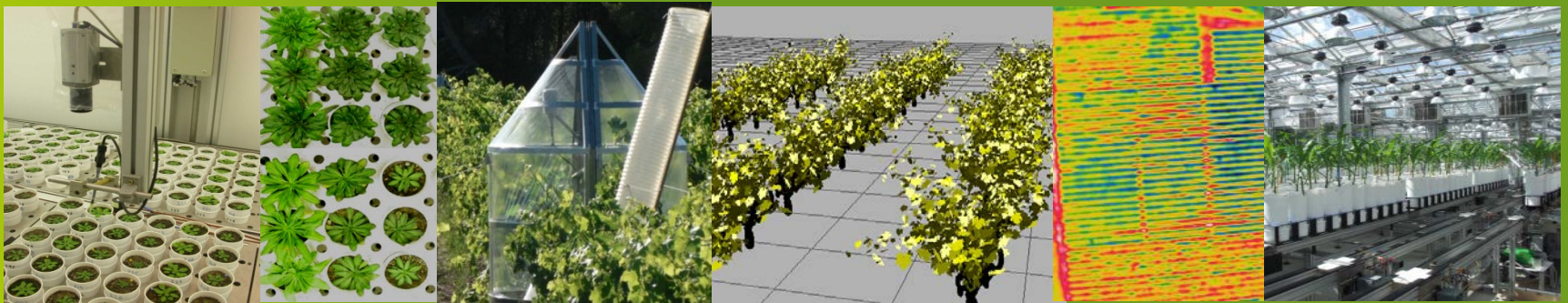


Crops for a changing climate: modeling helps to push the phenotyping frontier forward

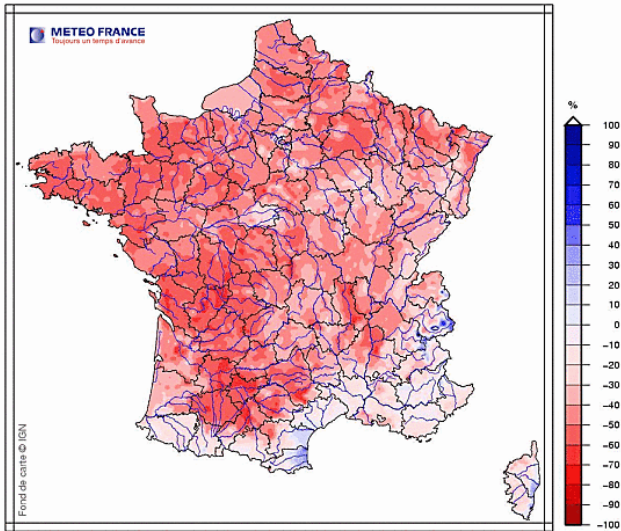


BERTRAND MULLER

MONTPELLIER
FRANCE



Climate change : more heat waves and drought episodes and more regions impacted



Soil humidity in spring
2011 in France

The Loire river in 2011

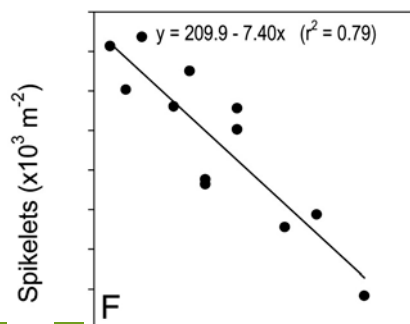
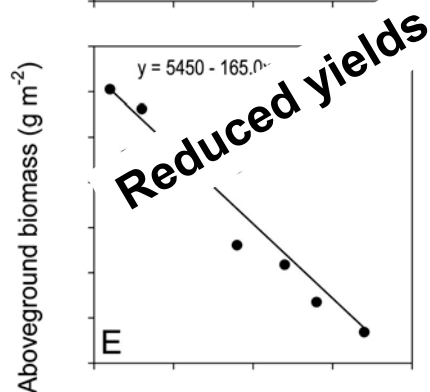
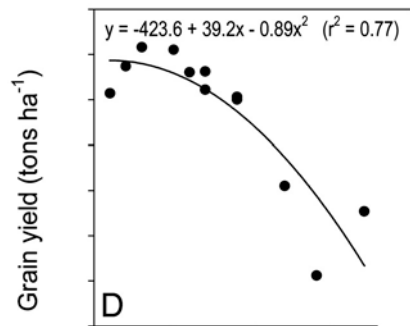


Dead ponderosa pine trees in
Bandelier National Monument,
New Mexico, USA. [Nate
McDowell]

Rice yields decline with higher night temperature from global warming

Shaobing Peng*, Jianliang Huang*, John E. Sheehy*, Rebecca C. Laza*, Romeo M. Visperas*, Xuhua Zhong*, Grace S. Centeno*, Gurdev S. Khush^{1,2}, and Kenneth G. Cassman^{3,4}

*Crop, Soil, and Water Sciences Division, International Rice Research Institute, DAPO Box 7777, Metro Manila, Philippines; ¹Crop Physiology and Production Center, College of Plant Science and Technology, Huazhong Agricultural University, Wuhan, Hubei 430070, China; ²Rice Research Institute, Guangdong Academy of Agricultural Sciences, Guangzhou, Guangdong 510640, China; ³University of California, Davis, CA 95616; and ⁴Department of Agronomy and Horticulture, University of Nebraska, Lincoln, NE 68583



Minimum temperature (°C)

lantes

Vol 437/22 September 2005/doi:10.1038/nature03972

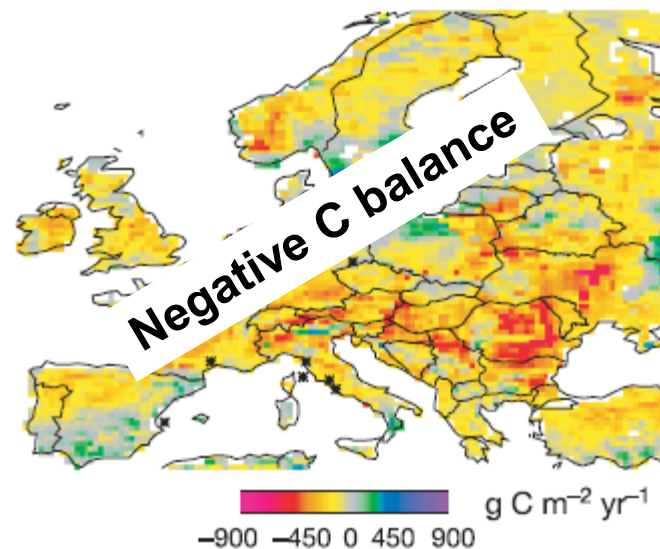
nature

LETTERS

Europe-wide reduction in primary productivity caused by the heat and drought in 2003

Ph. Ciais¹, M. Reichstein^{2,3}, N. Viovy¹, A. Granier⁴, J. Ogée⁵, V. Allard⁶, M. Aubinet⁷, N. Buchmann⁸, Chr. Bernhofer⁹, A. Carrara¹⁰, F. Chevallier¹, N. De Noblet¹, A. D. Friend¹, P. Friedlingstein¹, T. Grünwald⁹, B. Heinesch⁷, P. Keronen¹¹, A. Knohl^{12,13}, G. Krinner¹⁴, D. Loustau⁵, G. Manca^{2,†}, G. Matteucci^{15,†}, F. Miglietta¹⁶, J. M. Ourcival¹⁷, D. Papale², K. Pilegaard¹⁸, S. Rambal¹⁷, G. Seufert¹⁵, J. F. Soussana⁶, M. J. Sanz¹⁰, E. D. Schulze¹², T. Vesala¹¹ & R. Valentini²

primary productivity is unprecedented during the last century. An increase in future drought events could turn temperate ecosystems into carbon sources, contributing to positive carbon-climate feed-backs already anticipated in the tropics and at high latitudes^{1,2}.

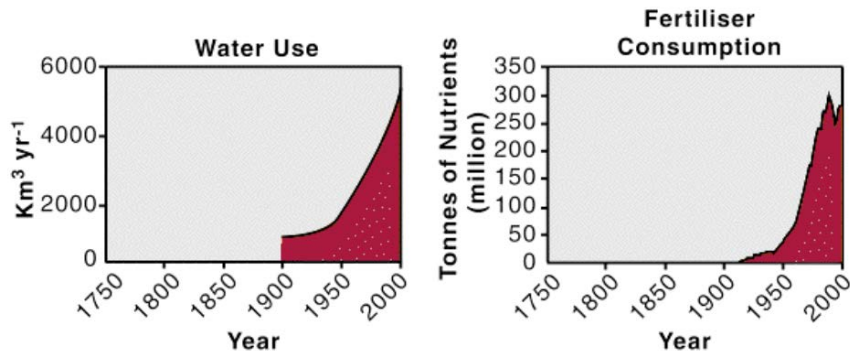


Irrigation ?

Water Resour Manage (2007) 21:35–48

DOI 10.1007/s11269-006-9039-x

ORIGINAL ARTICLE

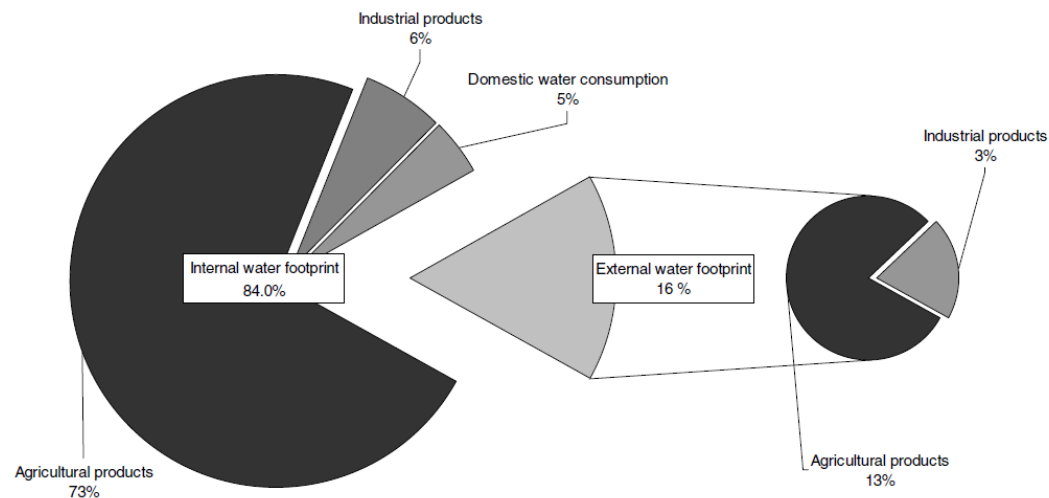


Water footprints of nations: Water use by people as a function of their consumption pattern

A. Y. Hoekstra · A. K. Chapagain

(Steffen et al. 2004 – *Global Change and the Earth System: A Planet under Pressure*)

The four major direct factors determining the water footprint of a country are: volume of consumption (related to the gross national income); consumption pattern (e.g. high versus low meat consumption); climate (growth conditions); and agricultural practice (water use efficiency).



✓ Mitigation

✓ Adaptation

Which levers for adaptation ?

