Bottom-up and top-down approaches – The value of modelling in trait dissection and phenotypic prediction

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CSIRO, Australia

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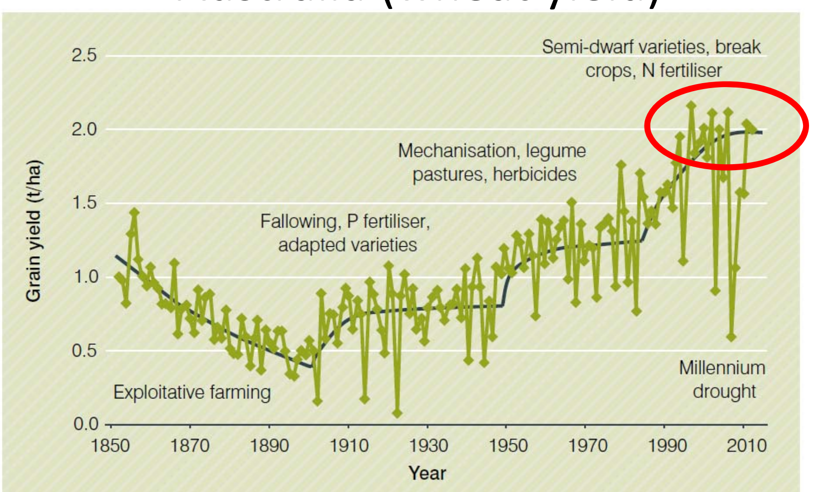
A major challenge

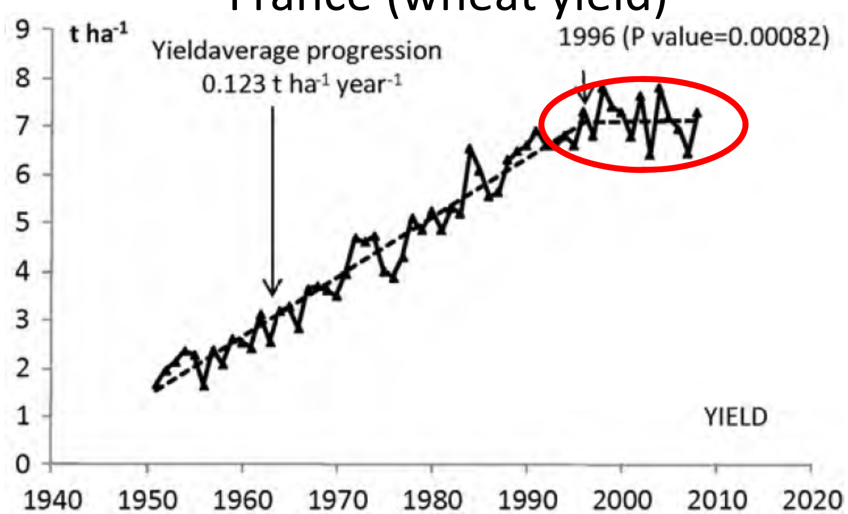
- By 2050: global population rising to 9 Billion, with changes in diet

⇒ Increase of world demand for crops by 70-100%
⇒ Major challenge for agriculture
Need to increase wheat yield from < 1% (current level) to > 1.7% per year

Australia (wheat yield)



France (wheat yield)



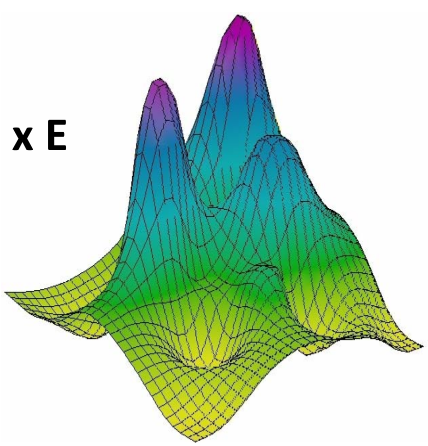
Fischer Byerlee and Edmeades (2014) Crop yields and global food security. ACIAR, Canberra
Brisson, Gate, Gouache, Charmet, Oury and Huard (2010) Field Crops Research 119:201-212.
http://www.wheatinitiative.org/about/objectives

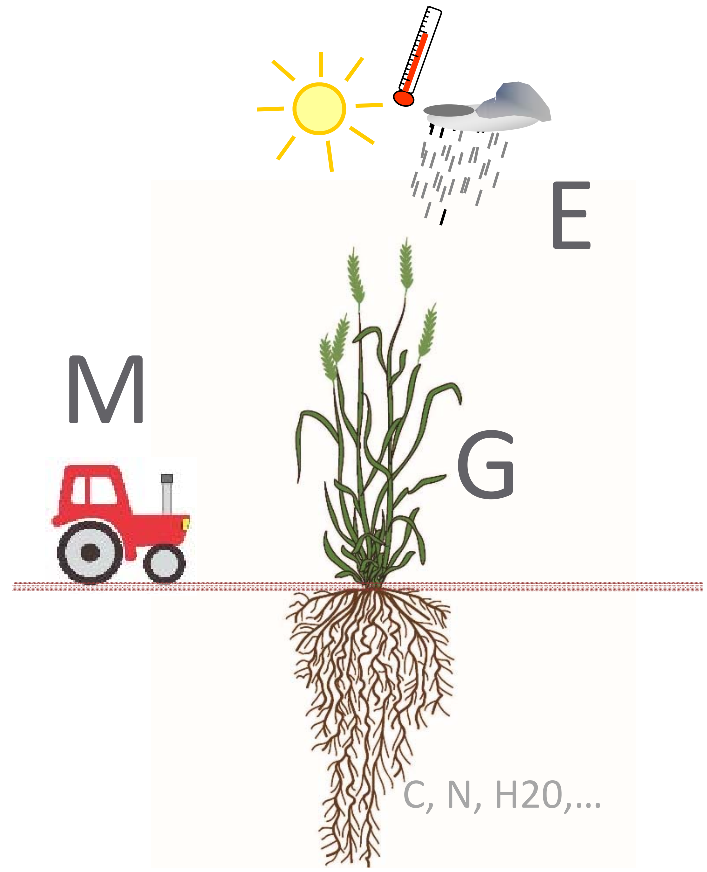
A major challenge

- Need to increase yield progress in diverse set of environments

- Complexity of the problem: Progress in crop improvement is limited by the ability to **identify favourable combinations** of **genotypes** (G) and **management** practices (M) in the target population of **environments** (E) given the resources available to search among possible combinations.

G x M x E





Hammer, Cooper, Tardieu, Welch, Walsh, van Eeuwijk, Chapman and Podlich (2006) Trends in Plant Science 11:587-593.

Modelling G x E x M interactions

- Dissect complex traits (stable relationships across G, E, M)

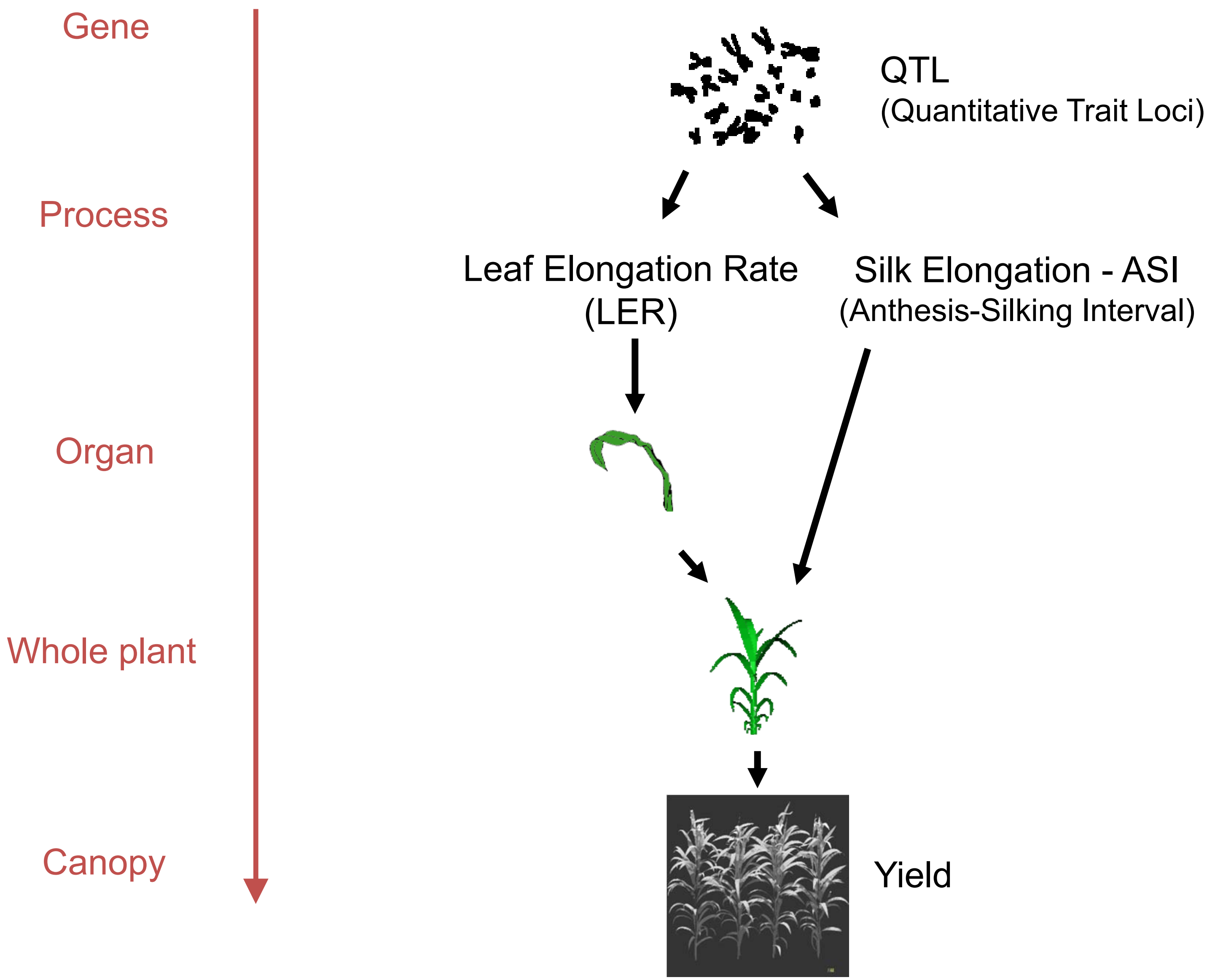
- Scale-up component traits (integration of G x E x M)

- Assess the value of traits in complex environments
  (simulations of G x E x M)

Part I – Multi-scale approach

Dissecting complex traits to work with stable relationships up to the crop level

A gene-to-phenotype modelling approach



A gene-to-phenotype modelling approach

Gene

Process

Organ

Whole plant

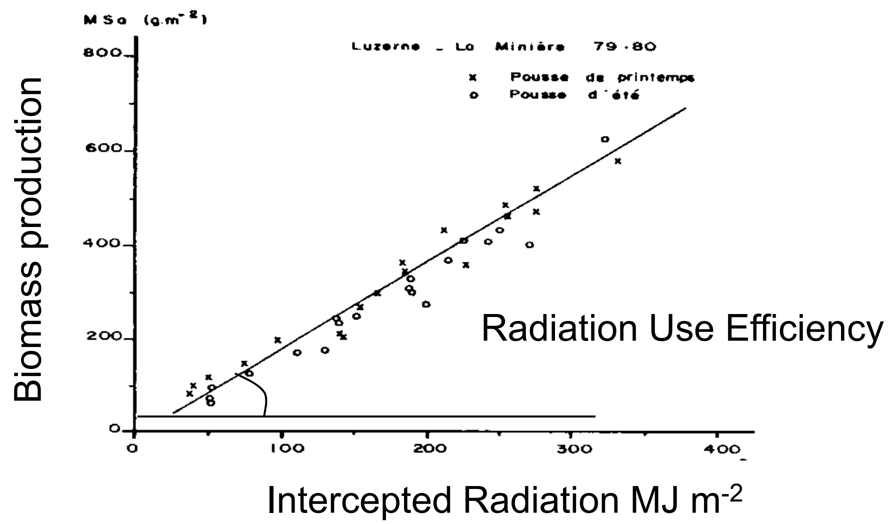
Canopy

QTL
(Quantitative Trait Loci)

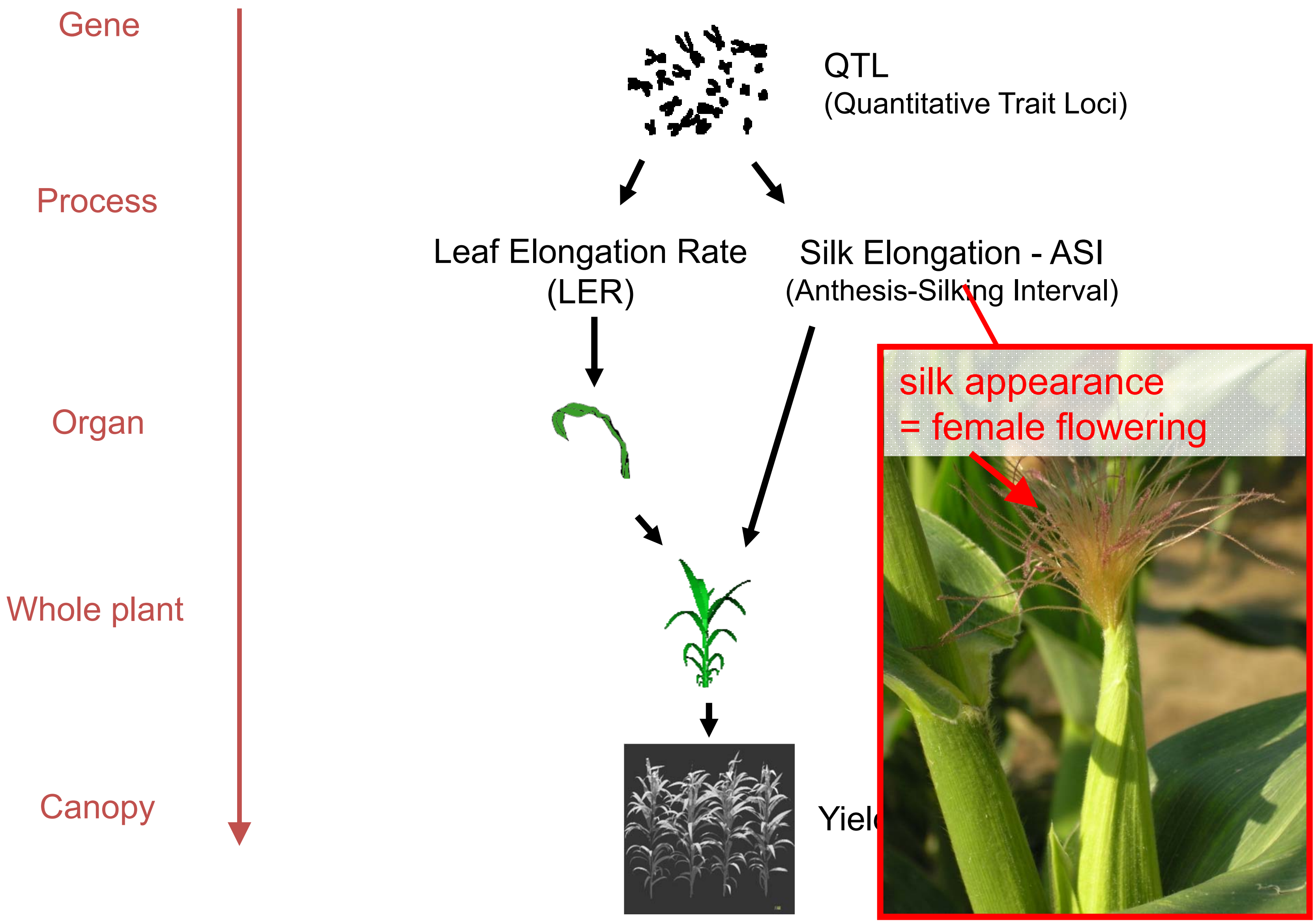
Leaf Elongation Rate
(LER)

