beta_t\left(H_1\right) \cdot r_1$$

$$T_2 = \left[ET_o \cdot f_t - \min\left(ET_o \cdot f_t, J\right)\right] \cdot \min\left(LAI_{\text{mod}}, 1\right) \cdot \beta_t\left(H_2\right) \cdot \left(1 - r_1\right)$$

TRANSPIRATION

$$E = ET_o \cdot f_b \cdot \beta_b\left(H_1\right)$$

BARE SOIL EVAPORATION

WUE-/LUE- MODEL

$$Re = r \cdot \frac{C}{cn} \cdot \phi \cdot g\left(Temp\right)$$

MAINTENANCE RESPIRATION

$$\varphi = 1 - \frac{LAI}{LAI_{\max}}$$

ALLOCATION FACTOR

$$LAI_{\text{mod}} = B_l \cdot SLA \cdot f_t$$

GROUND BASED LAI

$$LAI*_{\text{mod}} = LAI_{\text{mod}} \cdot \left(1 - \overline{\zeta}_{10}\right)$$

CORRECTED LAI

$$\zeta_{tot} = \zeta\left(H_1\right) \cdot r_1 + \zeta\left(H_2\right) \cdot \left(1 - r_1\right)$$

TOTAL WATER STRESS