- ✓ **Cropping systems**
- ✓ **Species**
- ✓ **Varieties**

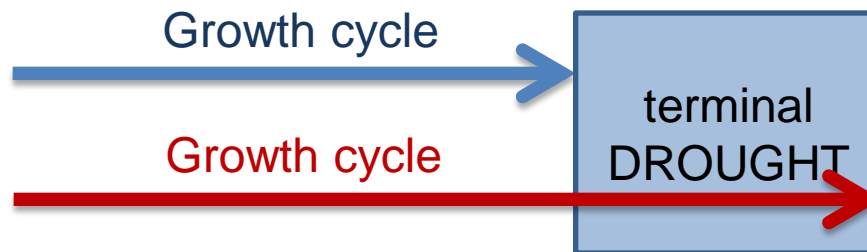
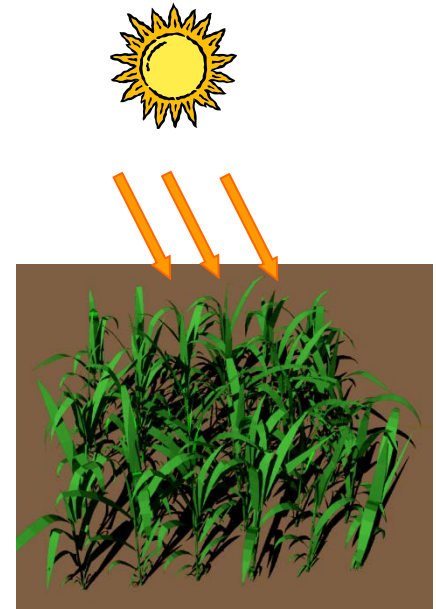
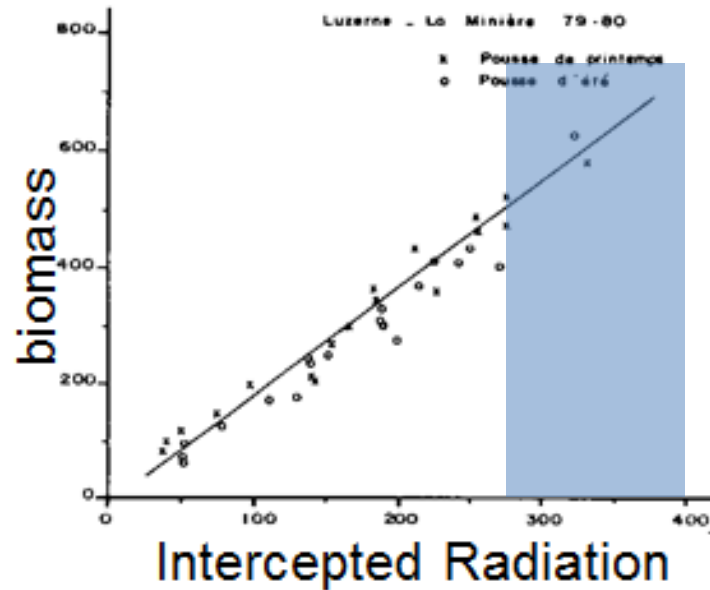
→ What plants do to adapt to drought & heat in natura ?

→ Can we design breeding schemes based on that knowledge ?

What plants do to face drought *in natura* ?

- ✓ Early flowering to escape drought periods
- ✓ Stomatal control to prevent water loss
- ✓ Enhanced root growth to access to deep layers
- ✓ Reduced leaf growth to minimize transpiring surface

- ✓ Early flowering (ESCAPE). Widely used strategy
 - BUT reduces growth cycle and costs C

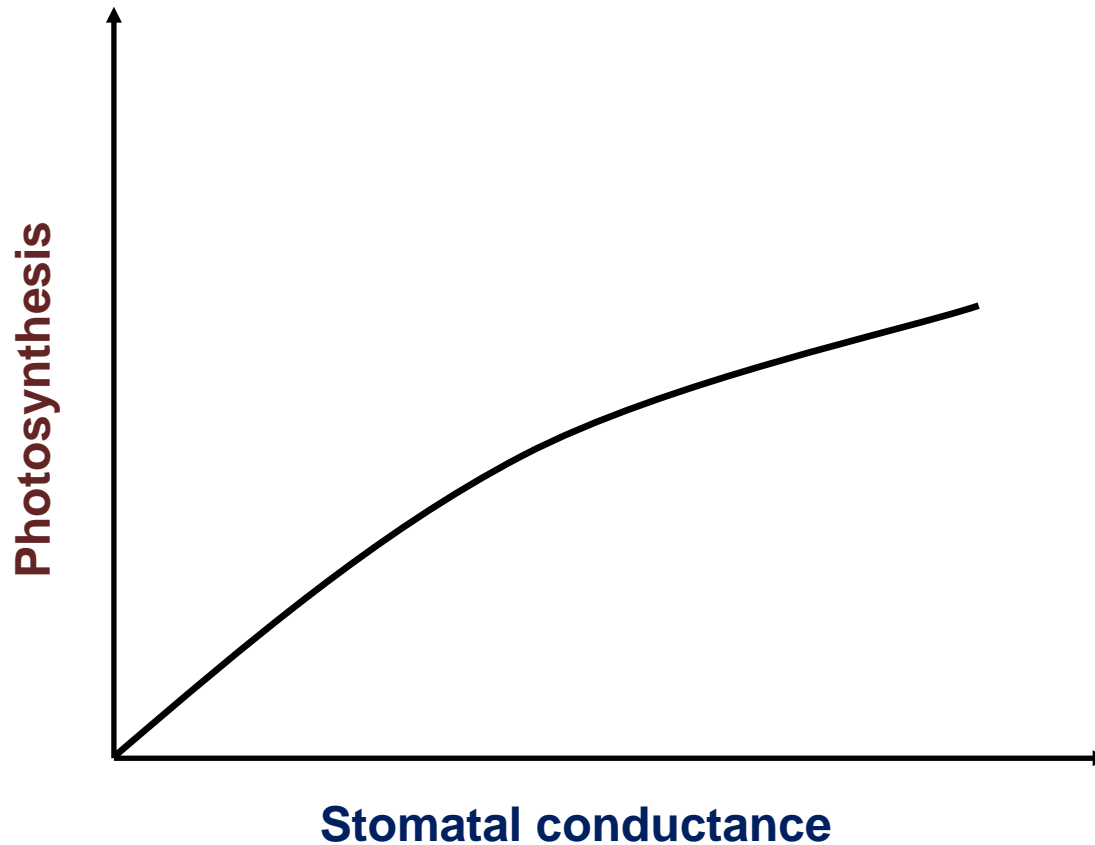
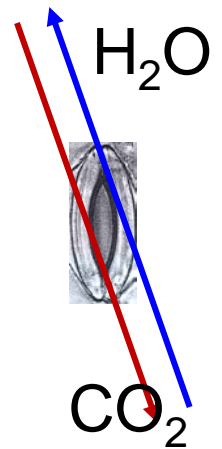
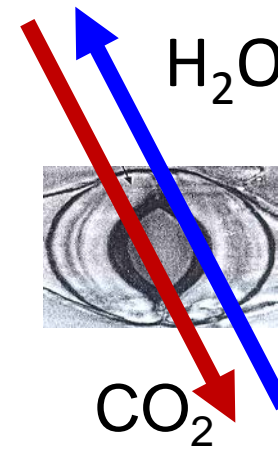


Biomass

Early varieties if terminal drought

✓ Stomatal control

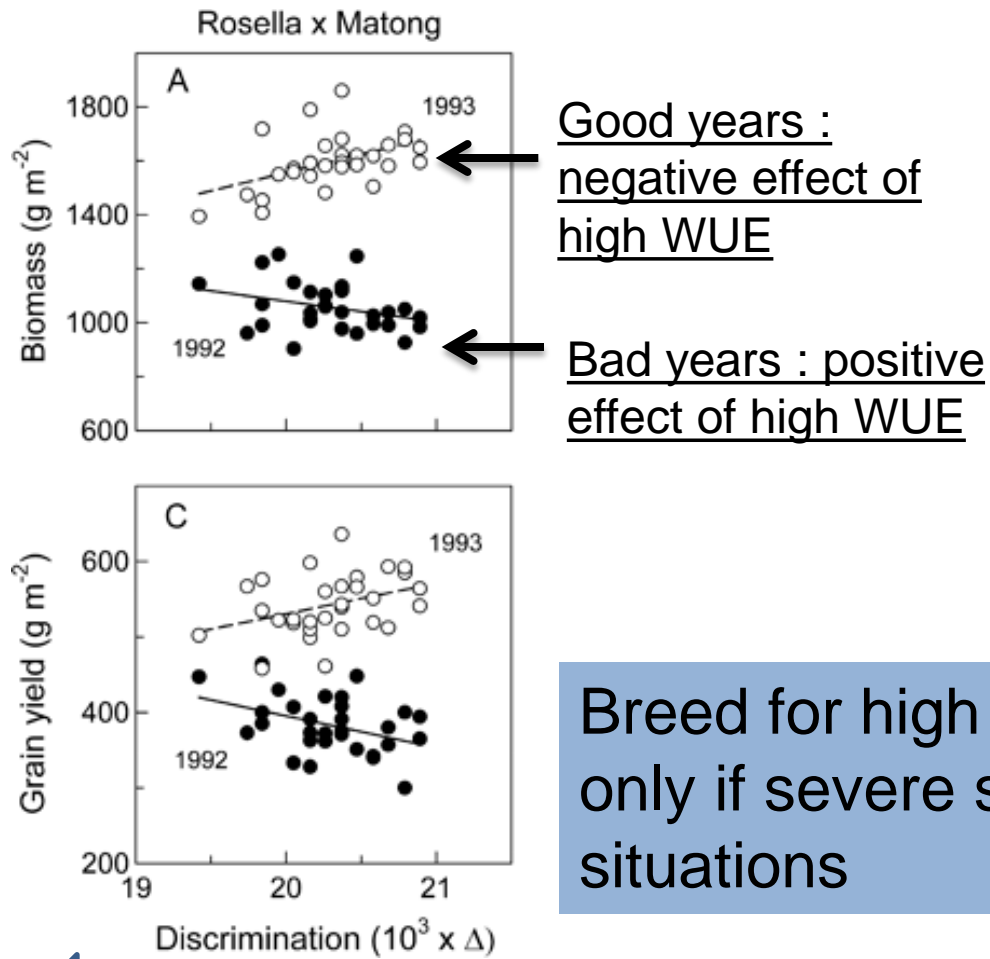
Water-use efficiency (trade-off between C and H₂O)



✓ Increasing WUE ?

Breeding for high water-use efficiency

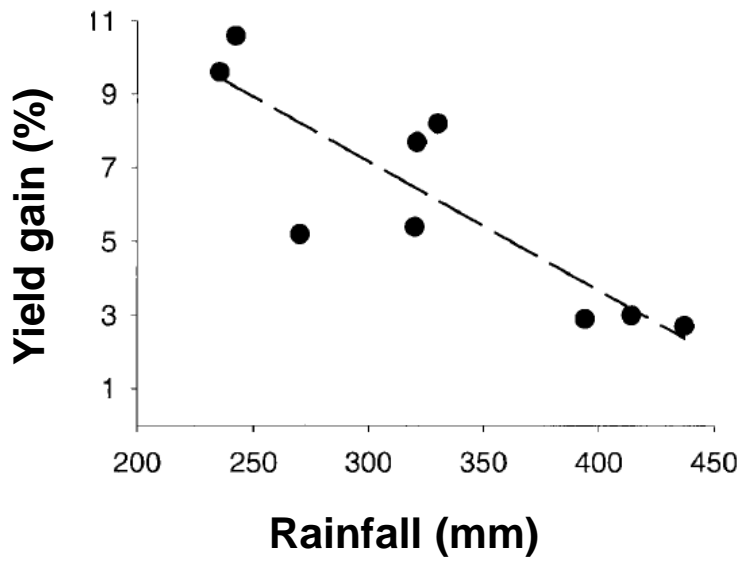
A. G. Condon^{1,*}, R. A. Richards¹, G. J. Rebetzke¹ and G. D. Farquhar²