Silk Elongation - ASI
(Anthesis-Silking Interval)

Leaf growth for light interception



A gene-to-phenotype modelling approach



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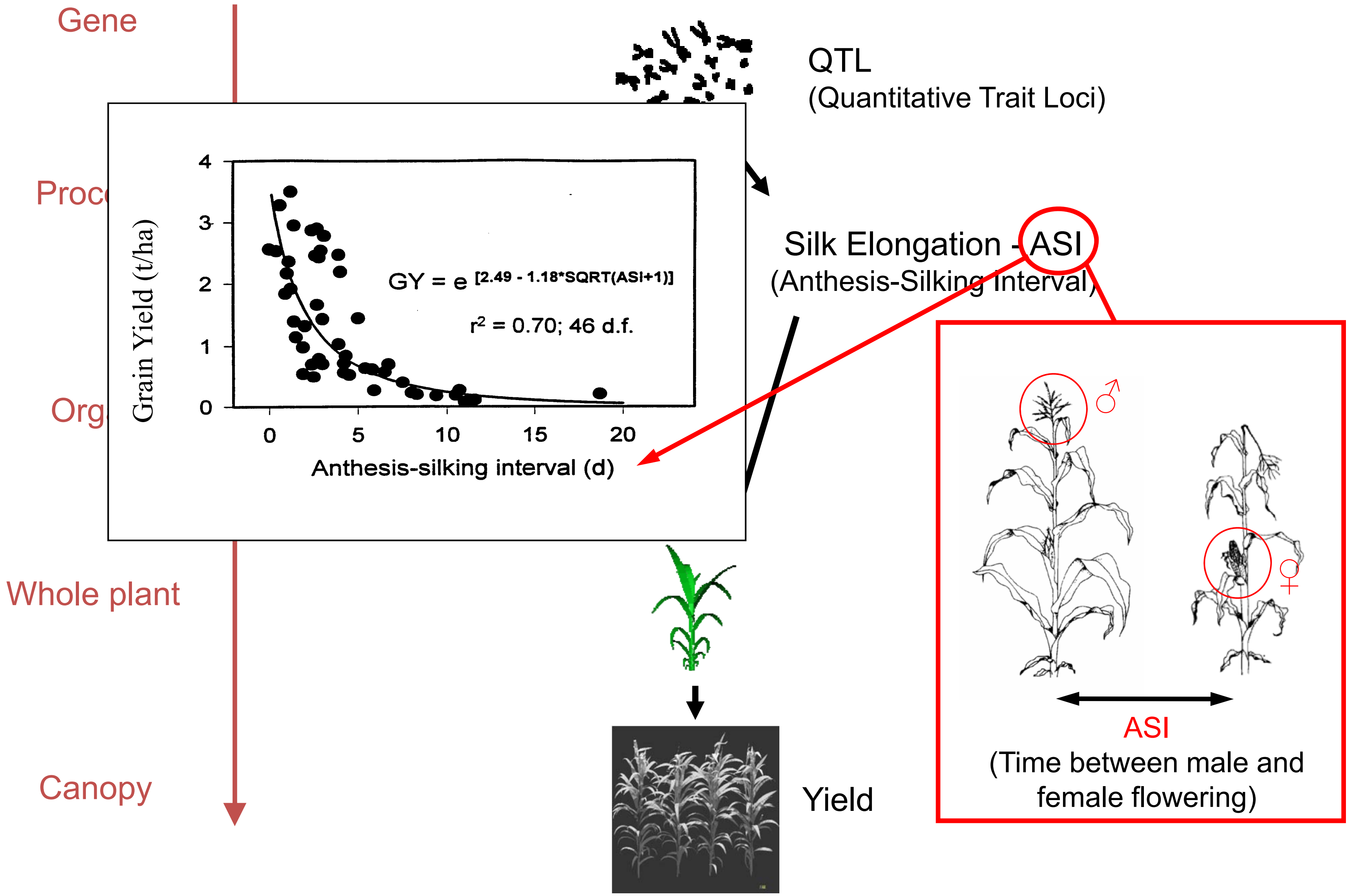

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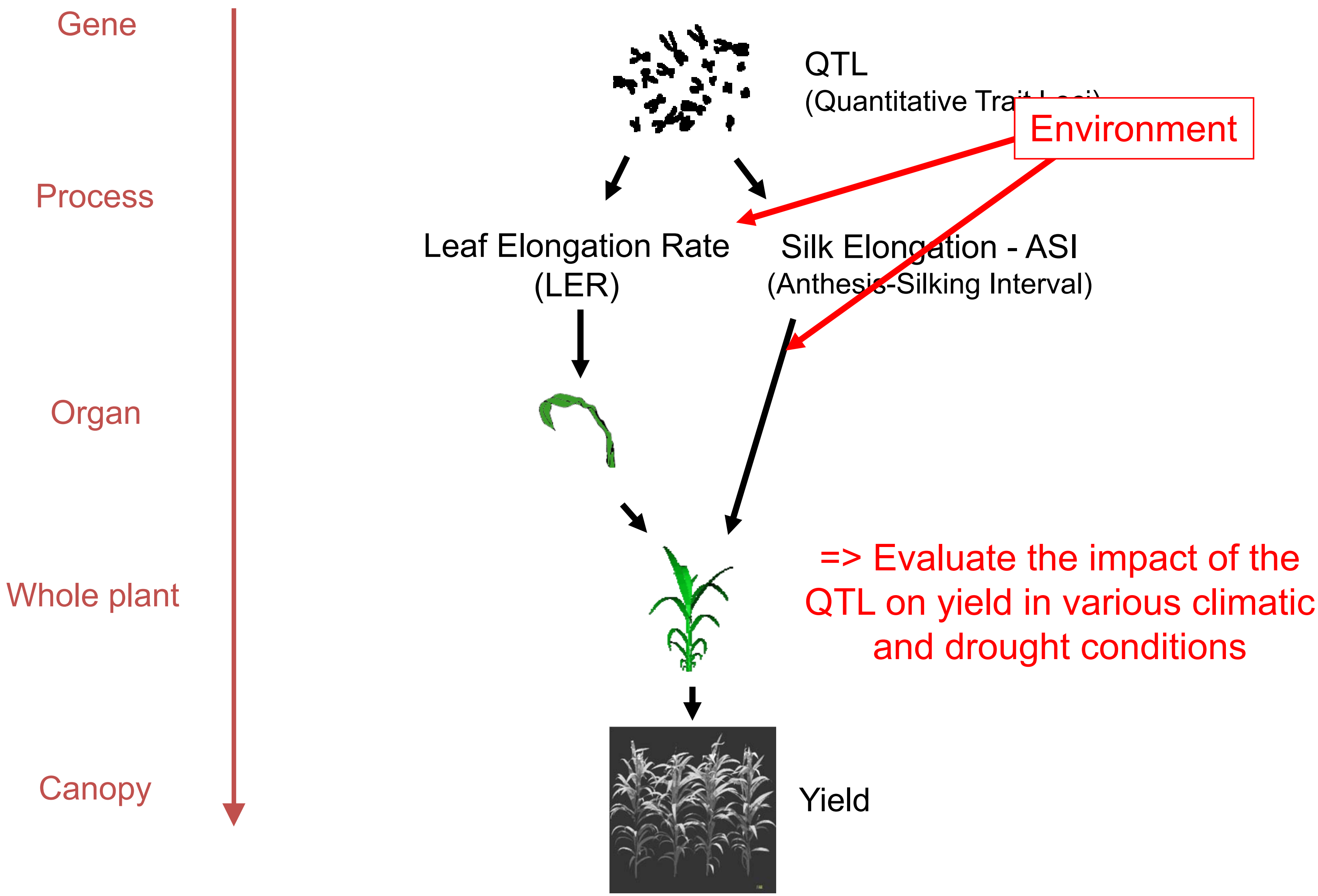
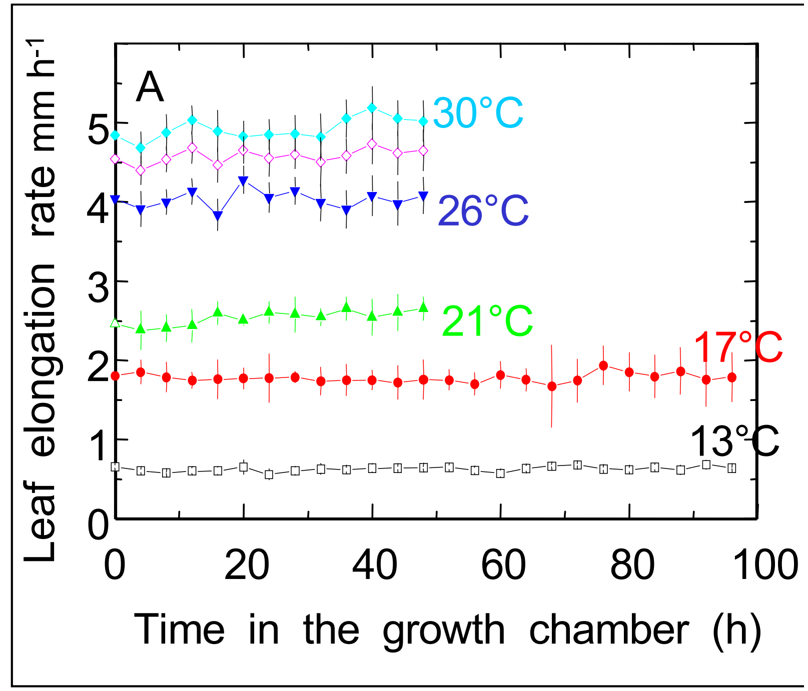


Leaf expansion in Maize

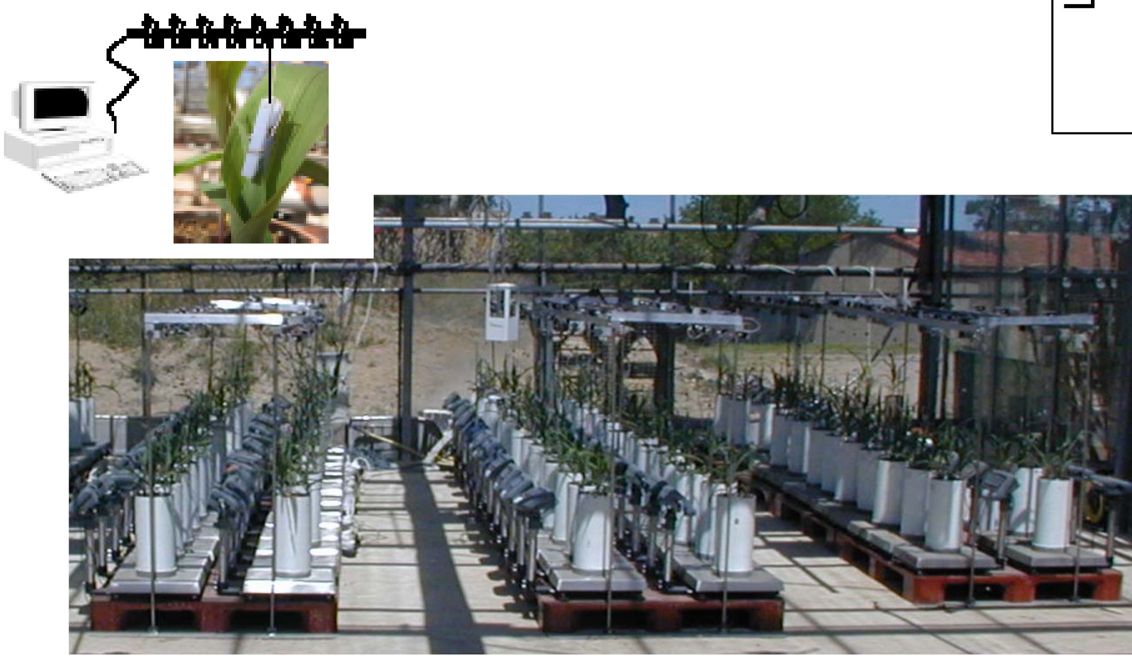
Monocot : period of linear expansion

Possibility to follow leaf expansion rate with a 15 minutes definition

Experimental set-up for 360 plants together

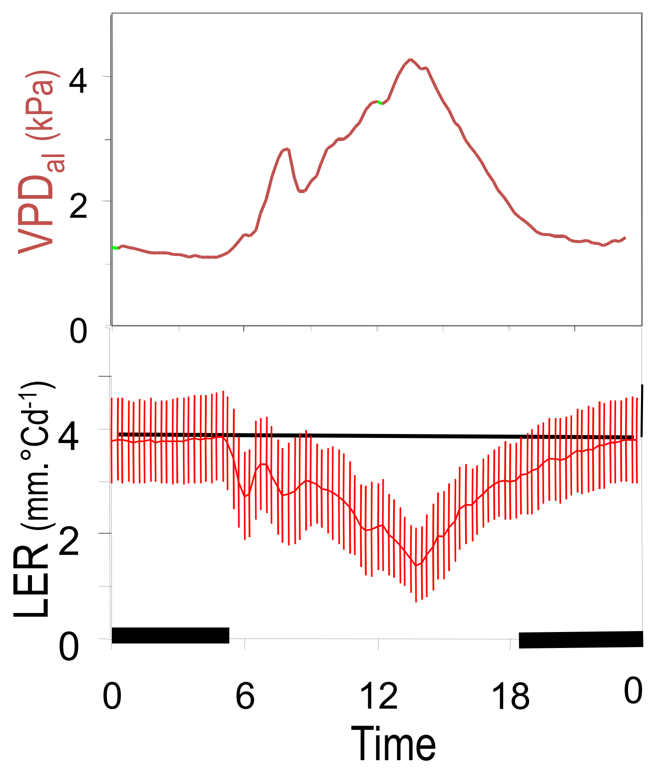


Ben Haj Salah & Tardieu 1995



Leaf expansion in Maize under drought conditions

- Instantaneous response of leaf expansion to an environmental stress



Sadok et al. submitted

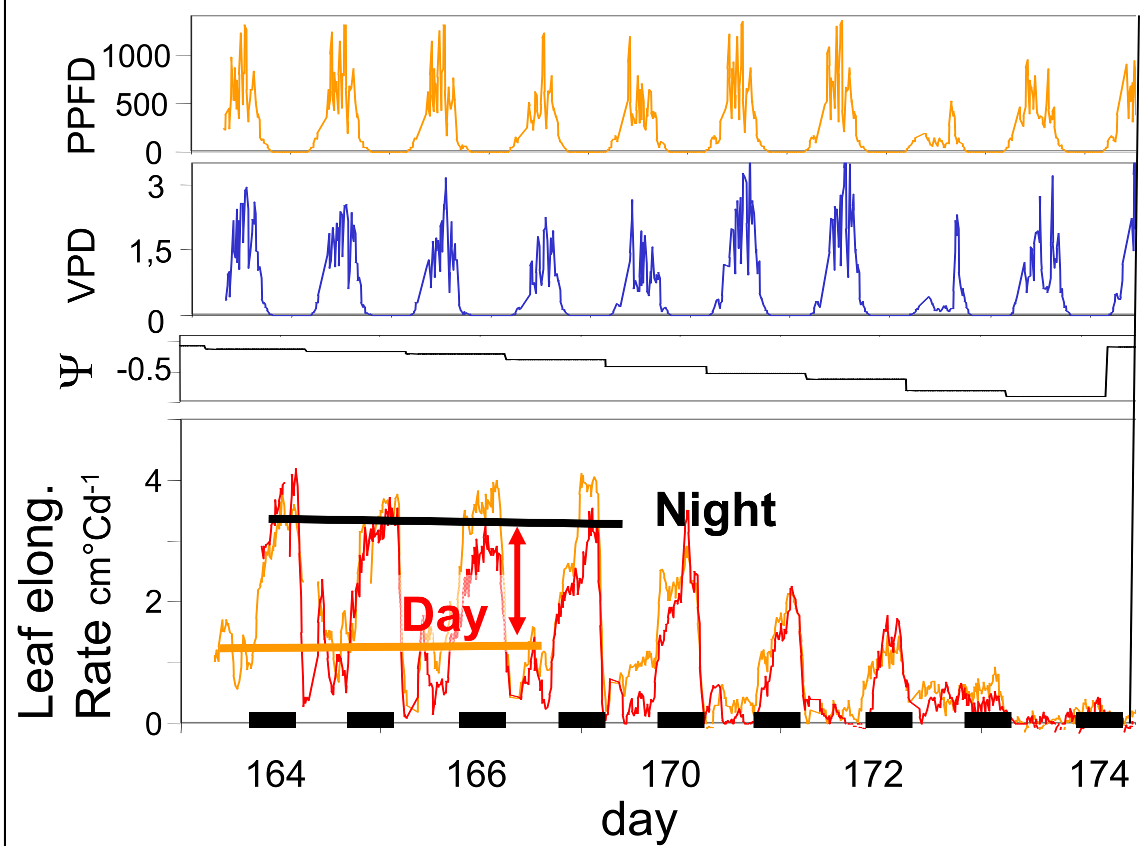
Leaf expansion in Maize under drought conditions