Good years :
negative effect of
high WUE

Bad years : positive
effect of high WUE

Breed for high WUE
only if severe stress
situations

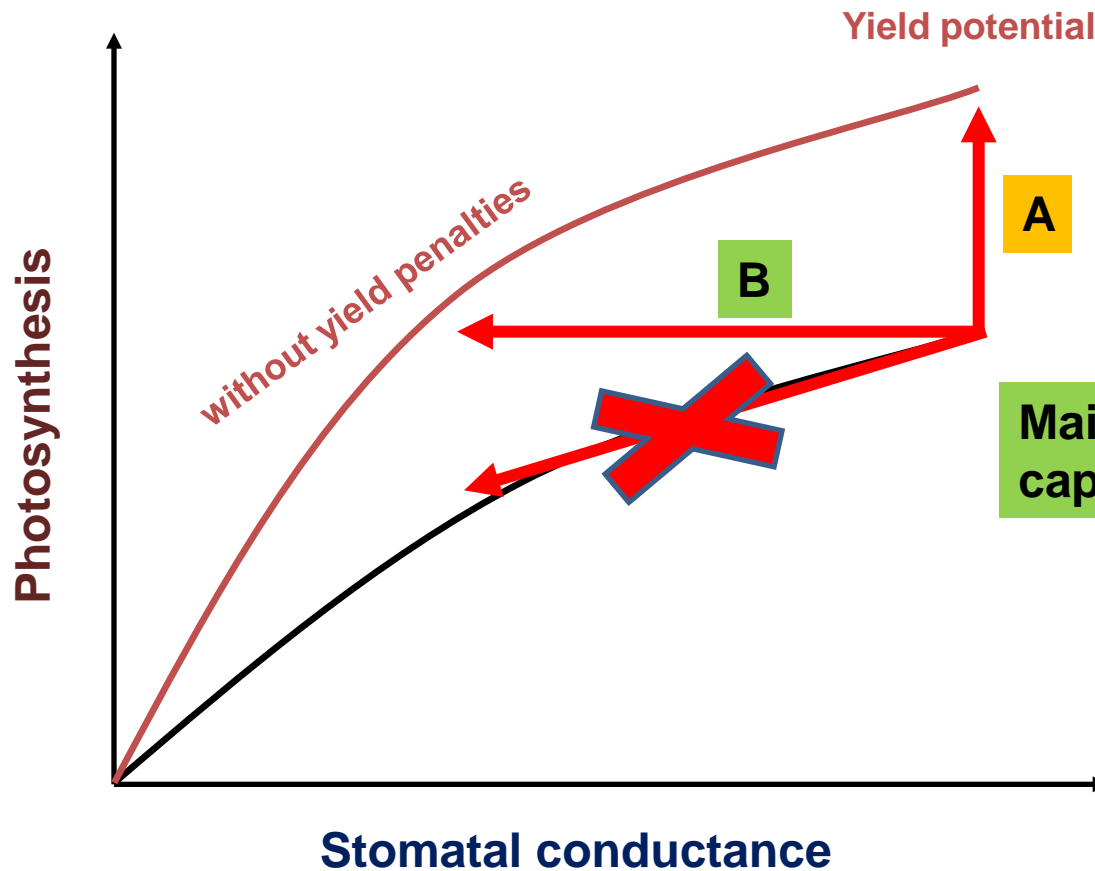
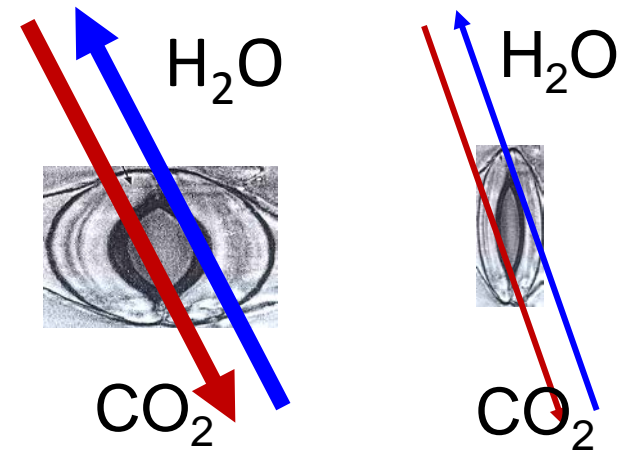


Rebetzke et al. 2002
Rainfed breadwheat
Australia

Water Use Efficiency

✓ Stomatal control

Water-use efficiency (trade-off between C and H₂O)



A

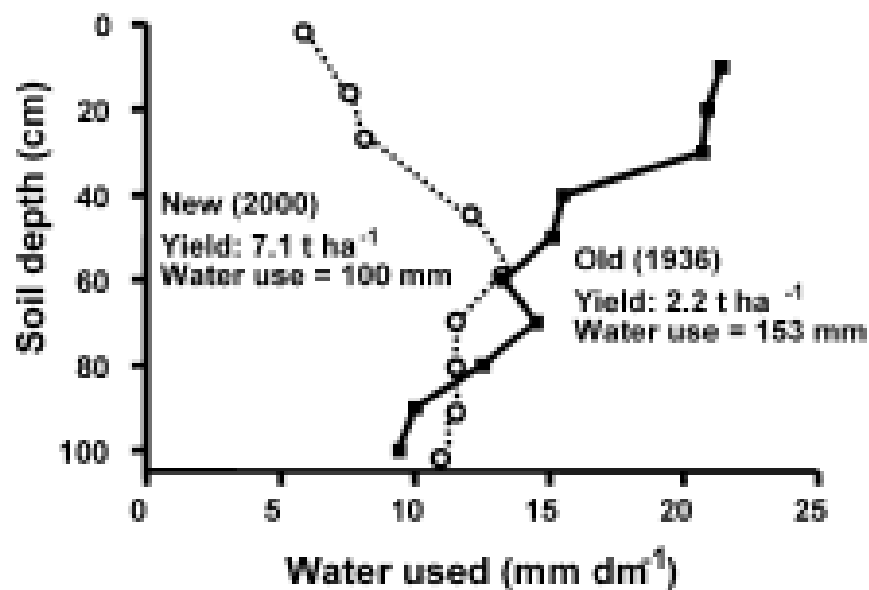
Improve productivity without using more water

Maintain photosynthetic capacities under water stress

✓ Large root systems ?

Positive if water at depth (Tuberosa et al. 2002)

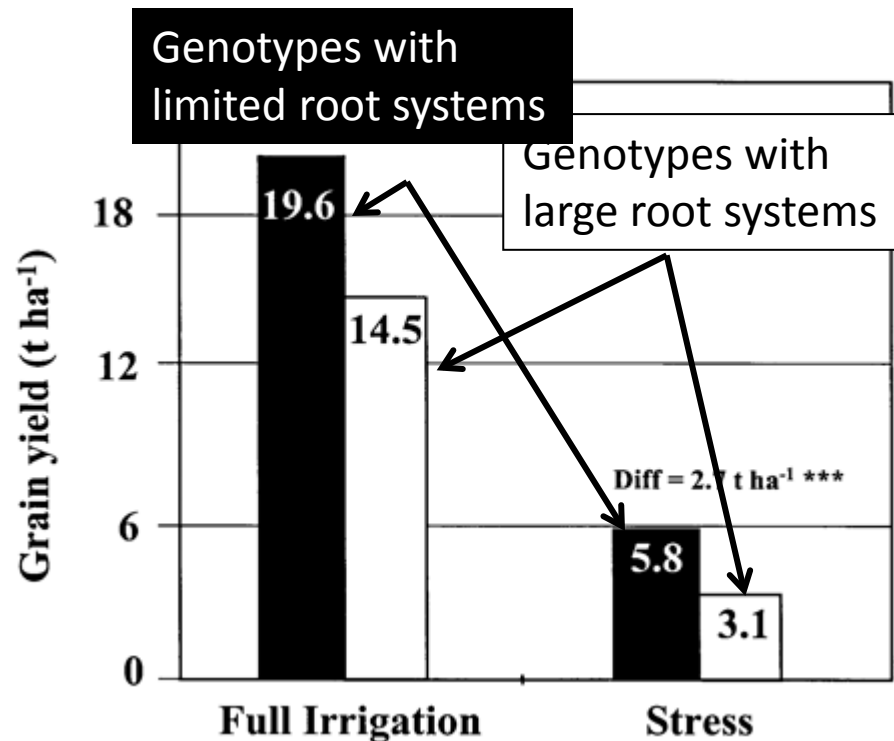
Negative if limited soil depth (Campos et al 2004, Bruce et al 2003) because it costs C



Improving drought tolerance in maize:
a view from industry

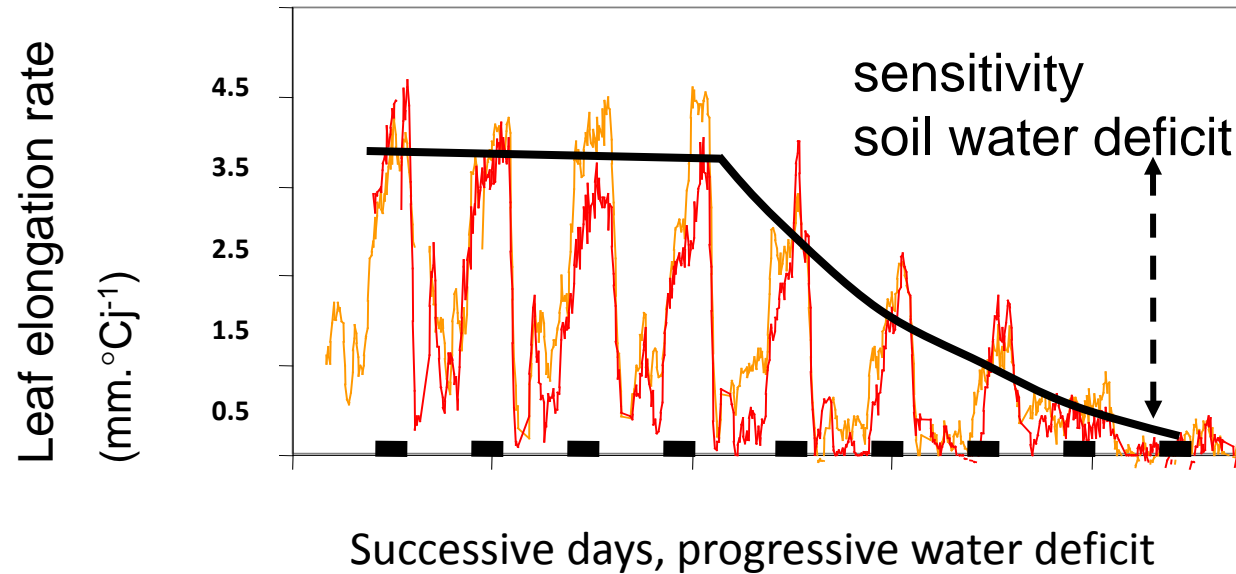
H. Campos*, M. Cooper, J.E. Habben,
G.O. Edmeades, J.R. Schussler

Pioneer Hi-Bred International Inc., 7250 NW, 62nd Avenue, P.O. Box 552, Johnston, IA 50131-0552, USA



Breed for deep root system
if... there is water at depth

✓ Reduced leaf expansion ?



- ✓ Reduces water consumption (save soil water)
- ✓ Negative : Intercepted light is reduced and yield is hampered

What plants do to face drought *in natura* ?

- ✓ Early flowering (ESCAPE). Widely used strategy
 - BUT reduces growth cycle and costs C
- ✓ Stomatal control
 - BUT reduces photosynthesis and costs C
- ✓ Root growth. Access to deep layers
 - BUT costs C to build roots
- ✓ Reducing leaf growth
 - BUT reduces light interception and costs C

All are conservative strategies

They must be used smoothly depending on the target

In front of hard conditions, should the plant continue business as usual (ie maintain growth and keep stomata open) or not ?



The cicada and the ant
Jean De la Fontaine

The answer is : it depends

Breeding for drought tolerance is an optimization process

1 - We need to have good climate models

2 - We need to assemble the most favourable alleles for the targeted climate scenarios

a : create new 'combinations of alleles'

- use existing germplasm
- use ancestor alleles
- create novel alleles (GM)

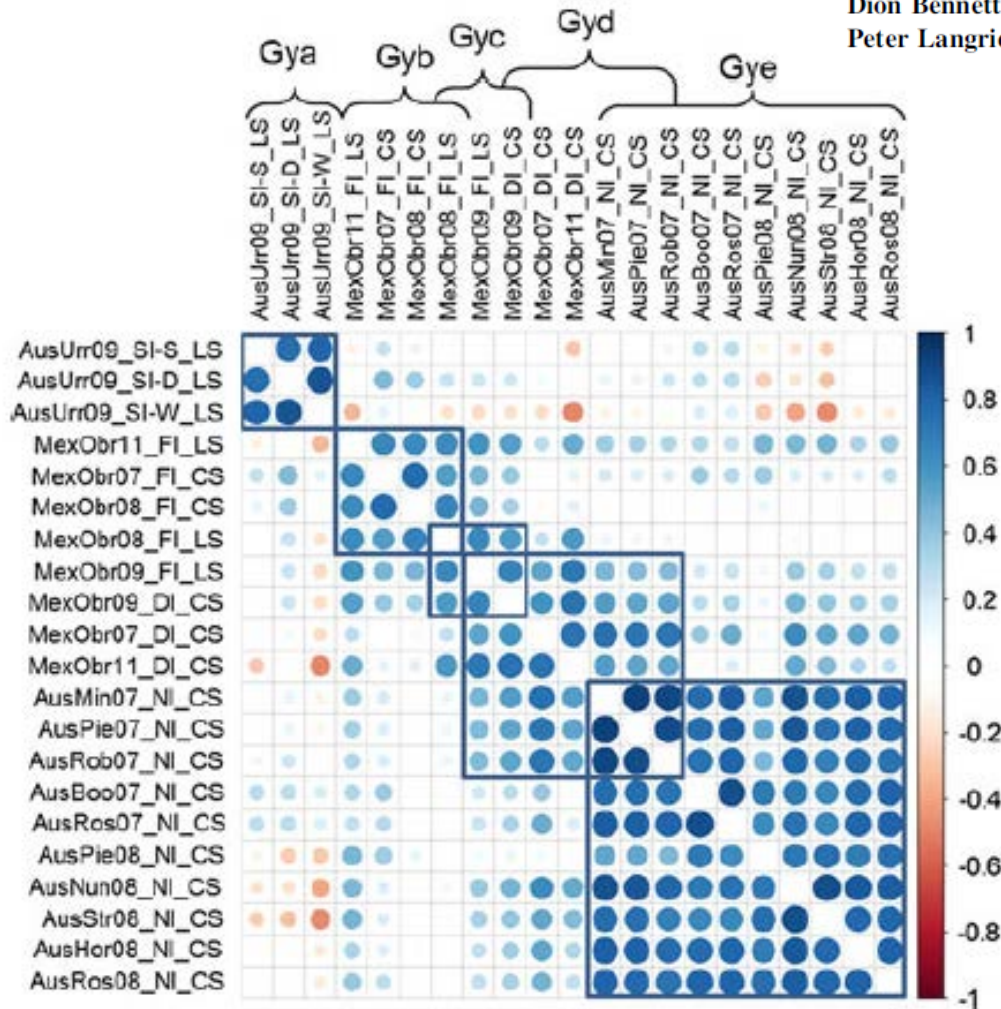
b : evaluate these 'combinations'

- field trials in Target Populations of Environments
- crop models incorporating genetic information

‘it depends’

Multi-environment analysis and improved mapping of a yield-related QTL on chromosome 3B of wheat

Julien Bonneau · Julian Taylor · Boris Parent ·
Dion Bennett · Matthew Reynolds · Catherine Feuillet ·
Peter Langridge · Diane Mather



On integrated traits
such as **yield**,
GxE interaction is
massive

Genotype ranking is neither
conserved among field trials in
Mexico or Australia nor within
Australia between irrigated and
non irrigated plots

‘it depends’

the G x E interaction



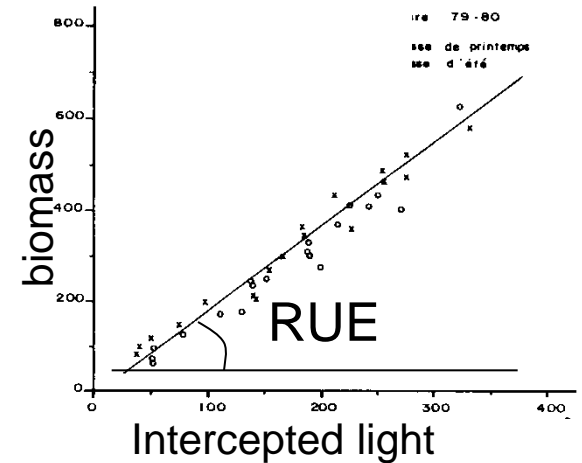
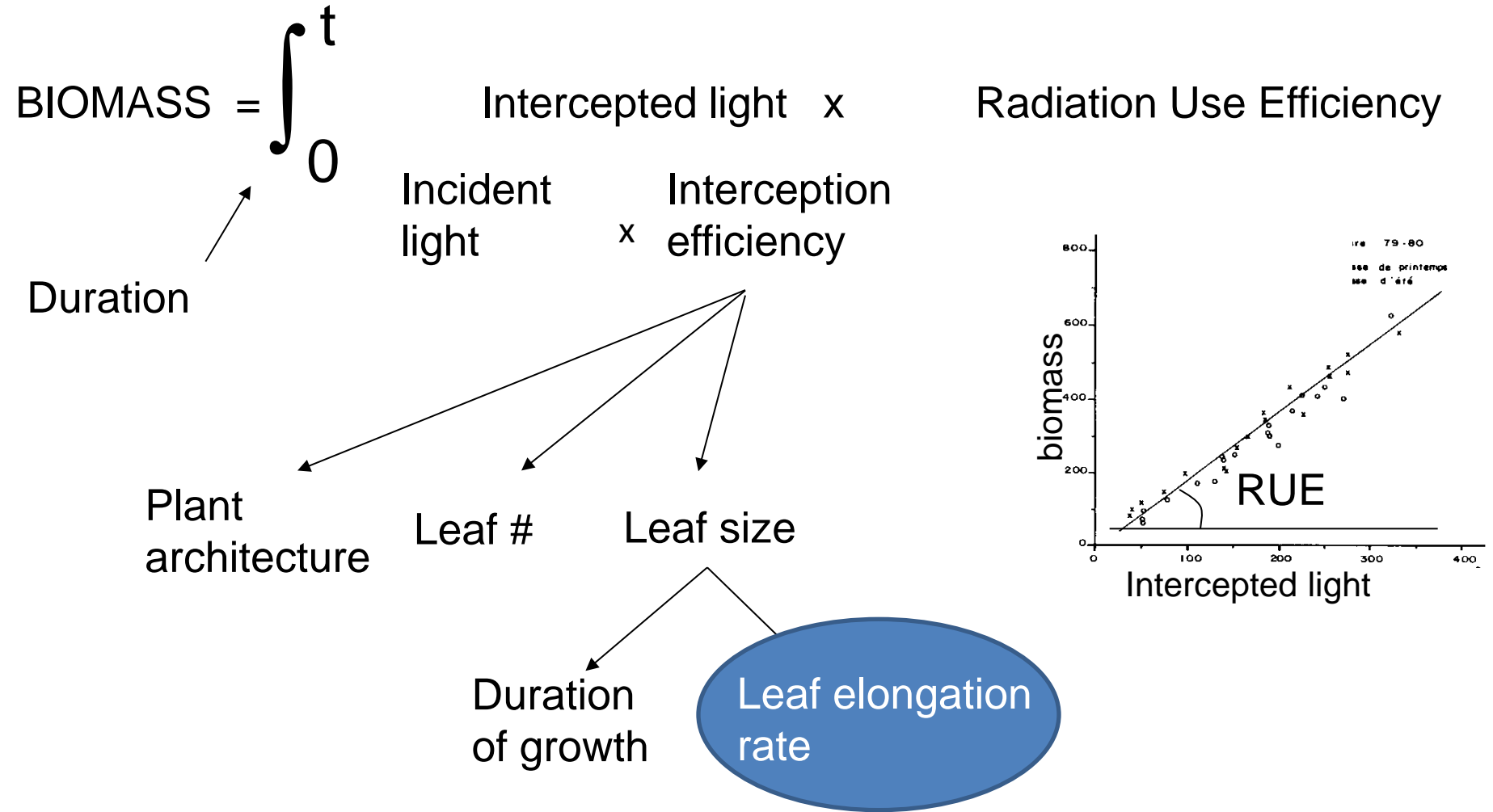
The best genotypes in one environment



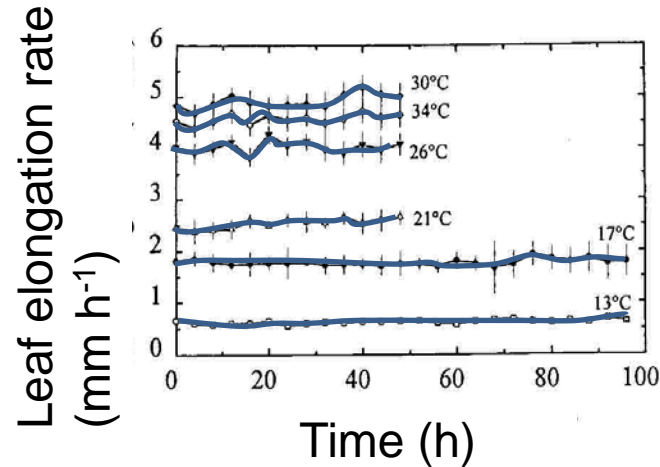
Are not necessarily the best in another

Models help to decompose integrated and poorly heritable traits into heritable parameters

A widely use model in Agronomy (Montieth, 1977)

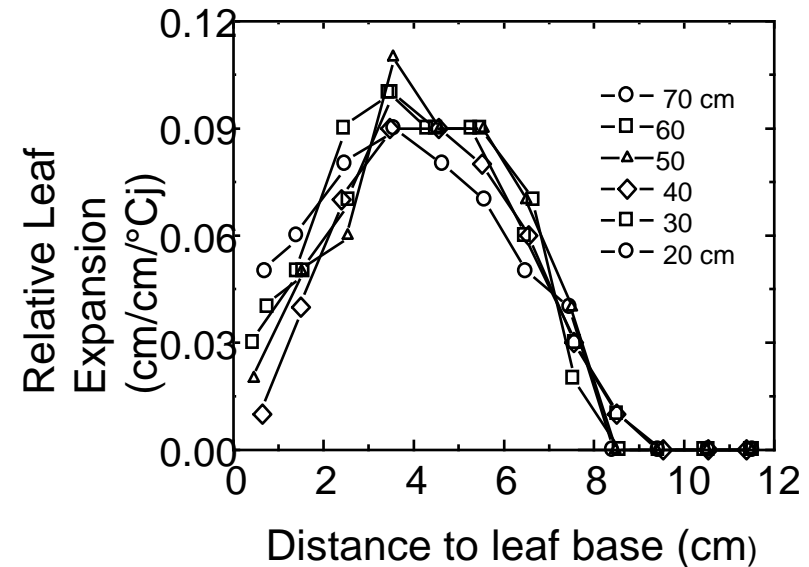
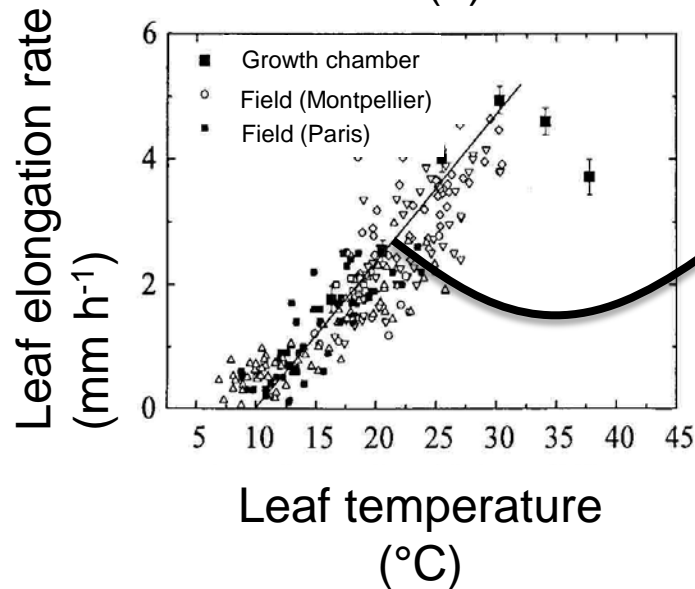