- Instantaneous response of leaf expansion to an environmental stress

- Under water deficit, the LER time course is accounted by 2 major stress :

. evaporative demand (VPD)
only during day time

$LER = (T-T_0)\ (a - bVPD_{fac})$



Leaf elongation rate for a 10-d period

Leaf expansion in Maize under drought conditions

- Instantaneous response of leaf expansion to an environmental stress

- Under water deficit, the LER time course is accounted by 2 major stress :

. evaporative demand (VPD)
only during day time

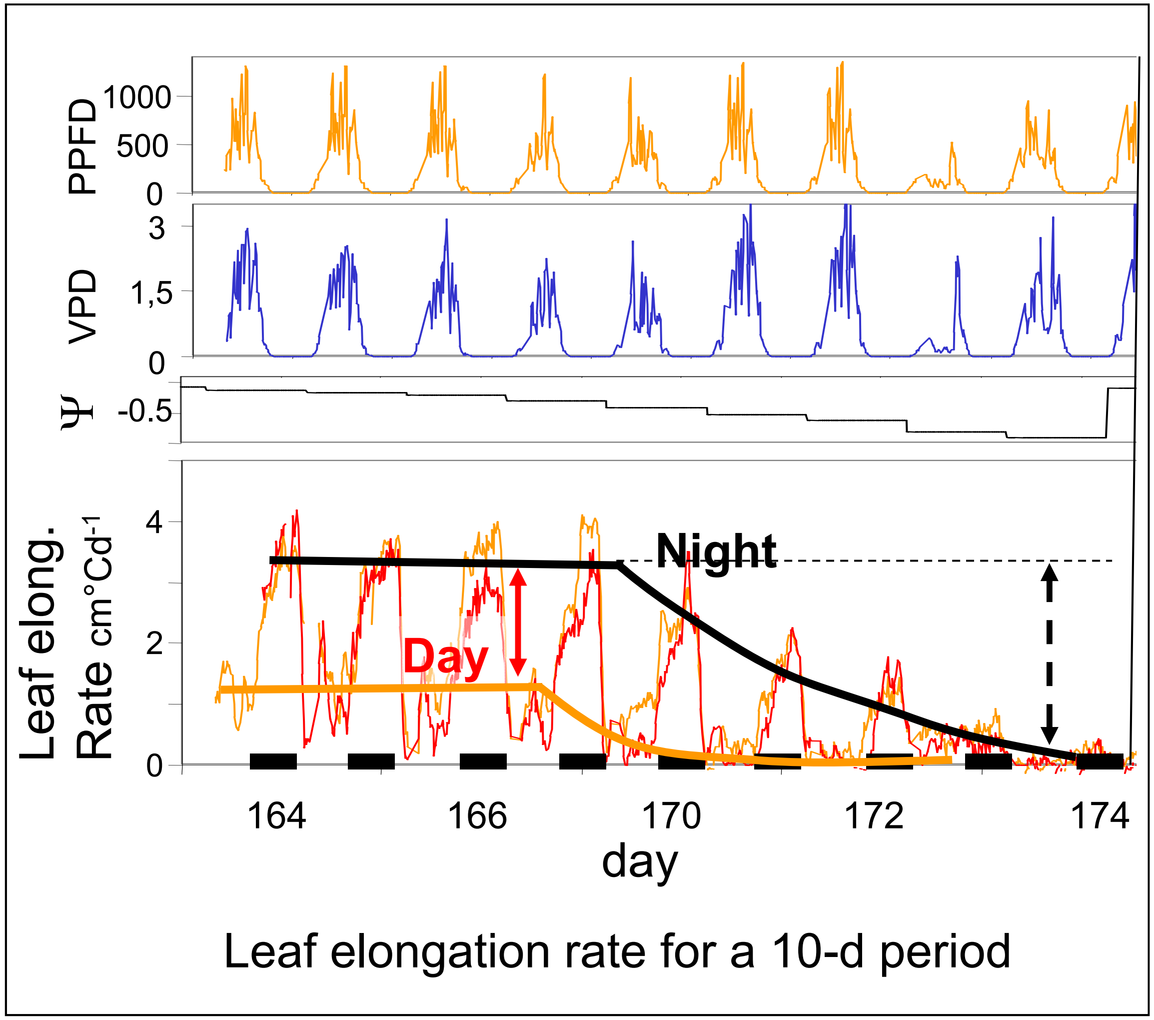
$$LER = (T-T_0)\ (a - bVPD_{fac})$$

. leaf predawn potential (ψ)
Decline of night values

$$LER = (T-T_0)\ (a - c\ \Psi)$$

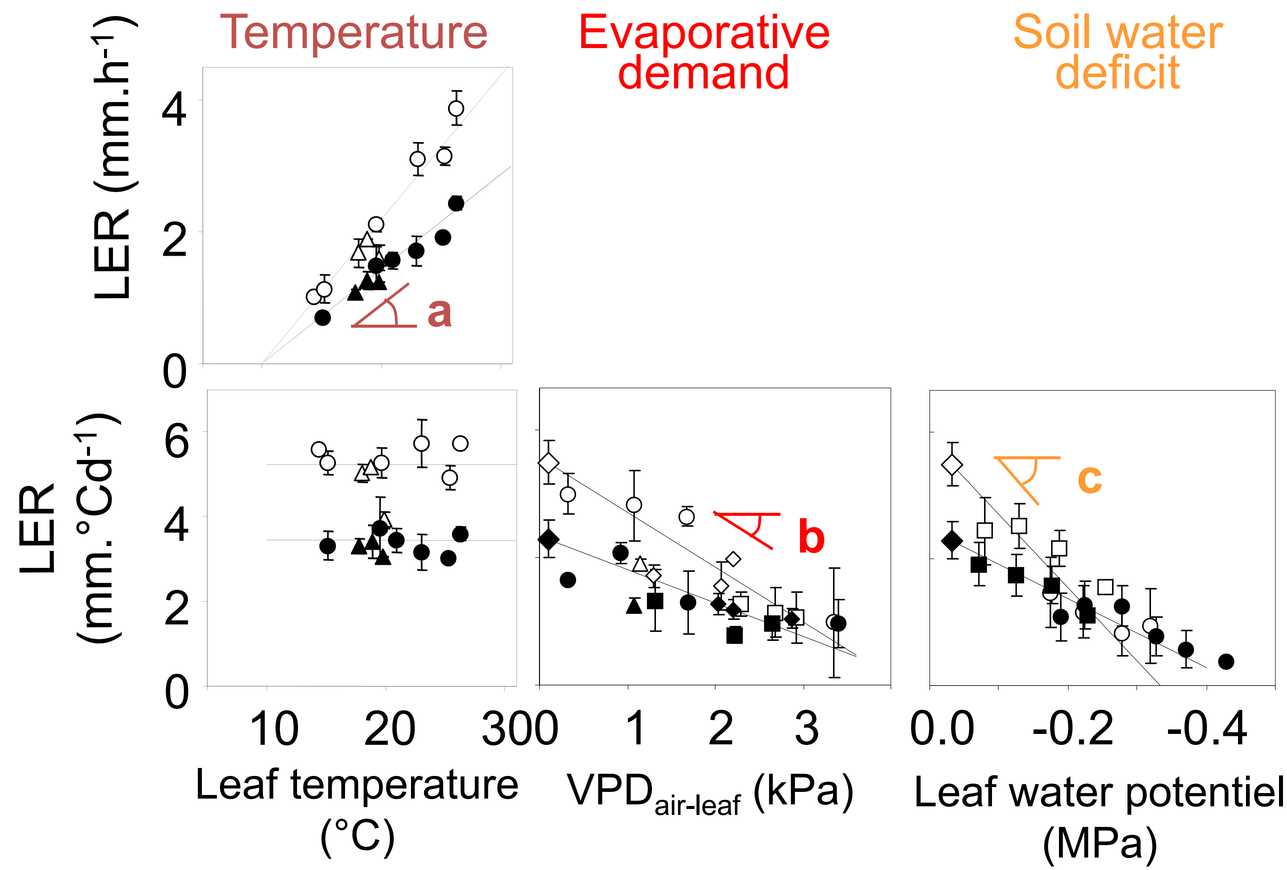
Time course modelled by the sum

$$LER = (T-T_0)\ (a - bVPD_{fa}\ -c\ \Psi)$$



Leaf elongation rate for a 10-d period

Leaf expansion in Maize under drought conditions
Response to temperature and soil and air water deficits

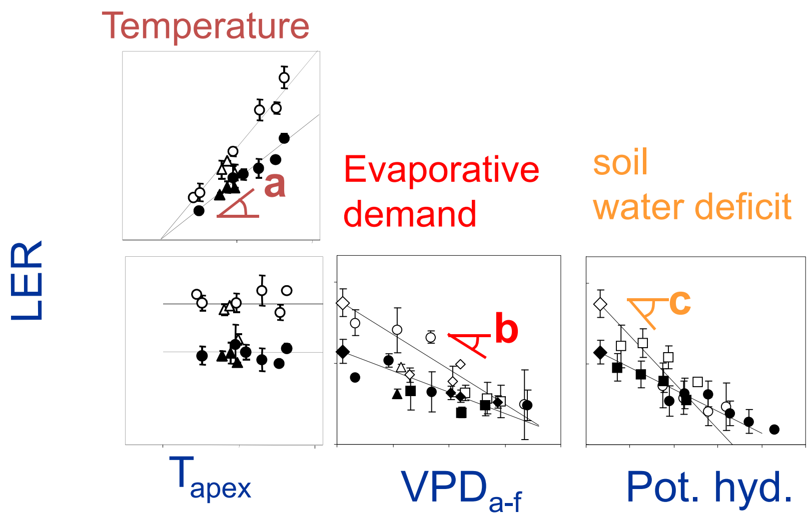


$$LER = dl/dt = (T-T_0)(a + b\ VPD_{air\text{-}leaf} + c\ \Psi)$$

1 genotype → 1 set of parameters of response curves (parameter 'indep.' of env.)

Reymond et al. 2003 Plant Phy

Modelling the effects of the genetic variability – Example: Leaf expansion rate in maize

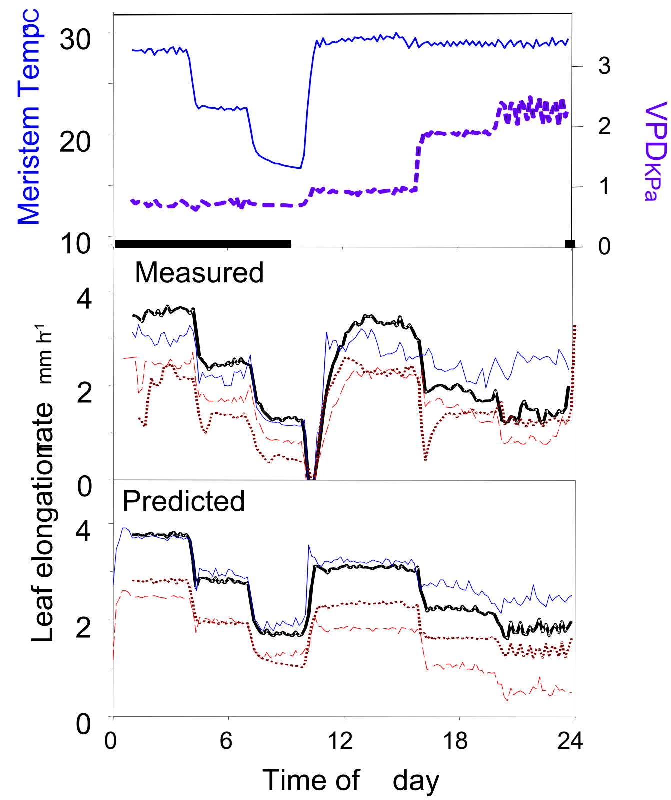


$$LER = dl/dt = (T-T_0)(a + b\ VPD_{air\text{-}feuille} + c\ \Psi)$$

$$a = \bar{a} + \Sigma\ \alpha\ QTL$$

$$b = \bar{b} + \Sigma\ \beta\ QTL$$

$$c = \bar{c} + \Sigma\ \gamma\ QTL$$

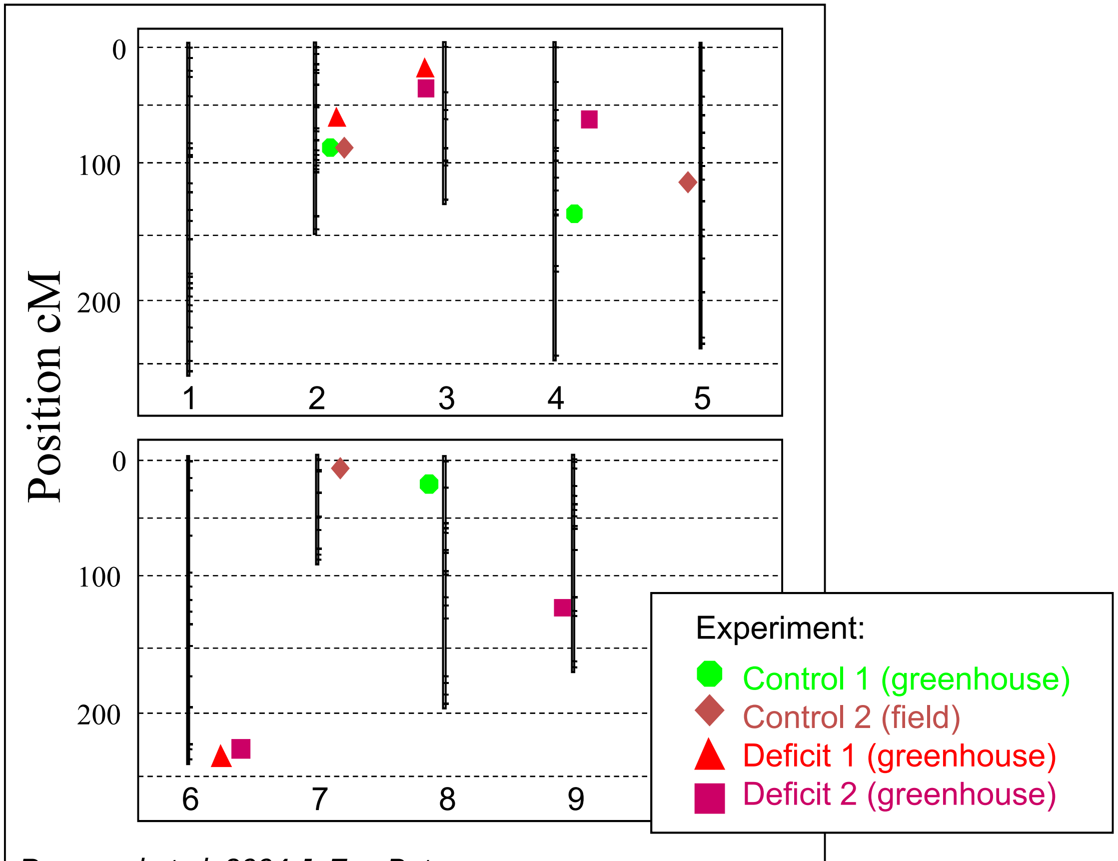


1 genotype → 1 set of parameters of response curves (parameter 'indep.' of env.)