In monocots, leaf elongation rate is linearly related to temperature



A very simple model

$$\Delta L / \Delta t = (T - T_0) \cdot a$$

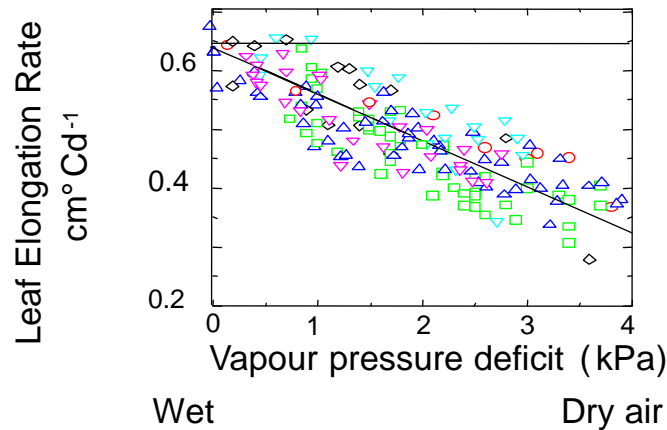


Muller et al 2001 JXB

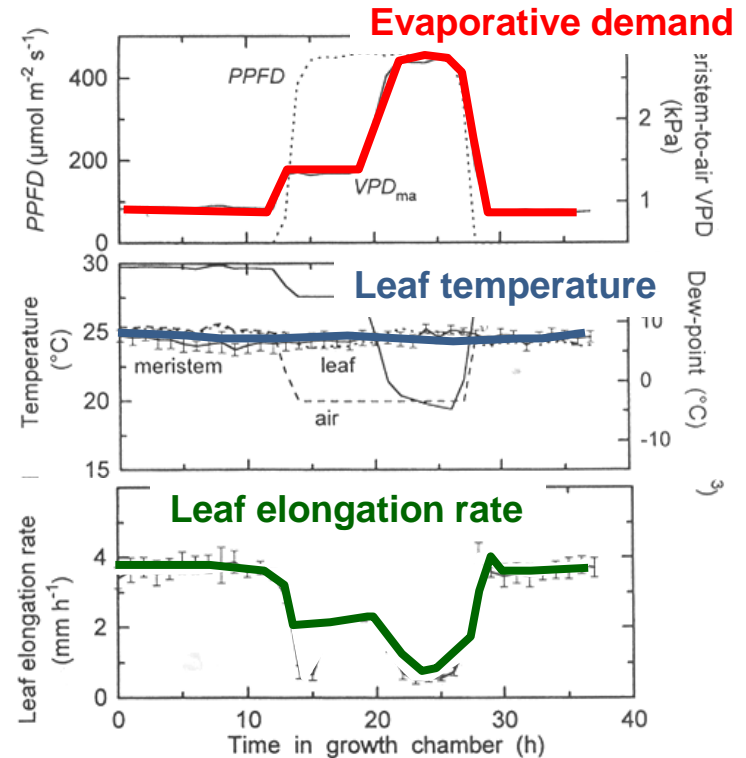
Because the leaf growing zone is temporarily invariant

Leaf elongation rate decreases linearly with VPD

(VPD = Vapor Pressure Deficit ~ air dryness)
also called evaporative demand



15 indep. experiments (field, greenhouse, growth chamber)



$$\Delta L / \Delta t = (T - T_0) \cdot (a - b \cdot \text{VPD})$$

Leaf growth rate linearly decreases with water deficit
(soil water potential)

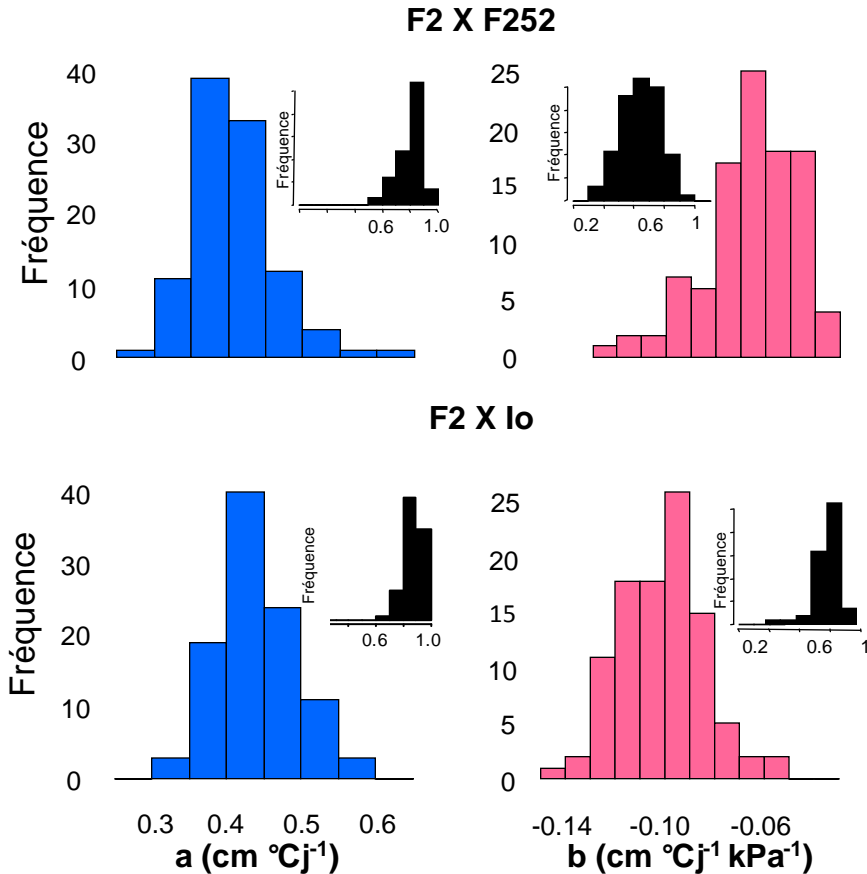
$$\Delta L / \Delta t = (T - T_0) \cdot (a - b \text{ VPD} - c \cdot \Psi)$$

A simple and robust (holds for greenhouse, growth chamber, field situations) model with 3 parameters a, b, c
(T_0 was genetically invariant)

Can we perform a genetic analysis of these parameters ?

There is genetic variability and we can identify QTLs

$$\Delta L/\Delta t = (T - T_0) \cdot (a - b \text{ VPD} - c \cdot \Psi)$$



Reymond et al 2003 Plant Physiol

Reymond et al 2004 JXB

Sadok et al 2007 PCE

The behavior of genotypes carrying original alleles combinations in original climatic scenarios can be predicted

$$\Delta L / \Delta t = (T - T_0) \cdot (a - b \text{ VPD} - c \cdot \Psi)$$

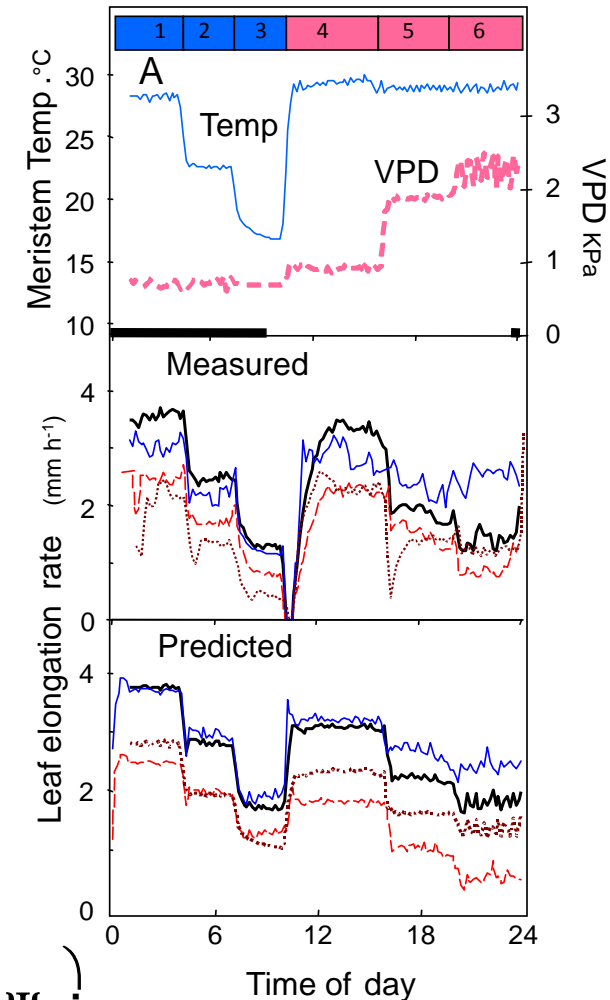
$$a = \bar{a} + \sum_i \alpha_i \text{QTL}_i$$

$$b = \bar{b} + \sum_i \beta_i \text{QTL}_i$$

The allelic effects are incorporated into the model

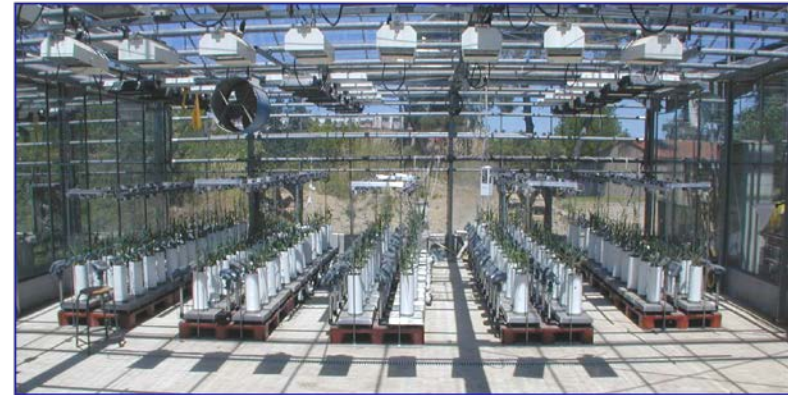
$$c = \bar{c} + \sum_k \chi_k \text{QTL}_k$$

$$\frac{\Delta L}{\Delta t} = (T - T_b) \cdot \left((\bar{a} + \sum_i \alpha_i \text{QTL}_i) - (\bar{b} + \sum_j \beta_j \text{QTL}_j) \cdot \text{VPD} - (\bar{c} + \sum_k \chi_k \text{QTL}_k) \cdot \Psi_w \right)$$