Reymond et al. 2003 *Plant Physiology* **131**:664-675.

Leaf expansion in maize under drought conditions
QTL related to environment responses

QTLs of leaf length

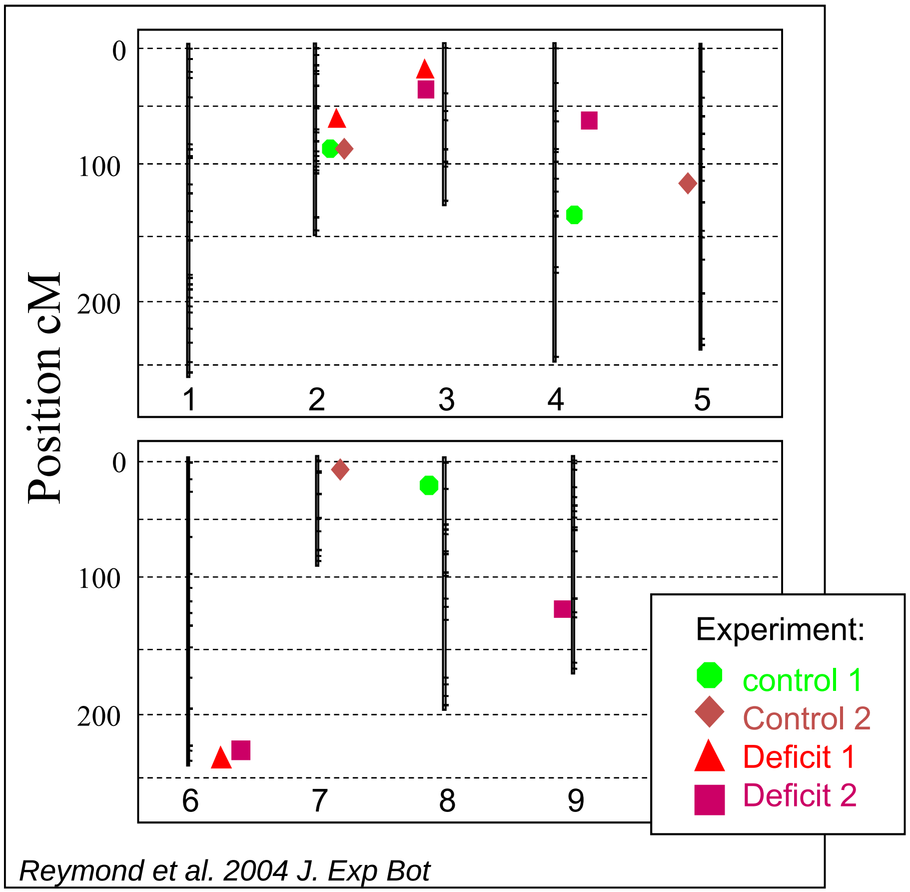


Reymond et al. 2004 J. Exp Bot

QTLs of leaf length were not stable among experiments

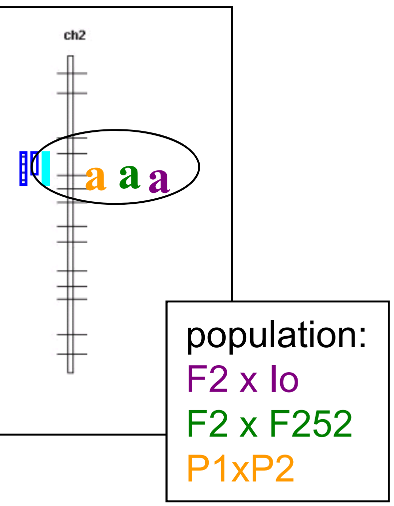
Leaf expansion in maize under drought conditions
QTL related to environment responses

QTLs of leaf length



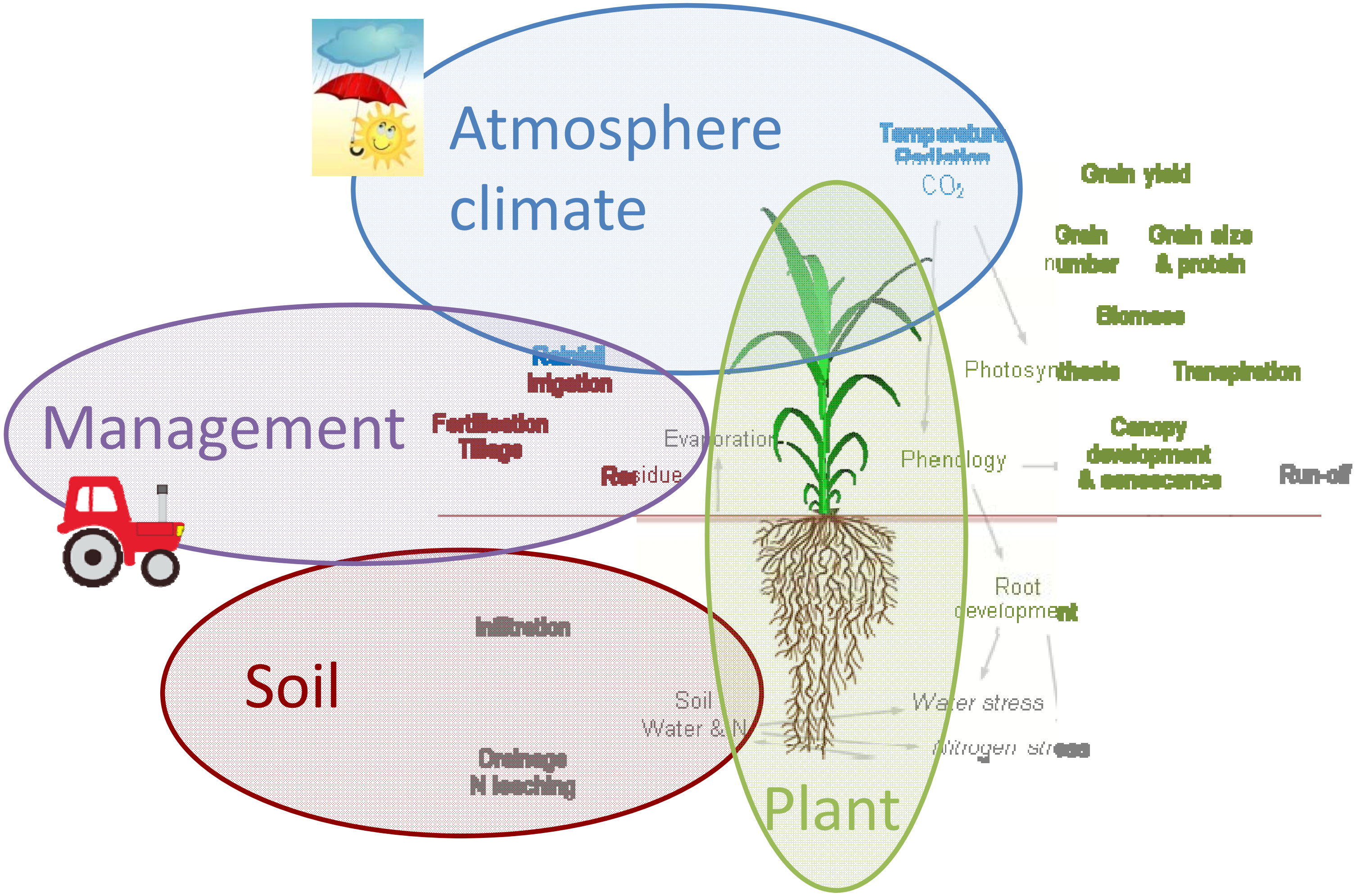
QTLs of leaf length were not stable among experiments

QTLs of maximum elongation rate (response to temperature)



A QTL co-location for slope *a* in three populations

Maize crop model – APSIM



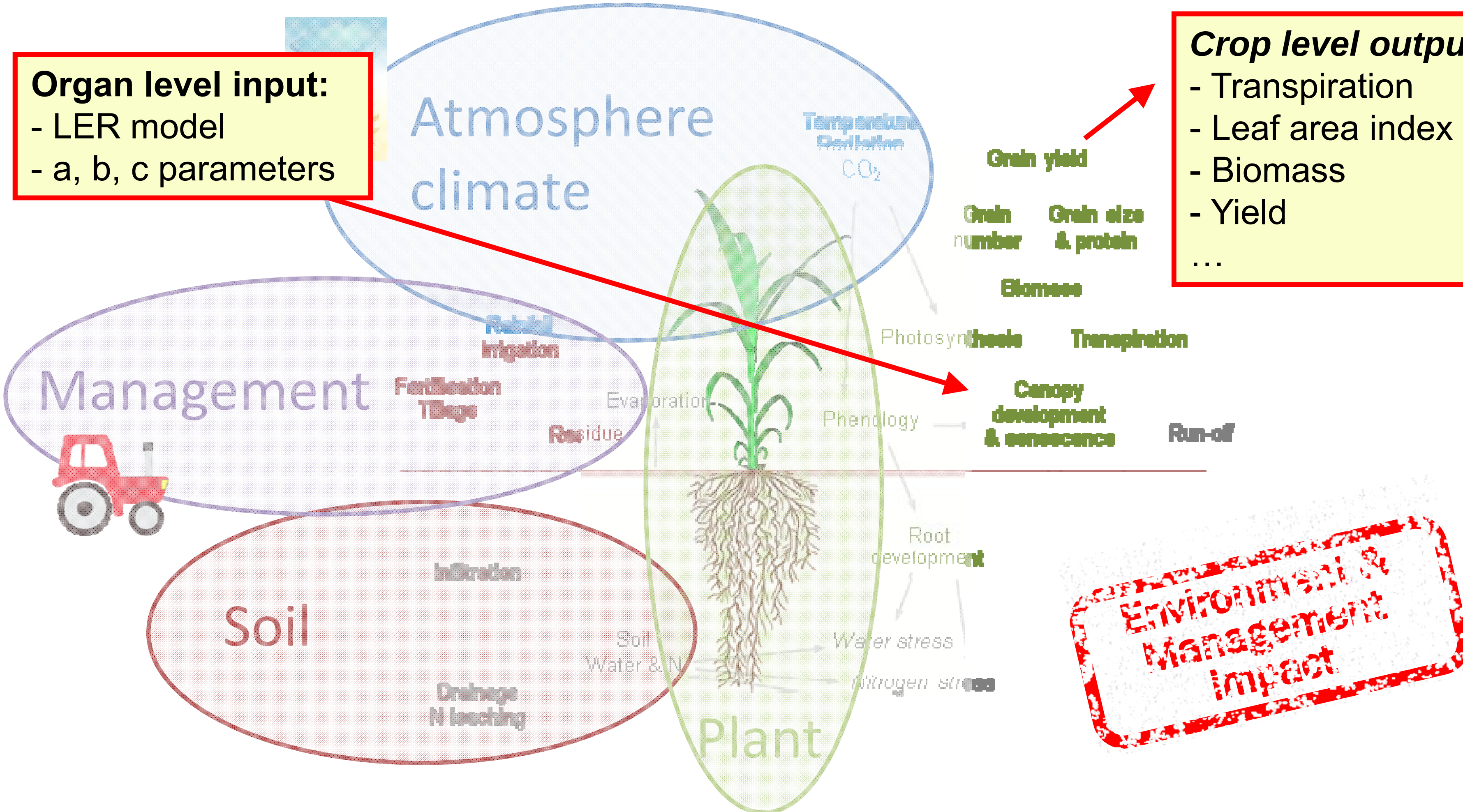
Chenu, Porter, Martre, Basso, Chapman, Ewert, Bindi, Asseng. Contribution of crop models to adaptation in wheat. Invited for submission in *Trends in Plant Science*

Holzworth, Huth, deVoil, Zurcher, Herrmann, McLean, Chenu, et al. (2014) APSIM – Evolution towards a new generation of agricultural systems simulation. *Environmental Modelling & Software* 62:327-350.

Multi-scale model - Integration of G x E x M interactions

Organ level input:
- LER model
- a, b, c parameters

Crop level output:
- Transpiration
- Leaf area index
- Biomass
- Yield
…



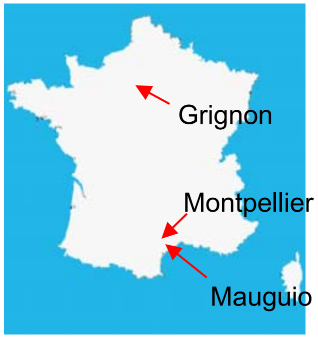
Integration of leaf model into APSIM crop model

Chenu et al (2008) PCE 31:378-391.