Now analysing the data

Automated high throughput setups
have been developed



Now developing automated tools for phenotyping



<http://bioweb.supagro.inra.fr/phenodyn/>

Sadok et al. 2007 PCE

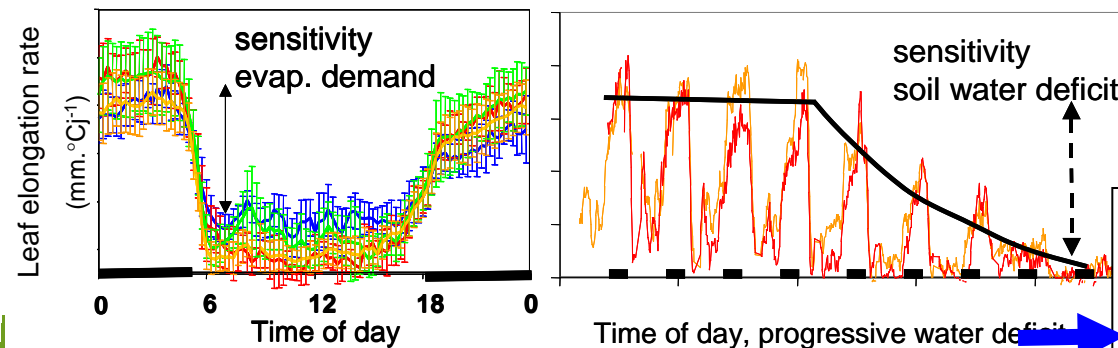
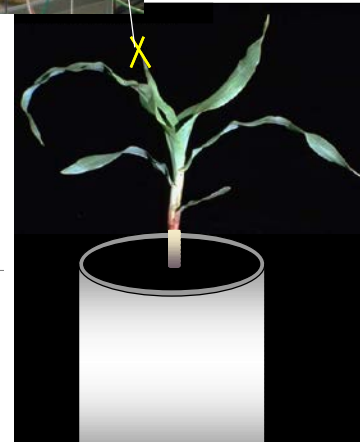
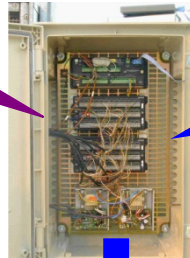
Welcker et al. 2007 Plant Physiol

Parent et al 2009 Plant Physiol

- 480 plants
- Automated Irrigation
- Leaf growth step = 15min

Transpiration

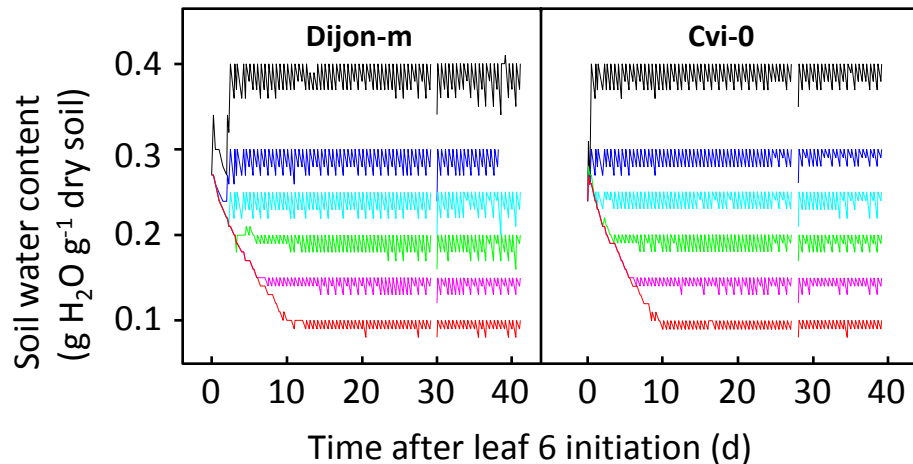
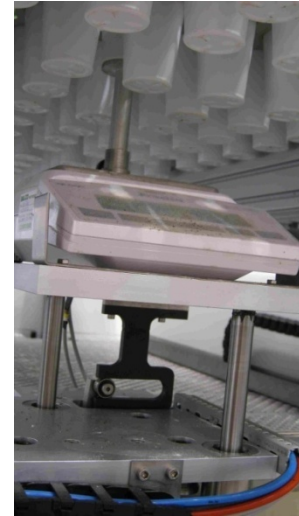
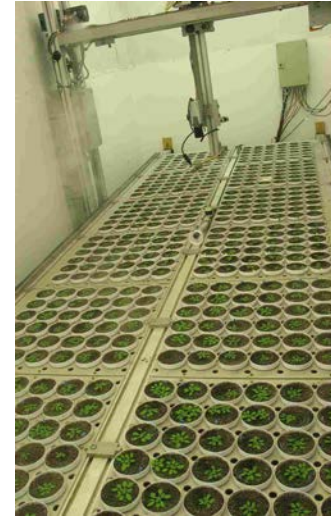
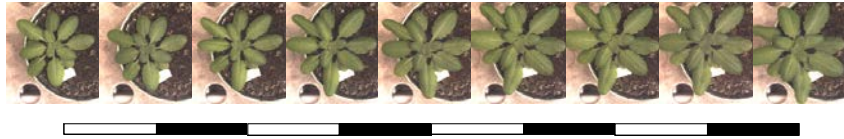
Growth



Phenodyn DB
1000s of kinetics :



- 500 plants /automaton
- 3 automatons
- Time step for growth = 12h
- Vertical and lateral imaging
- Visible or IR or fluorescence



<http://bioweb.supagro.inra.fr/phenopsis/>

Granier et al. 2006 *New Phytol*

Tisne et al. 2008 *Plant Physiol*

Hummel et al 2010 *Plant Physiol*

Vile et al. 2011 *PCE*

A large (1700 plants, 300 m²) automated platform to impose various scenarios of water deficits and measure leaf growth and transpiration in a range of species



1700 plants

<http://bioweb.supagro.inra.fr/phenoarch/>

Variables



3D Imaging

NIR Imaging

Plant architecture, LAI

RUE

Biomass accumulation

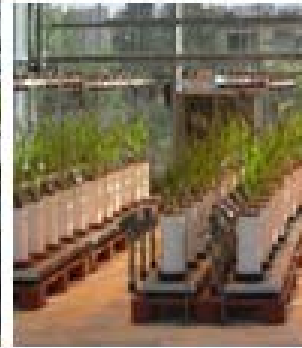
Transpiration

WUE

Species tested so far : maize, sorghum, rice, grapevine, pea

Gathered in one single ensemble

Montpellier Plant Phenotyping Platform (M3P)



PHENO
PSIS

PHENO
ARCH

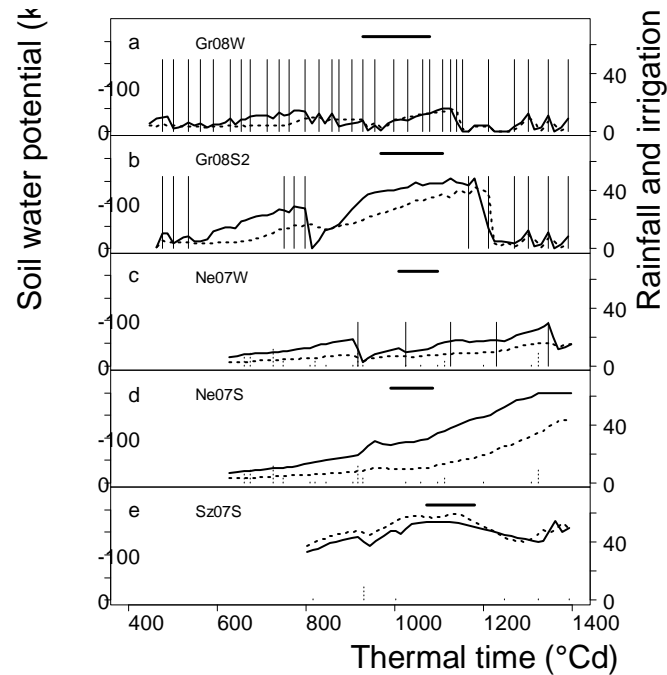
PHENO
DYN

Maize, wheat, rice, canola, grapevine, arabidopsis etc...

Examples of achievements

Validation of platform data in the field

Resiliences in fields and PF parameters correlate well (maize)

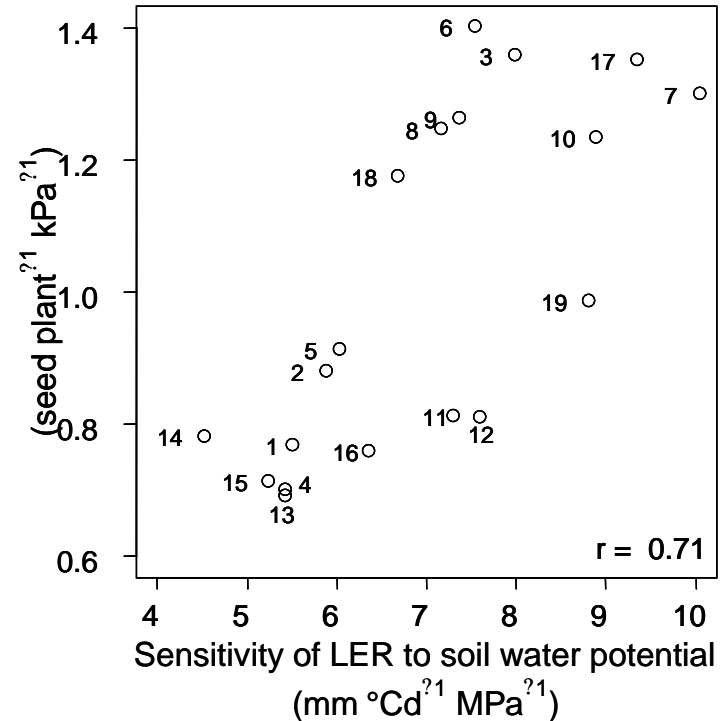


Drought index

19 genotypes

Sensitivity Index

Sensitivity field



Sensitivity platform

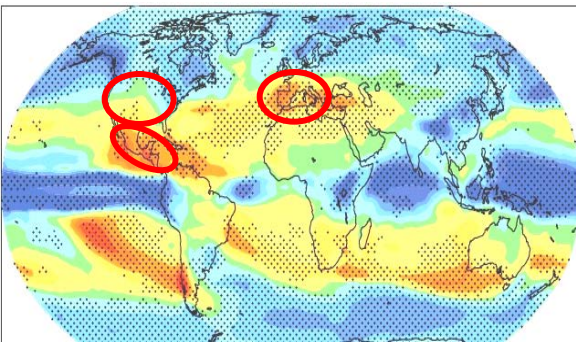
Phenodyn

Chapuis et al , EJA2012 – coll. Limagrain

19 genotypes, 5 scenarios

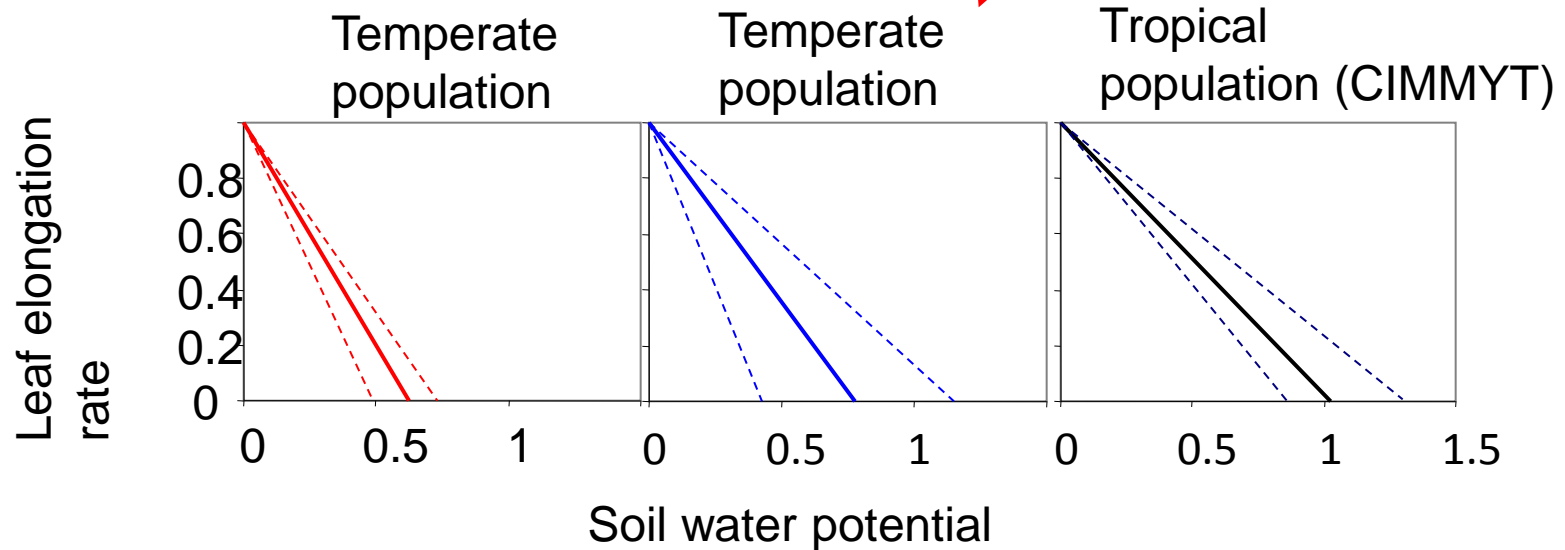
Genetic variation within the species (maize)