Test of the model

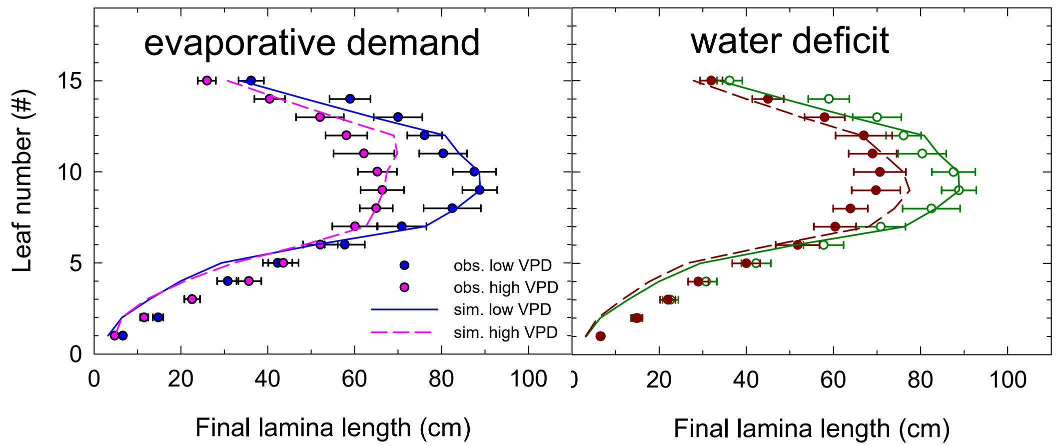
Exp.	Location	Sowing date	Treatment	Radiation	Rain	Temperature	$VPD_{air-meristem}$
				($MJ\ m^{-2}$)	(mm)	(°C)	(kPa)
GR92ap	Grignon, North of France	April 27,1992	control	21.1	62	15.6	1.098
GR92ap	Grignon, North of France	April 27,1992	water deficit	21.1	0	15.6	1.111
MP94jl	Montpellier, South of France	July 19, 1994	control	20.7	30	24.8	2.551
MP94jl	Montpellier, South of France	July 19, 1994	water deficit	20.7	30	24.8	2.66
MP95ma	Montpellier, South of France	May 16, 1995	control	22.7	39	20	1.49
MP95jn	Montpellier, South of France	June 20, 1995	control	23.9	13	24	1.95
MP95jn	Montpellier, South of France	June 20, 1995	water deficit	23.9	13	24	2.054
MP95jl	Montpellier, South of France	July 10, 1995	control	21.6	88	24.7	2.066
MP95jl	Montpellier, South of France	July 10, 1995	water deficit	21.6	88	24.7	2.086
MA97ma	Mauguio, South of France	May 14, 1997	control	19.1	151	19.5	1.359
MA97jn	Mauguio, South of France	June 18, 1997	control	21.3	65	22	1.596
MA98ma	Mauguio, South of France	May 20, 1998	control	23	47	21.1	1.7

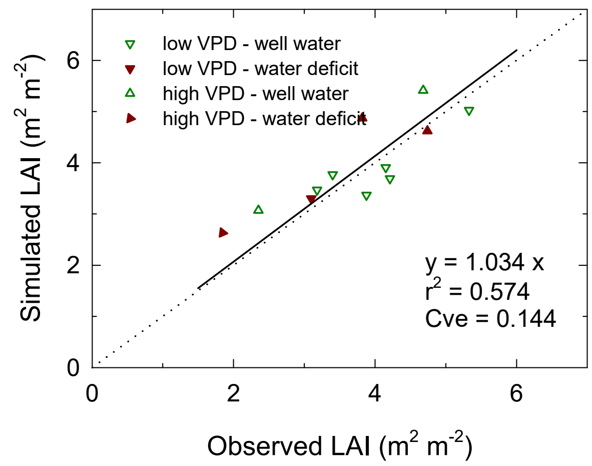
- 1 situation => Parametrisation of the model
- 11 situations => Test of the model



Chenu et al. PCE 2008

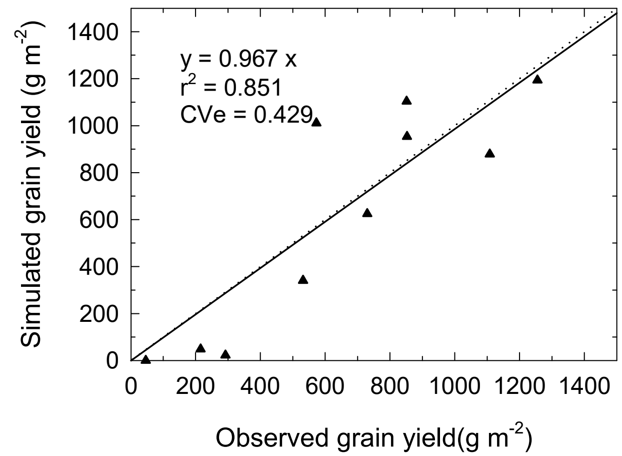
Test of the model





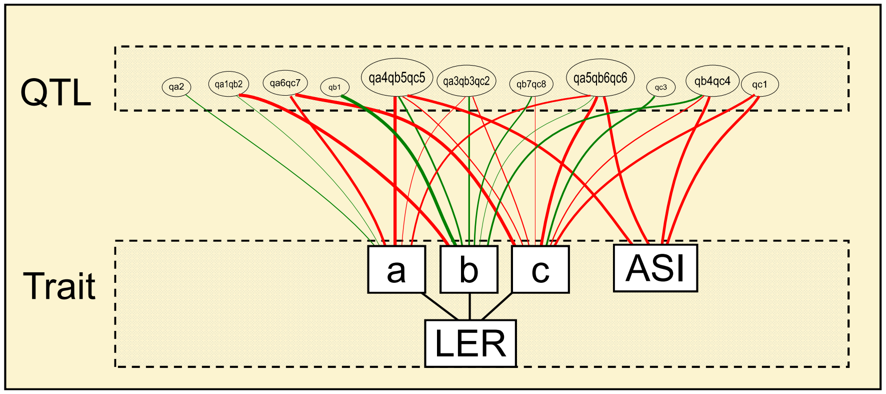
Accurate predictions
of leaf elongation, LAI and yield
in contrasting climatic and drought conditions
(12 field conditions)

=> Capacity to simulate G x E
for leaf area & yield
=> G-to-P prediction

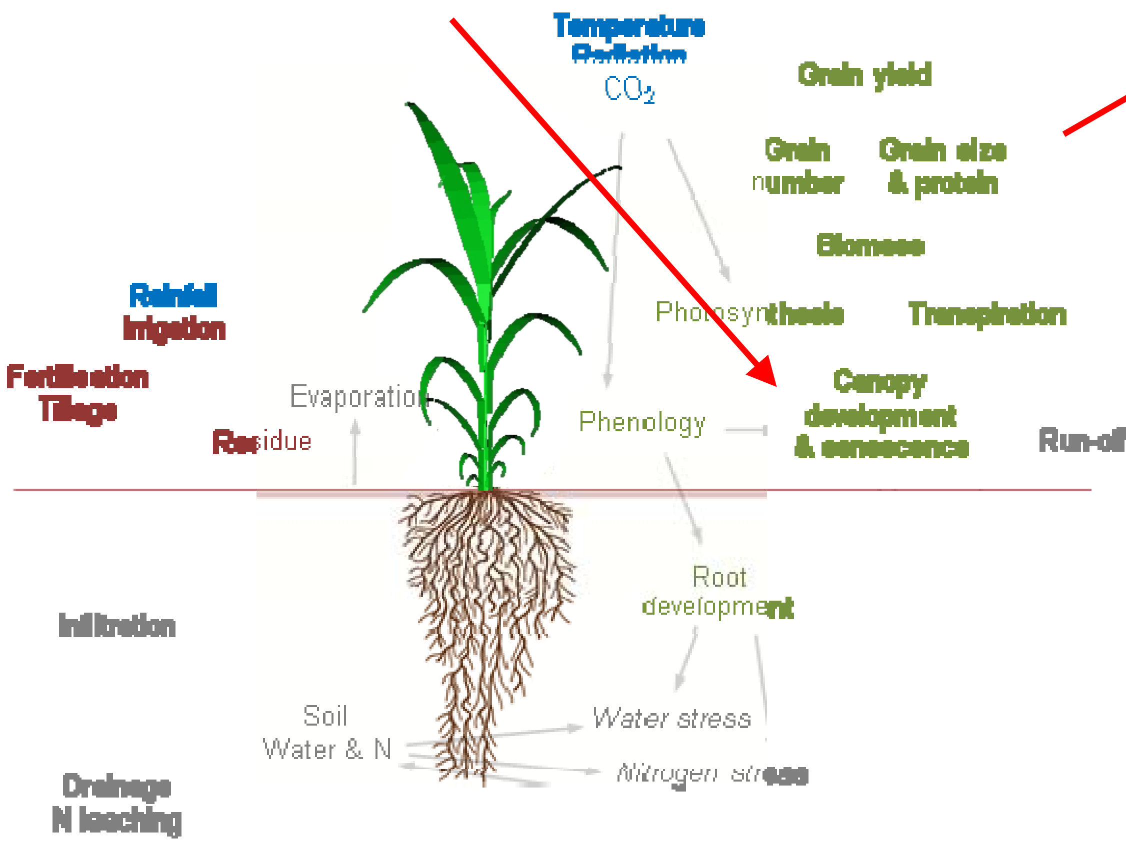


Chenu et al. PCE 2008

QTL network

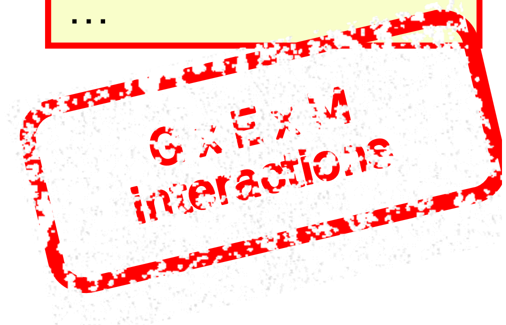


Welcker et al. J. Exp. Bot. 2007



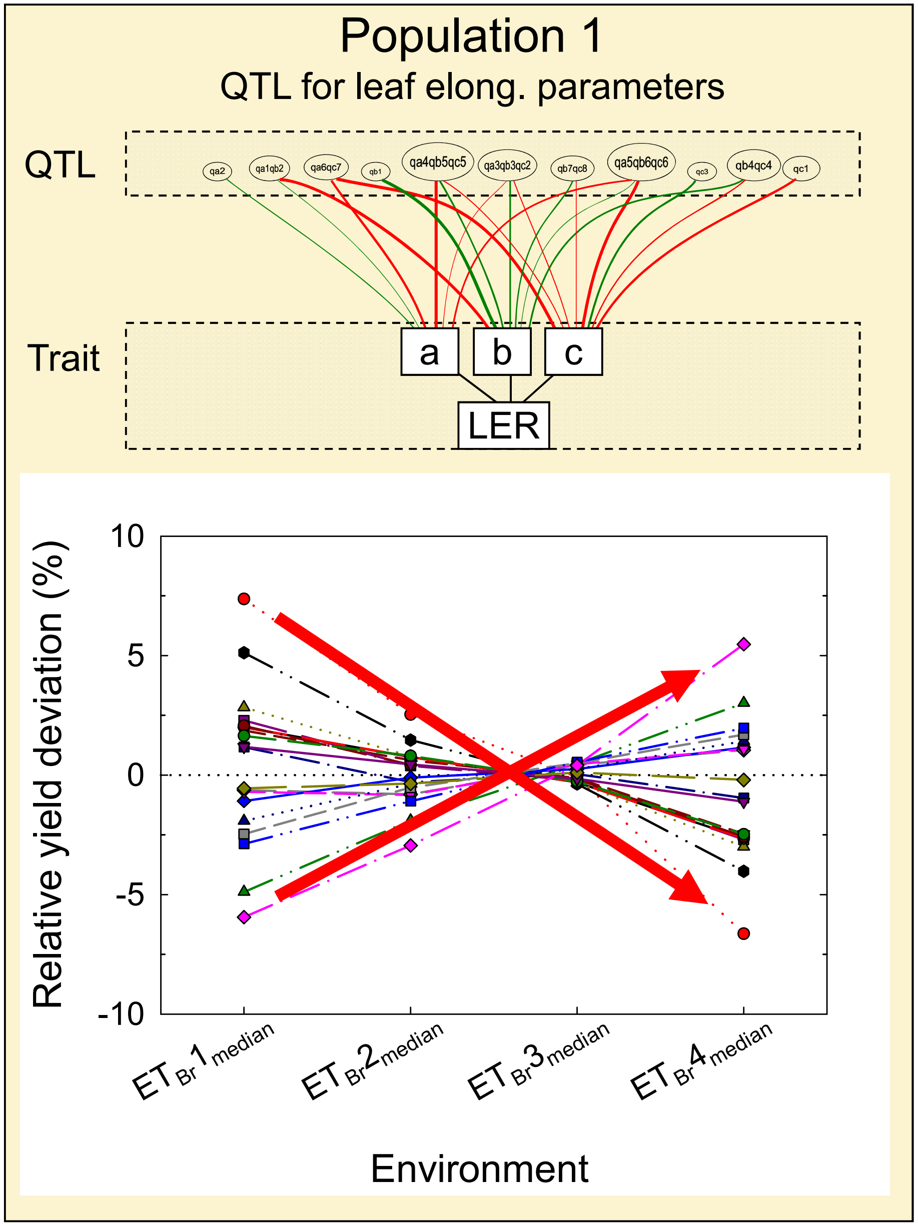
Crop level output:
- Leaf area index
- Transpiration
- Yield

…

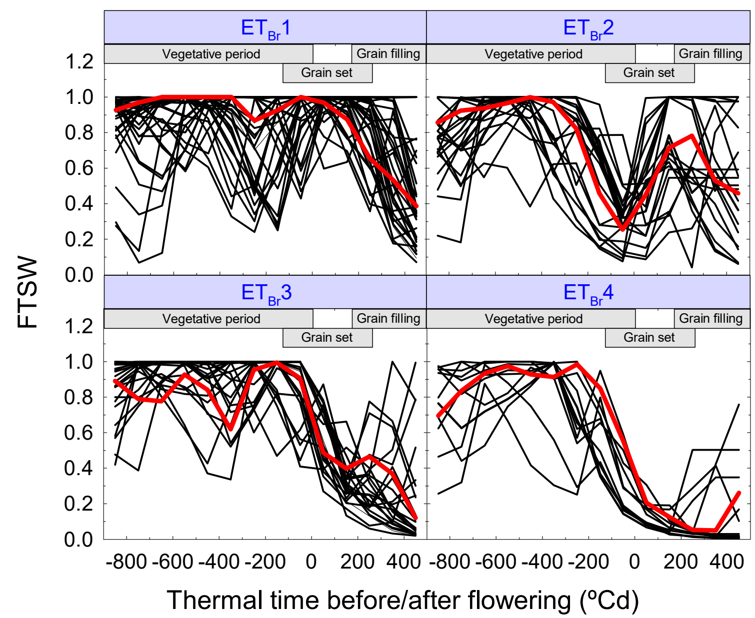


Chenu et al (2008) PCE 31:378-391.
Chenu et al (2009) Genetics 183:1507-1523.

Evaluation of the effect on yield in Sete Lagoas - Brazil



- Cross-over interactions for yield
- Genetic variability simulated highly varies across env.

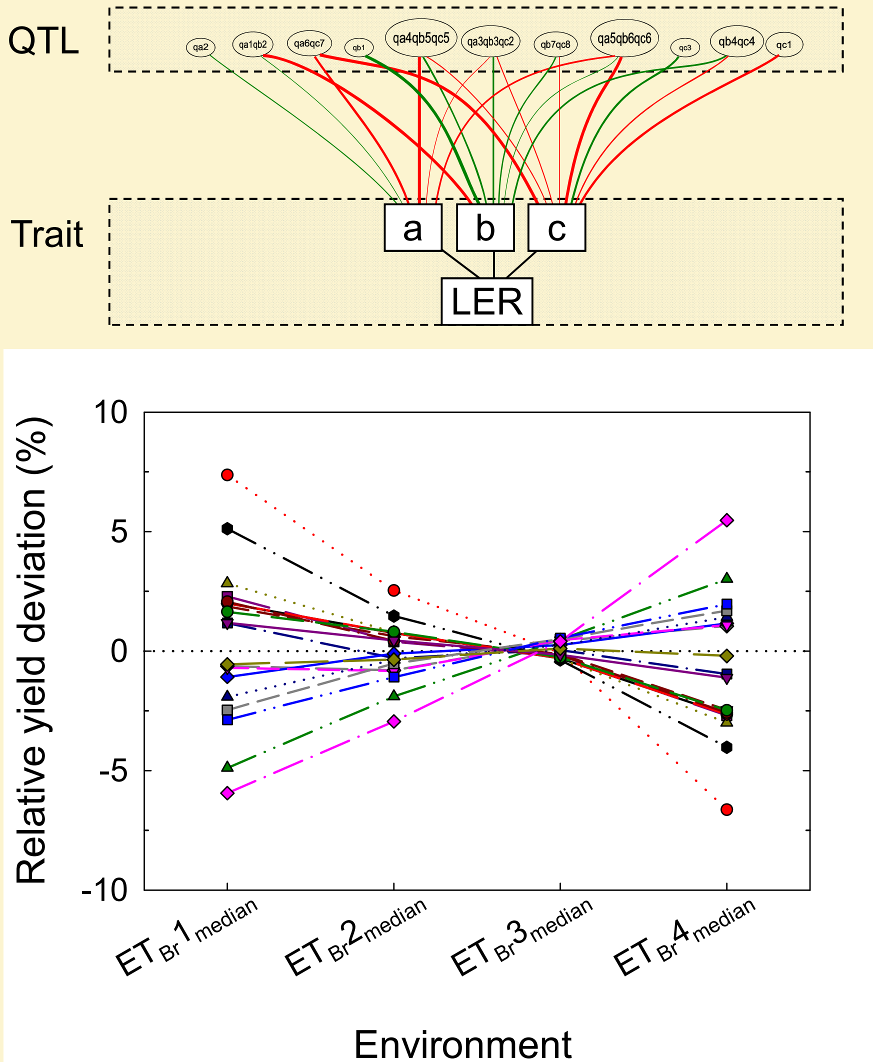


Chenu et al. Genetics 2009

Evaluation of the effect on yield in Sete Lagoas - Brazil

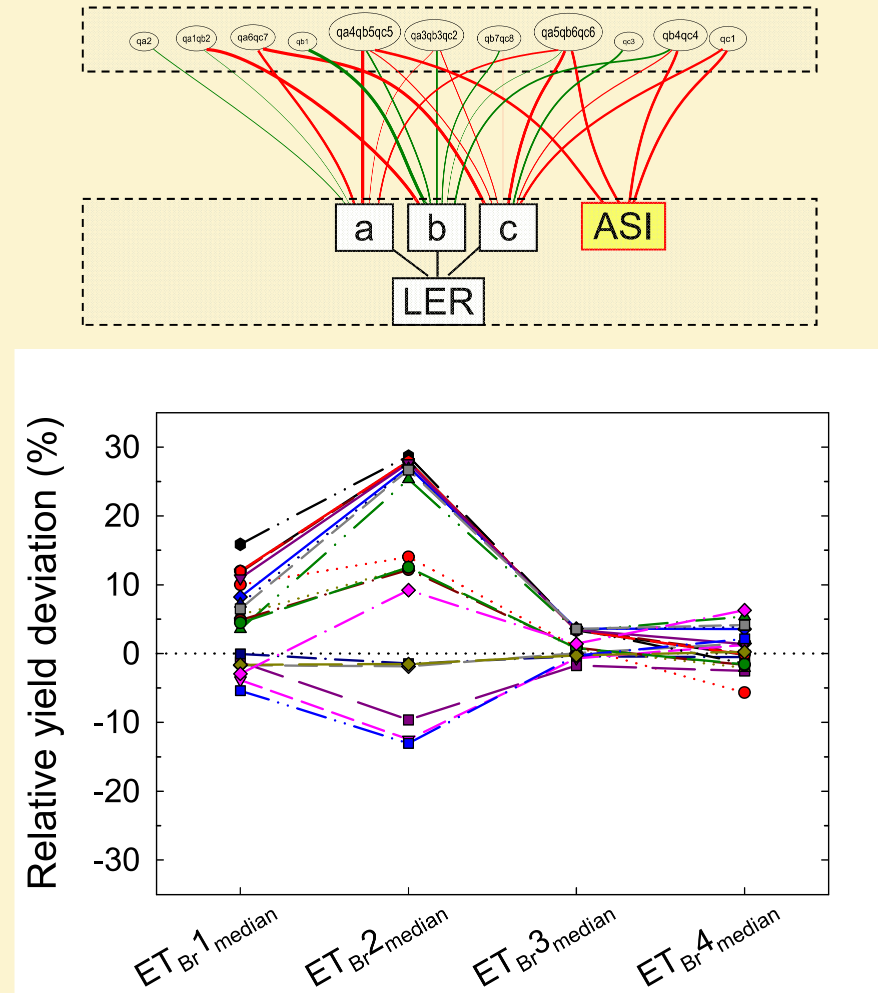
Population 1

QTL for leaf elong. parameters



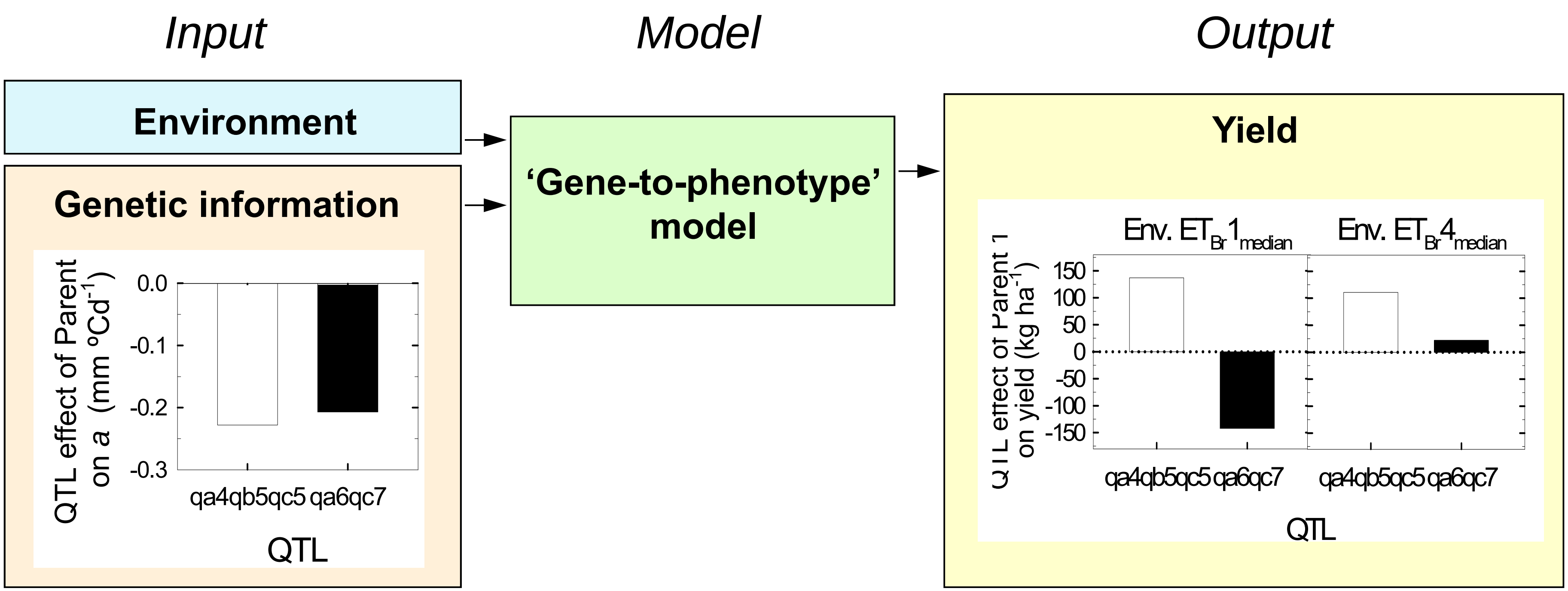
Population 2

QTL for leaf and silk elong. parameters



Chenu et al (2009) Genetics 183:1507-1523.

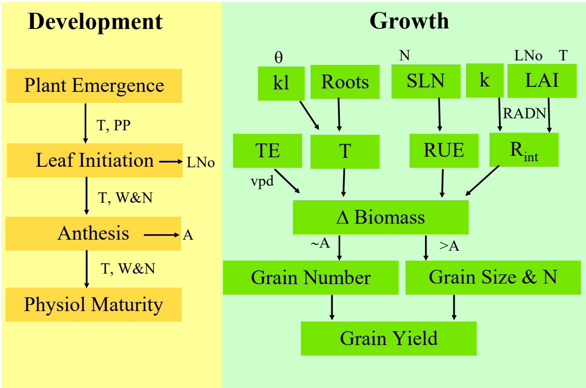
Estimation of the yield impact of organ-level QTL



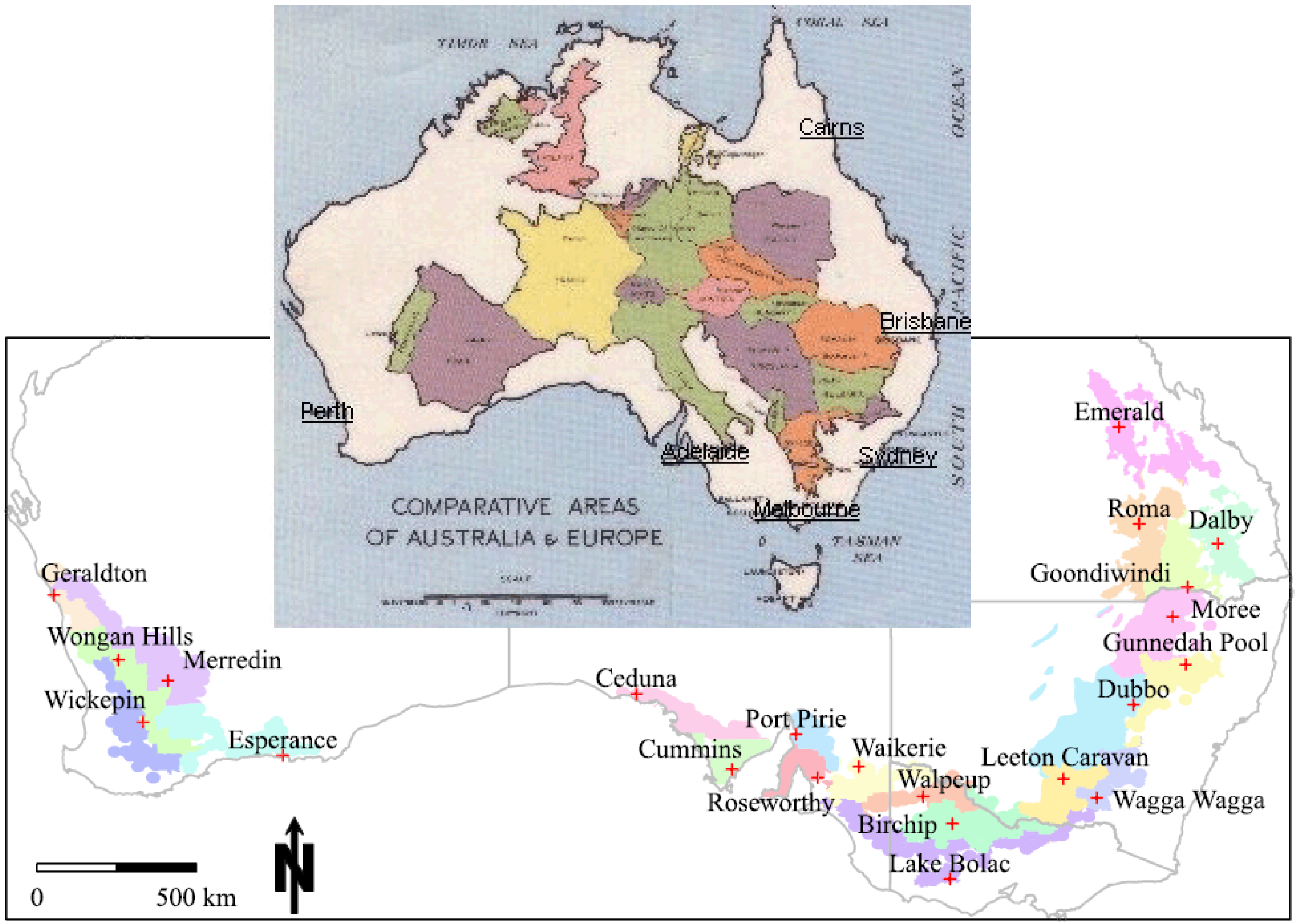
The effect of single QTLs with similar effect on leaf growth may have substantially different effects on yield in different environments

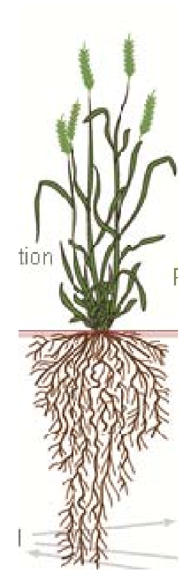
Chenu et al (2009) Genetics 183:1507-1523.

II - Evaluating the value of traits



APSIM-wheat in Australia

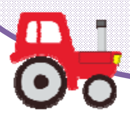




Trait value in a very variable environment (drought)
- Environment characterization -

Comprehensive sampling

Mana



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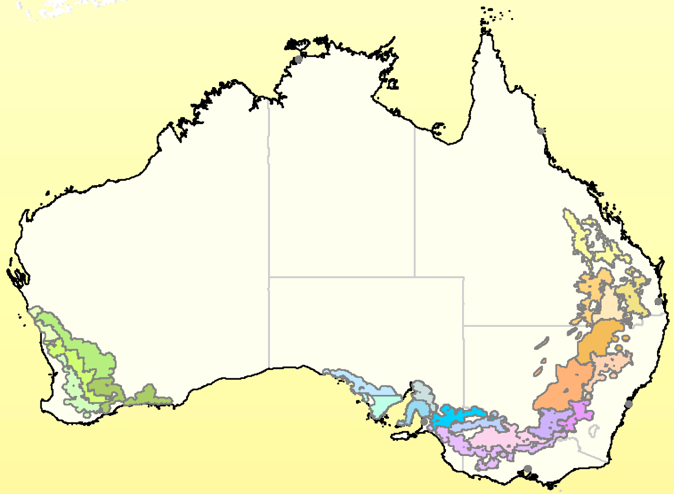
attern