Large variability of sensitivities between populations



$$dI/dt = (T - T_0) (a - b \text{VPD}_{la} - c \Psi)$$

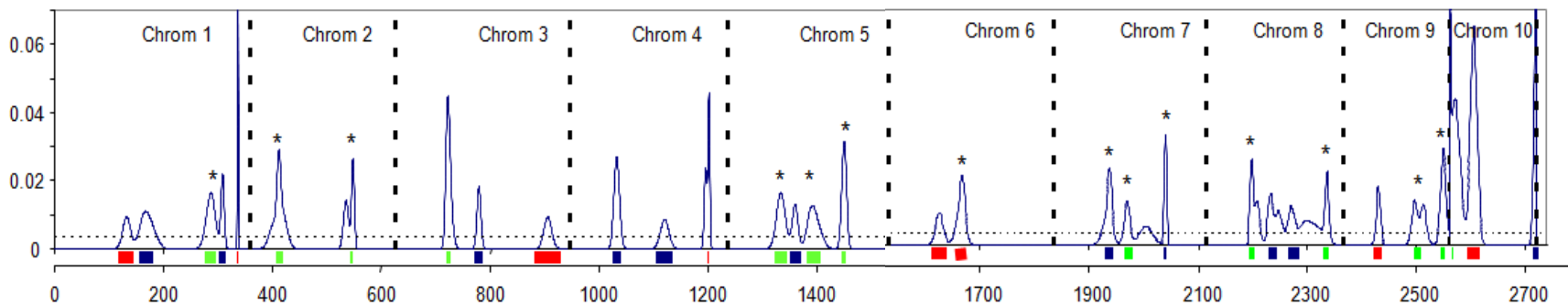
sensitivity to
soil water deficit



Welcker et al. 2012.

Consensus QTLs for model parameters

Meta analysis of consensus regions in tropical + temperate populations



Overview and Meta-analysis of QTL affecting response of growth to water deficit in maize (Welcker et al – in prep)

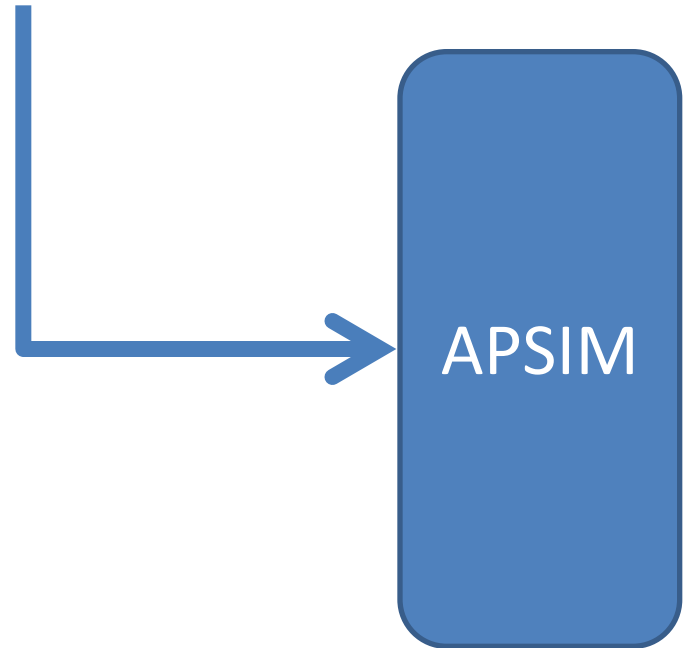
- MQTL Sensitivity to evaporative demand
- MQTL Sensitivity to soil water deficit
- MQTL for both sensitivities

Reymond et al. 2003 Plant phy 114, 893–
Welcker et al. 2007 J. Exp Bot 58, 339–
Sadok et al 2007 PCE30, 135–
Welcker et al 2011, Plant Phy 147

Embarking the model into existing crop models

CSIRO platform APSIM

$$\frac{\Delta L}{\Delta t} = (T - T_b) \cdot \left((\bar{a} + \sum_i \alpha_i QTL_i) - (\bar{b} + \sum_j \beta_j QTL_j) \cdot VPD - (\bar{c} + \sum_k \chi_k QTL_k) \cdot \Psi_w \right) \cdot \frac{1}{T}$$

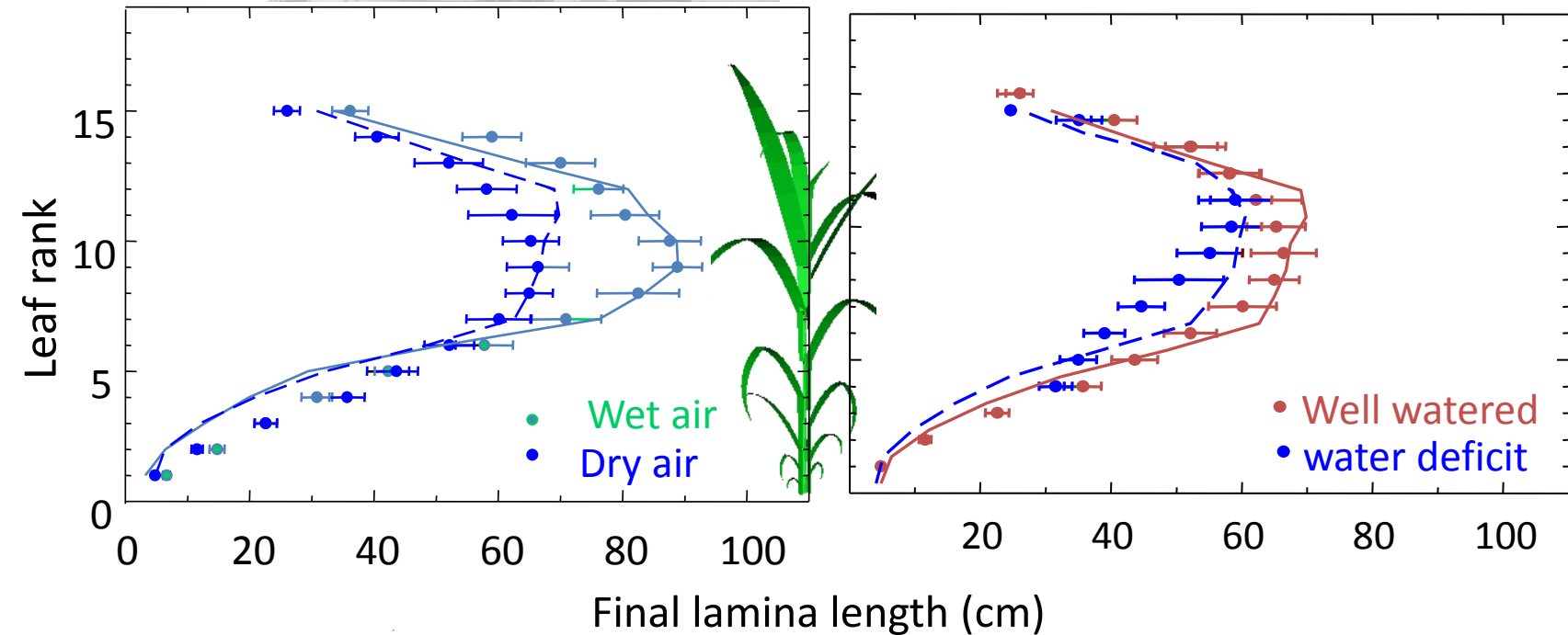


Keating et al 2003. European Journal of Agronomy 18, 267-288.

McCown et al 1995. Mathematics and Computers in Simulation 39, 225-231.

Model validation

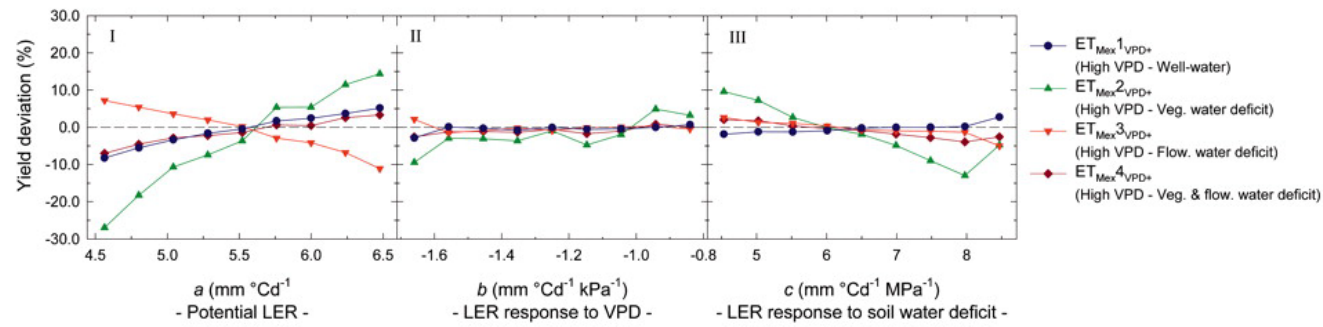
Simulation of leaf surface in the field from model parameters



Observed (symboles) and simulated (lignes) in contrasted field conditions

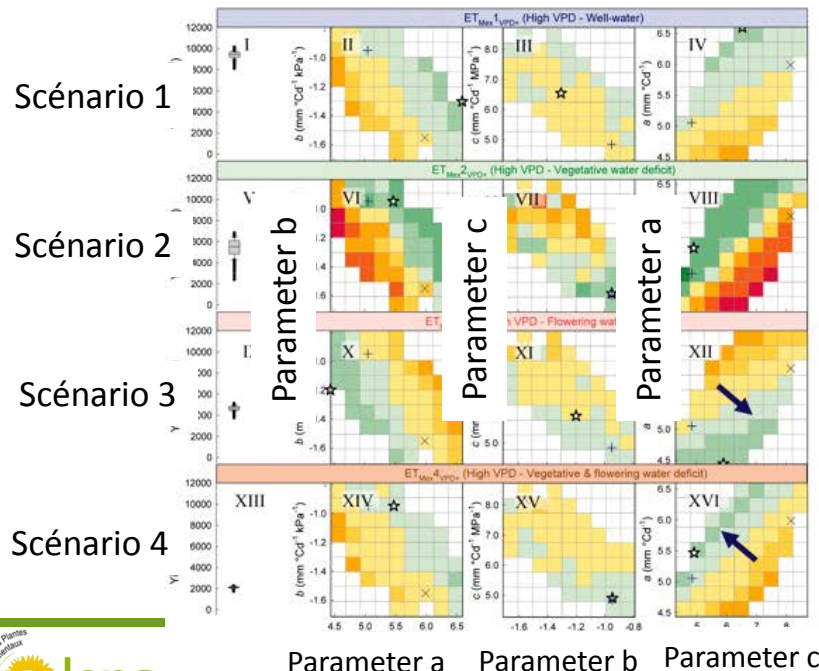
Chenu et al. 2008 Plant Cell Environment