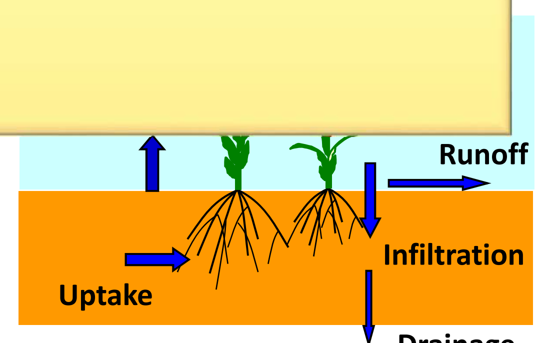
Simulations for

- 60 locations
- 5 sowing dates
- 5 initial soil water
- 123 years

____

~185 000 environments

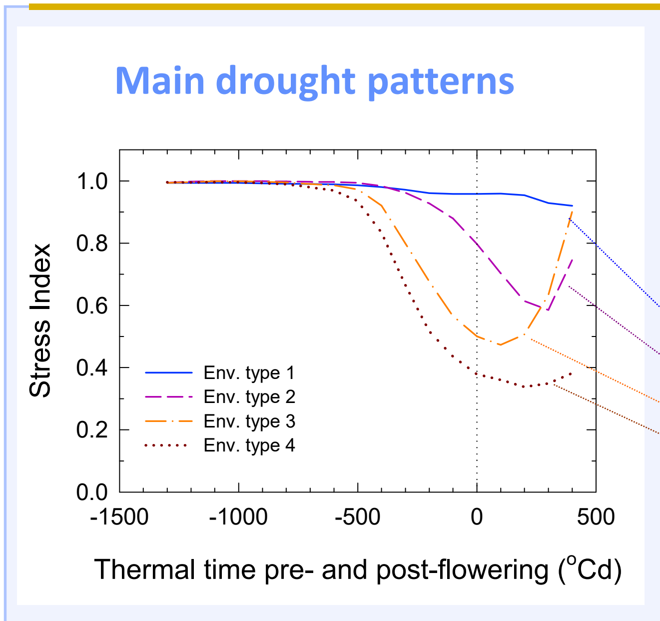
fall

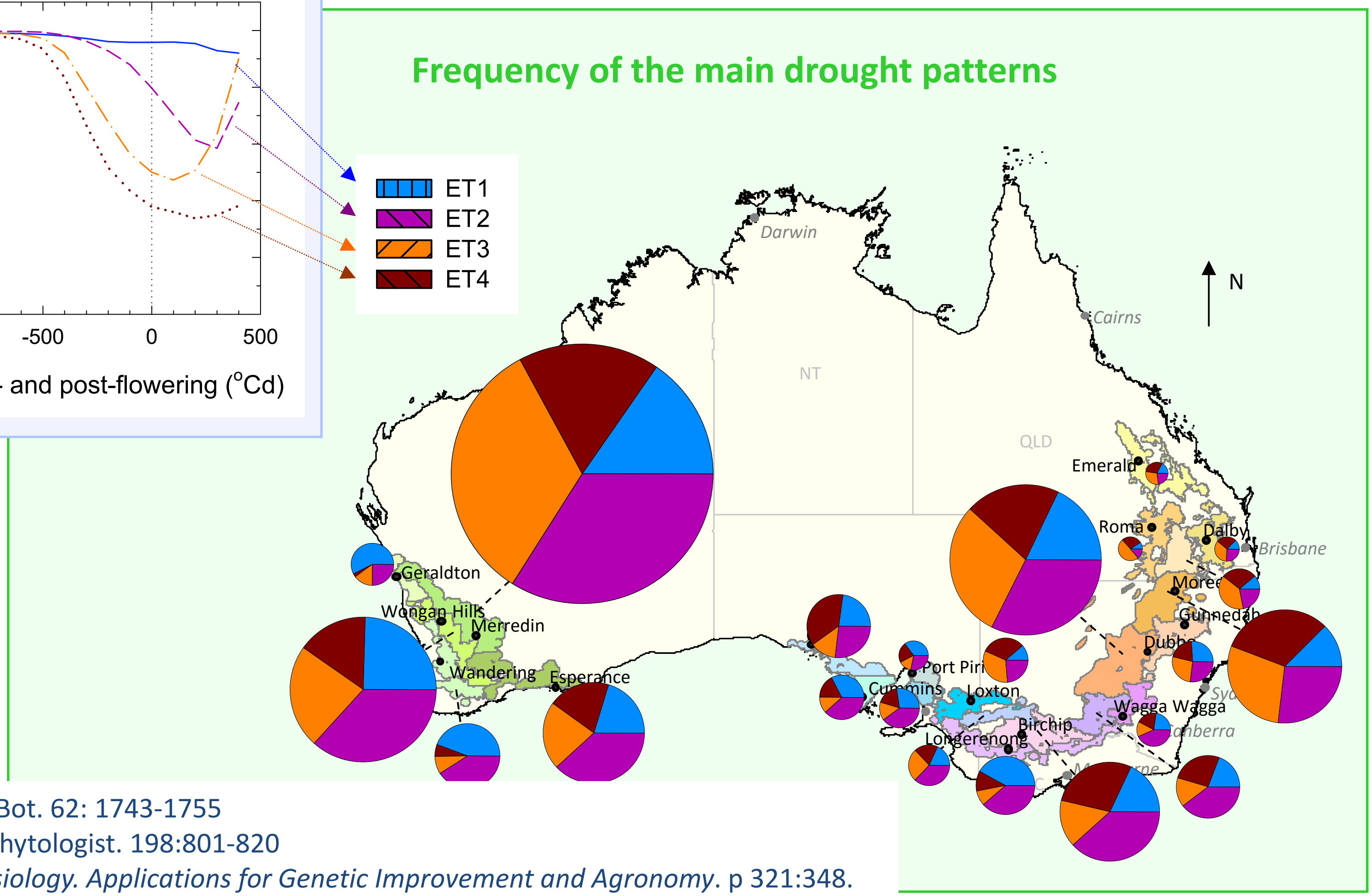


Chenu et al. Contribution of crop models to adaptation in wheat. Invited for submission in *Trends in Plant Science* (IF: 12.9)

Holzworth al. (2014) APSIM – Evolution towards a new generation of agricultural systems simulation. *Environmental Modelling & Software* 62:327-350.

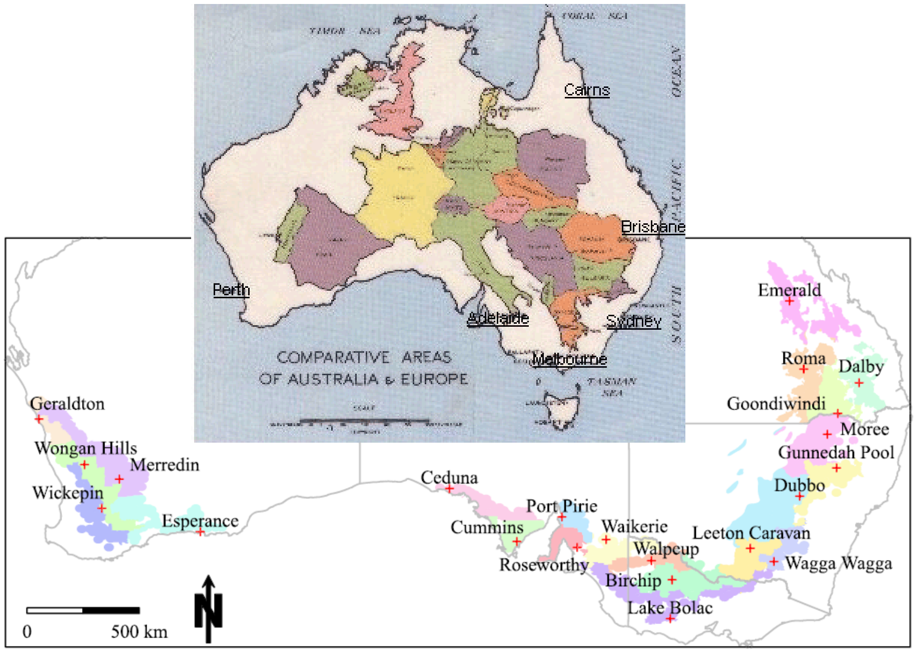
Trait value in a very variable environment (drought)
- Environment characterization -

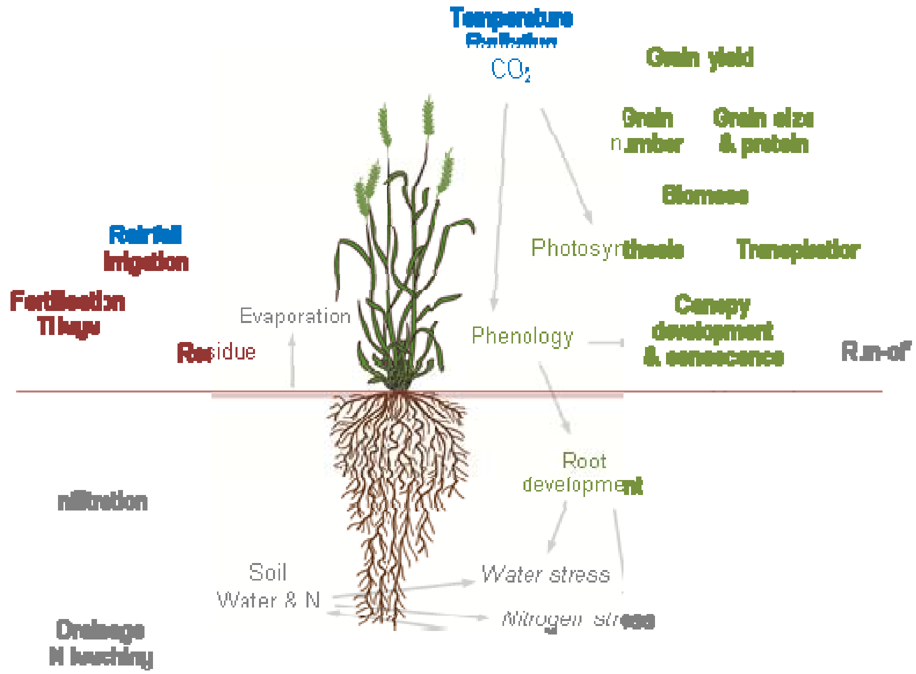


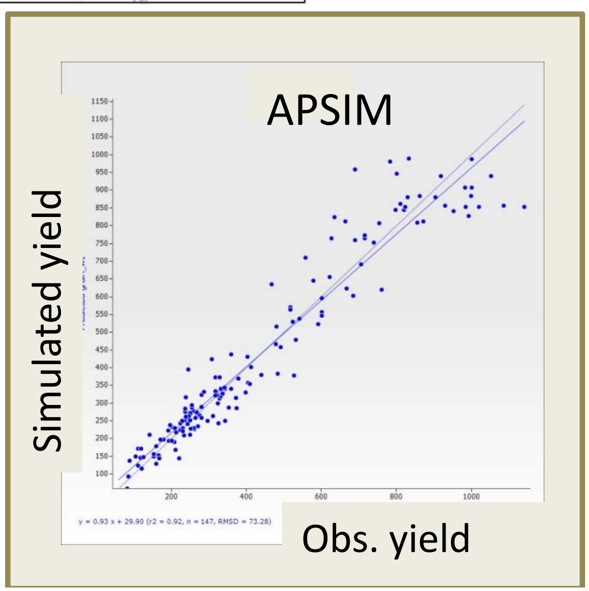


Chenu et al 2011. J. Exp. Bot. 62: 1743-1755
Chenu et al. 2013. New Phytologist. 198:801-820
Chenu 2015 In: *Crop Physiology. Applications for Genetic Improvement and Agronomy*. p 321:348.

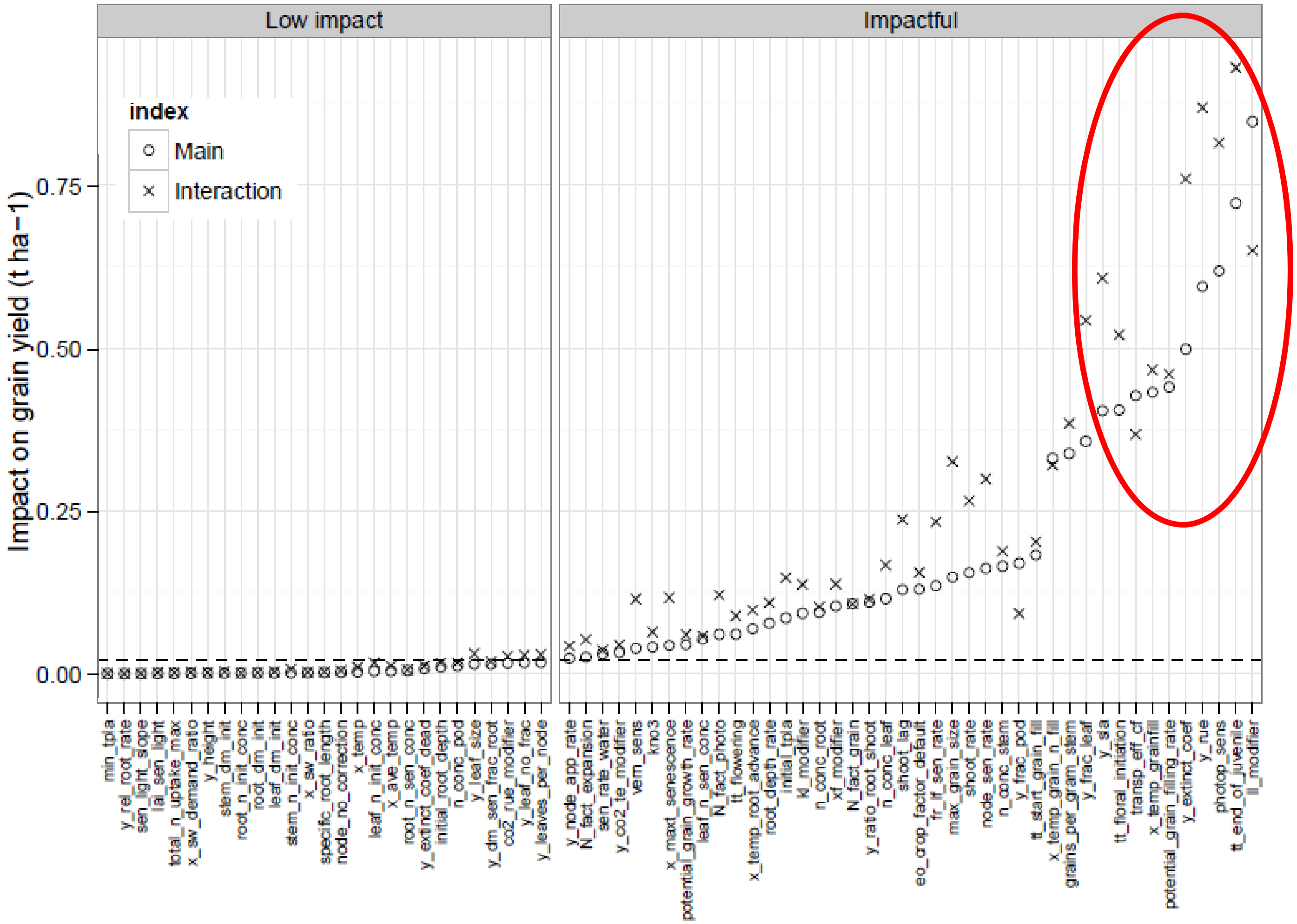
APSIM-wheat in Australia







Impactful traits/parameters for wheat in Australia



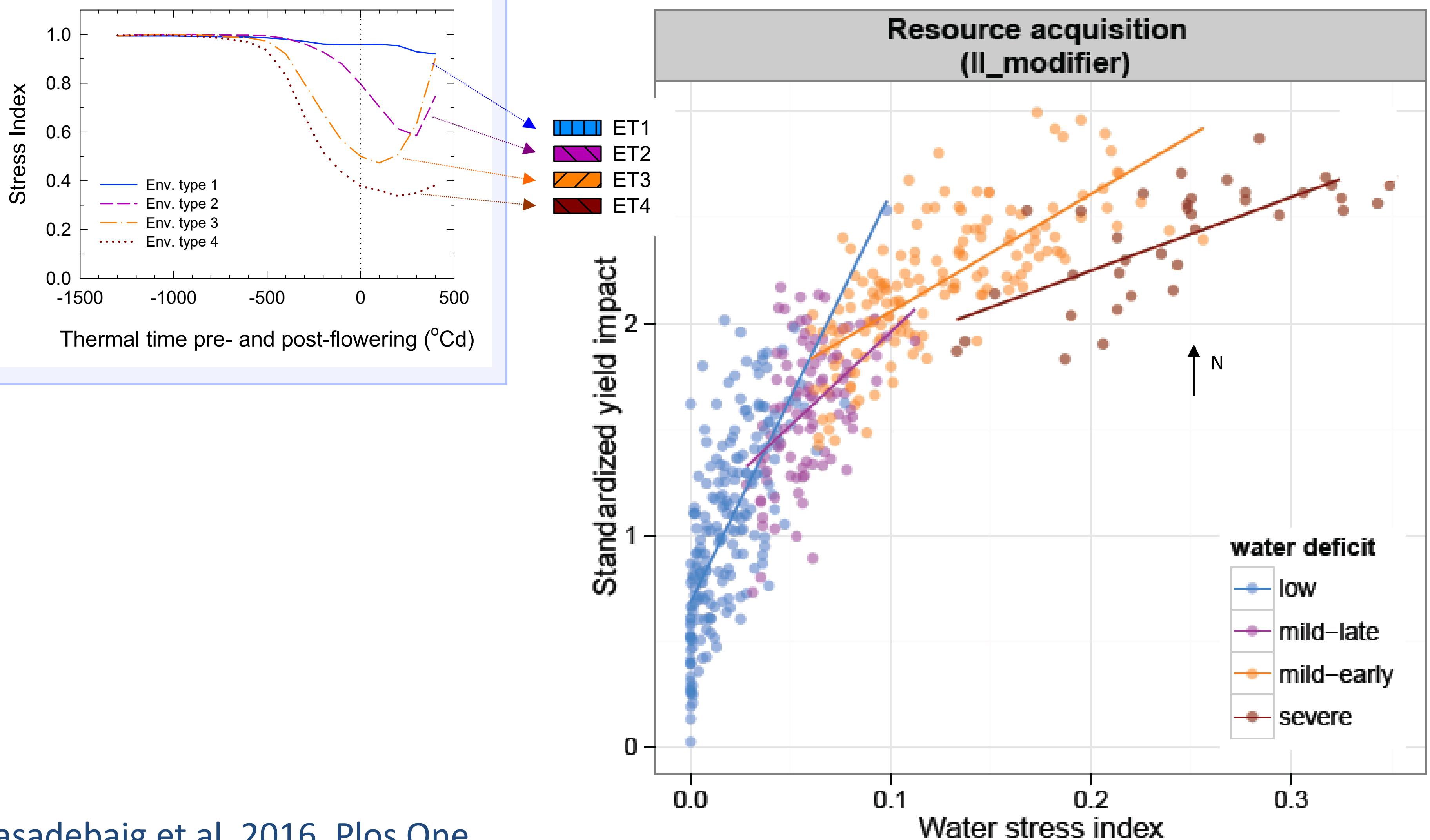
Global sensitivity analysis for APSIM-wheat parameter
Trait value +/- 20% of the reference value