Average effect for single parameters



4 scenarios

Average effect for combination of parameters

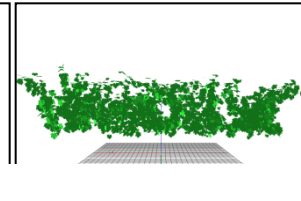
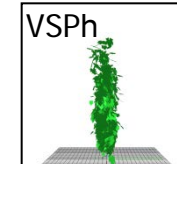
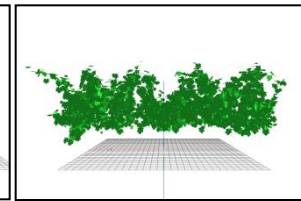
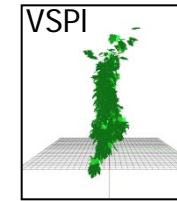
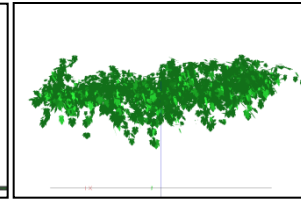
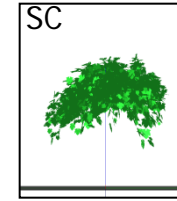
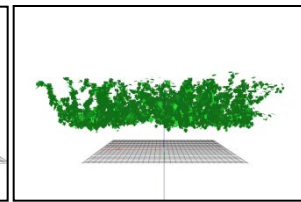
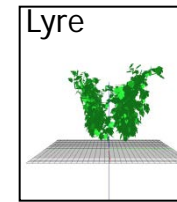
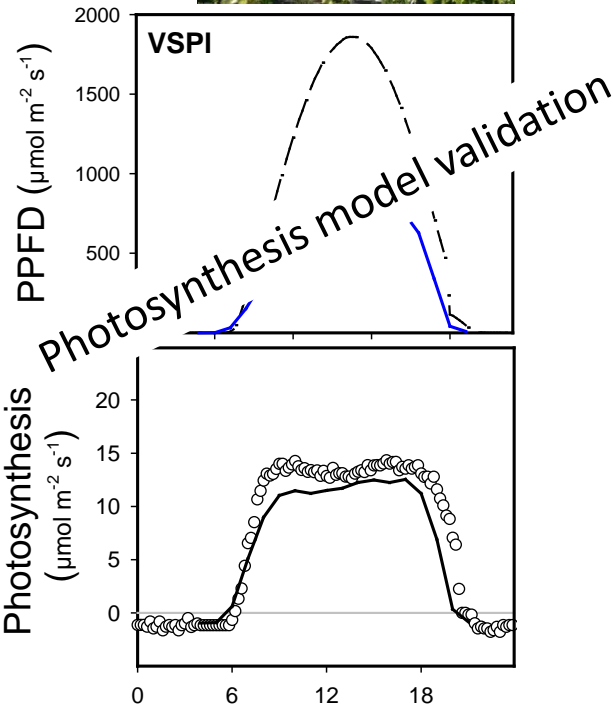


The model predicts the best combinations of alleles depending on the scenarios

Parameter a Parameter b Parameter c

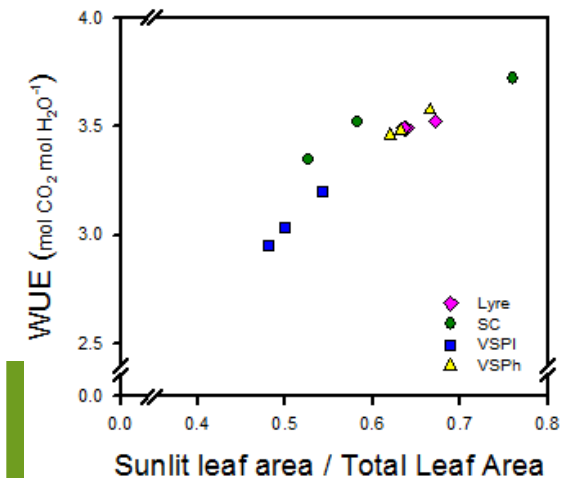


A modeling approach to evaluate various vineyard management practices for Water Use



- Water Use Efficiency is high in Lyra

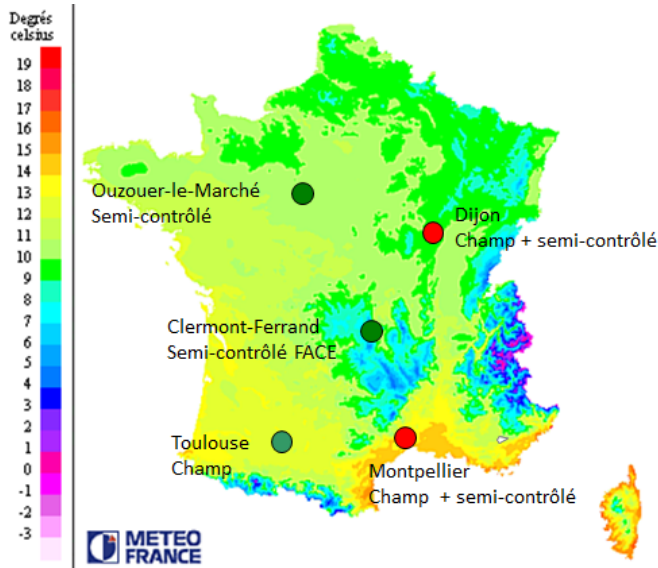
- Water Use Efficiency depends on the % of leaves exposed to light



PHENOME (coord. F Tardieu)

Objectives

- Coordinate a network of hundreds of field plots, along a climatic gradient to host thousands of genotypes
- Disseminate techniques and concepts related to phenotyping
- WP sensing (Fluorescence, hyperspectral, thermal IR thermique + 3D)
- WP Information Systems
- WP data cleaning



5 sites , field and controled conditions

25 M€ funded, 8 years

- same initiatives in Germany, Australia...

- EPPN : already operating

- IPPN

Take-home messages

- ✓ Drought has deleterious effects on plant production and breeding for optimized responses to drought is a key challenge
- ✓ Breeding for drought tolerance is an optimization process that can benefit from modeling approaches
- ✓ Simple models can be used focusing on heritable parameters
- ✓ High throughput phenotyping platforms can help to characterise model parameters for hundreds of genotypes
- ✓ Model assisted smart phenotyping strategy can help to lead breeding programs into the design of climate adapted varieties

maize

grapevine

CSIRO

F Tardieu
C Welker

T Simonneau
E Lebon

G Hammer
K Chenu

M Reymond
W Sadok
B Parent
C Frois
G Dignat
Llorenç Cabrera

J Prieto



Agricultural Model Intercomparison and Improvement Project (AgMIP)

A set of partners to the Agmip project



Adaptation of agriculture and forestry to climate change (INRA META-PROGRAMME)

- ✓ Theme 1. Assessment and management of the medium-term risks and opportunities associated with climate variability and extreme weather;
- ✓ Theme 2. Regionalised and sectoral projections and scenarios of the long-term impacts of climate change;
- ✓ Theme 3. Long-term adaptation options.
- ✓ These themes are each split into four dimensions:
 - observation,
 - experiments and modelling,
 - assessment of costs and benefits,
 - dissemination and innovation.

Joint Programing in Research Agriculture, Food Security and Climate Change



FACCEJPI

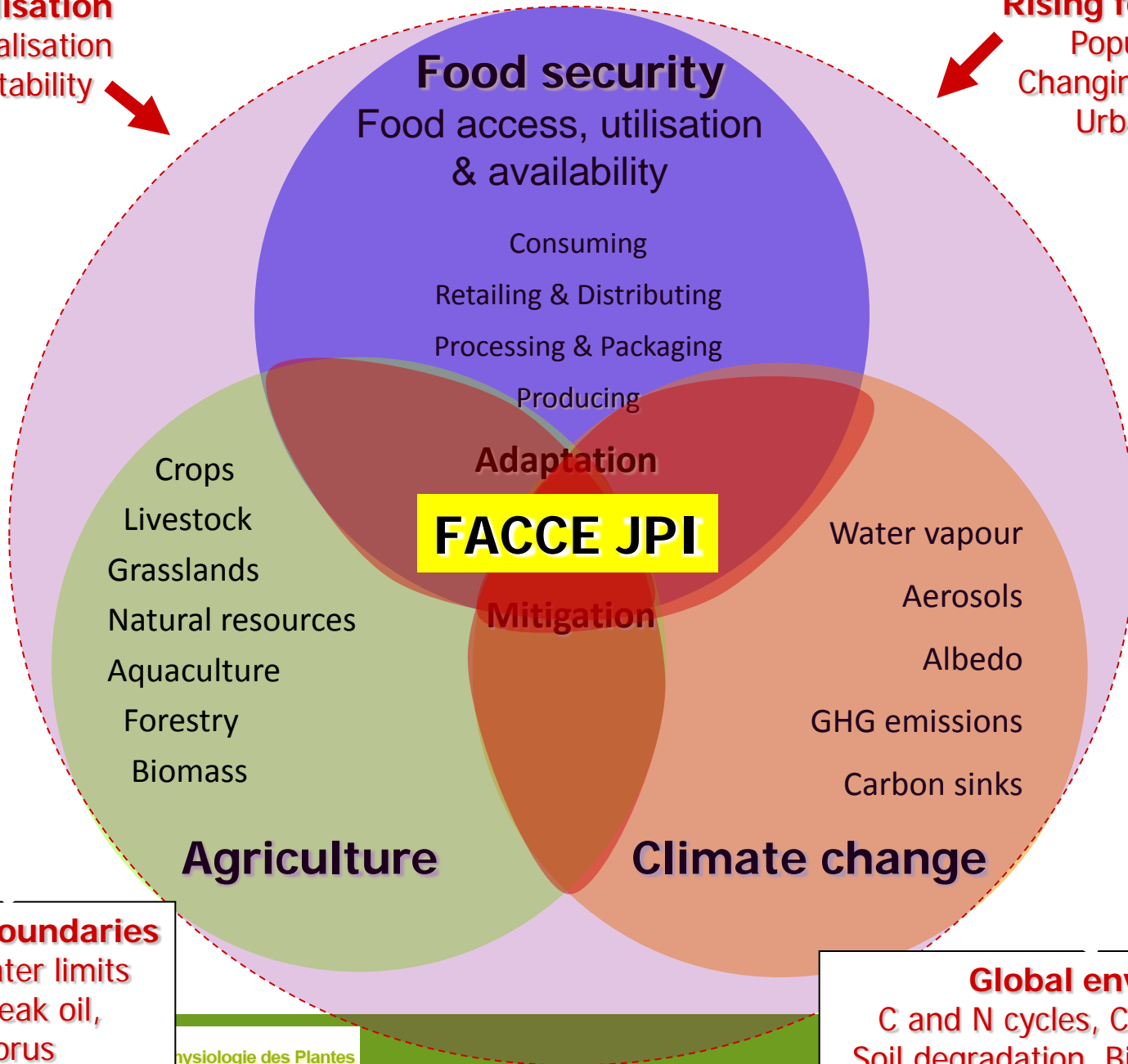
www.faccejpi.com



Agriculture Food Security and Climate Change

Globalisation
Liberalisation
Market instability

Rising food demand
Population rise
Changing food habits
Urbanisation



Planetary boundaries
Land & water limits
GHG limits, Peak oil,
Peak phosphorus

Global environ. Change
C and N cycles, Contaminants
Soil degradation, Biodiversity loss