Casadebaig et al. 2016 Plos One

Partitioning
Transp. Eff.
Grain filling
Architecture
Phenology
Roots

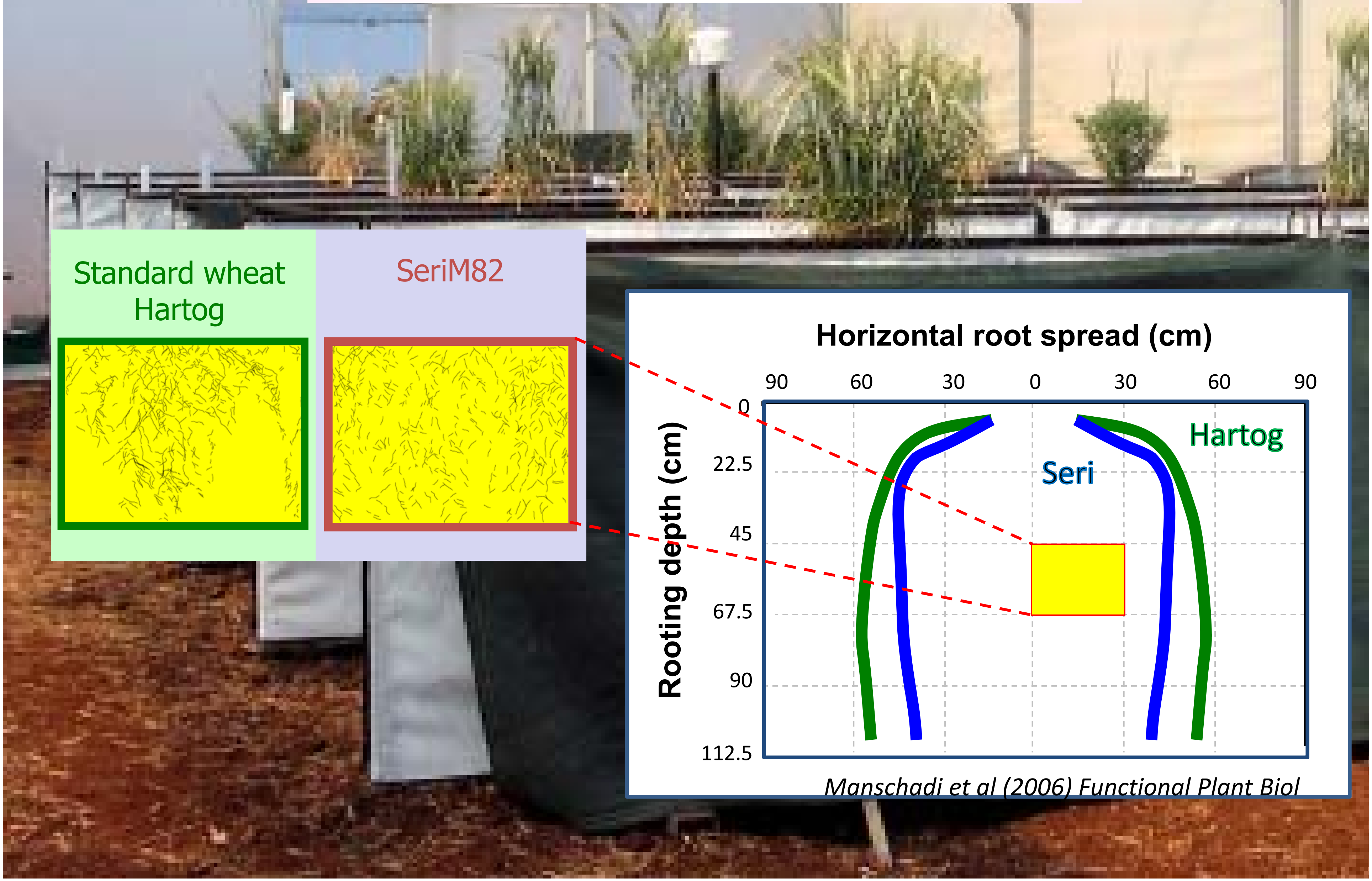
Trait value in a very variable environment (drought)

Main drought patterns

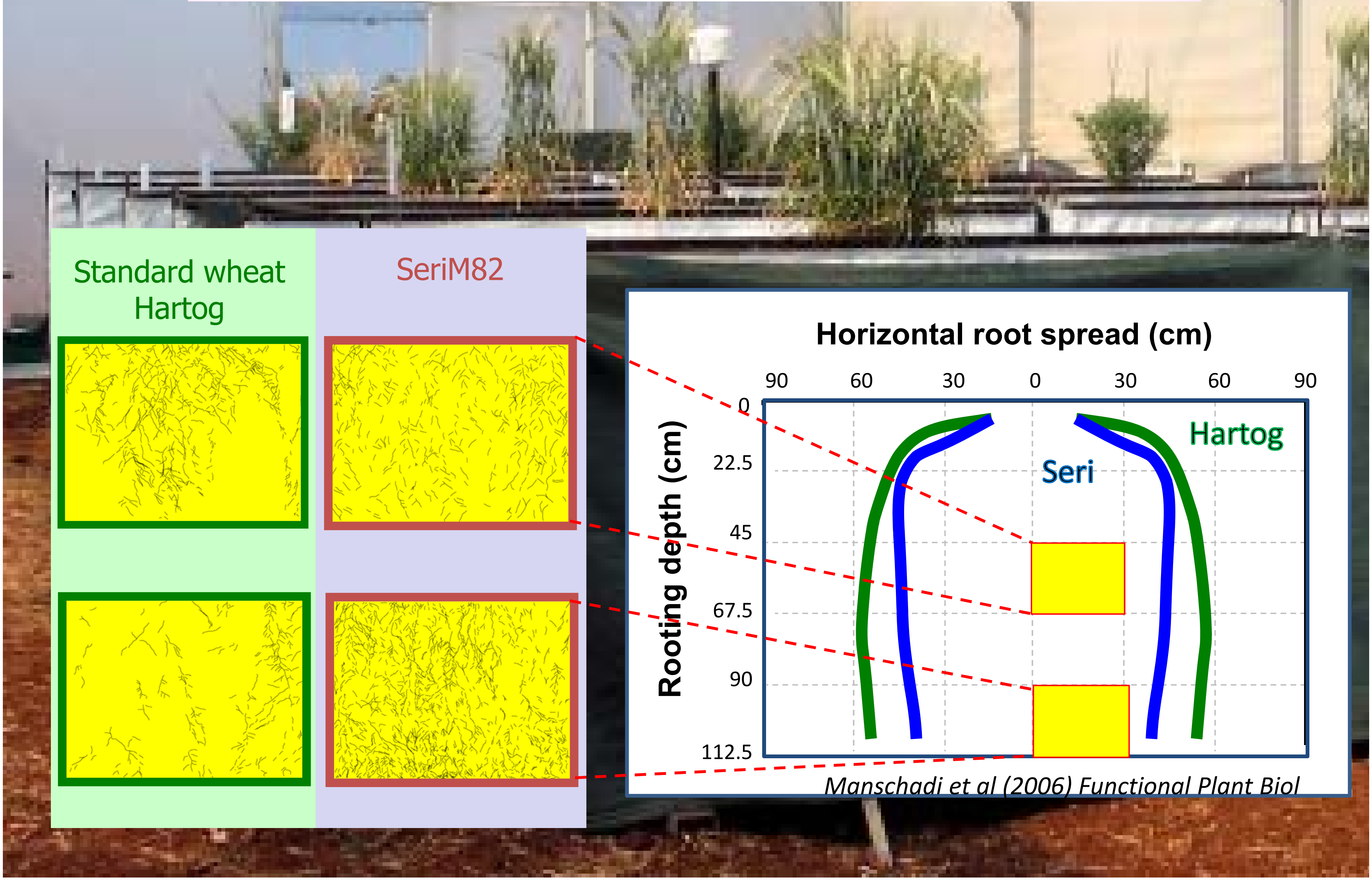


Casadebaig et al. 2016. Plos One

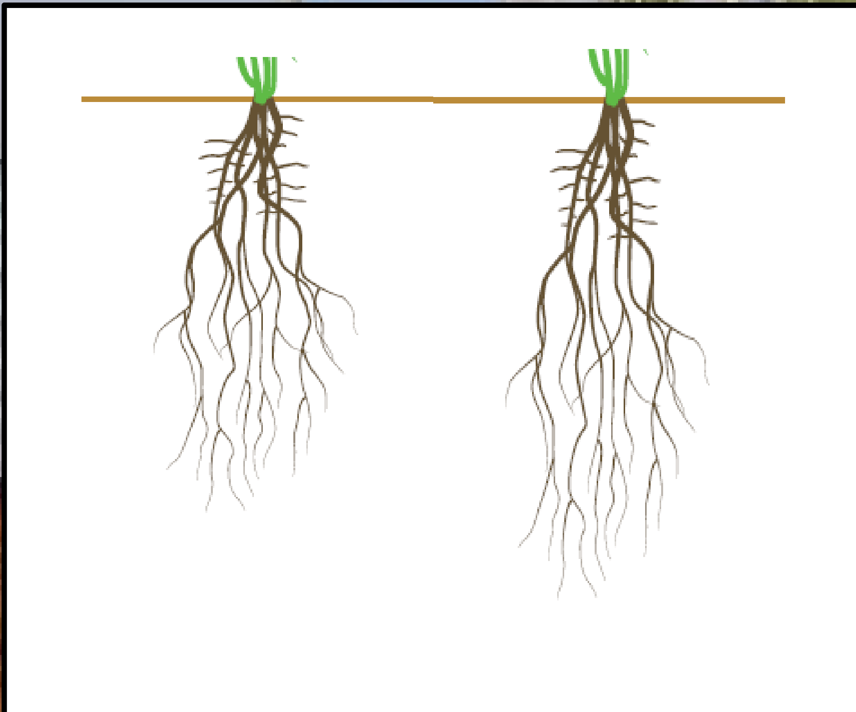
Trait 1- Better root repartition



Trait 2- Better root occupancy at depth



Trait 3- Quicker root growth rate

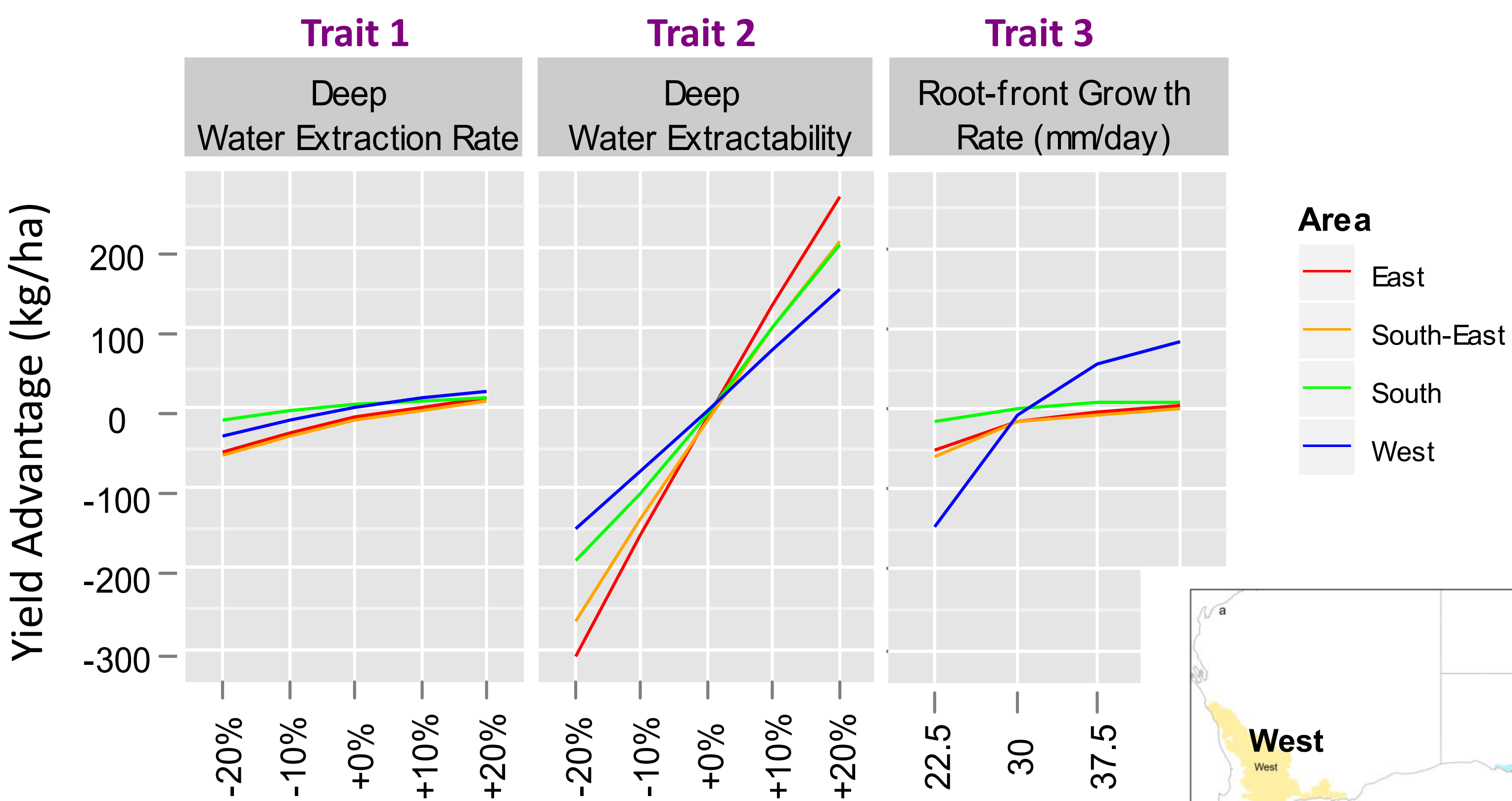


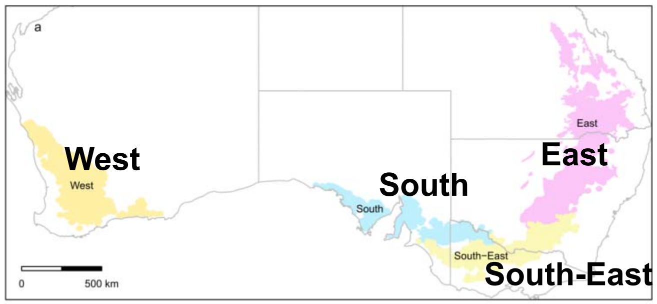
Root growth rate in wheat varies from 0.8 to 1.8 mm $^{o}Cd^{-1}$

(Kirkegaard and Lilley 2007 and 2011; Forrest et al. 1985; Barraclough 1984…)

Value of traits in target environments

How variability in root traits impacts yield in the Wheatbelt?

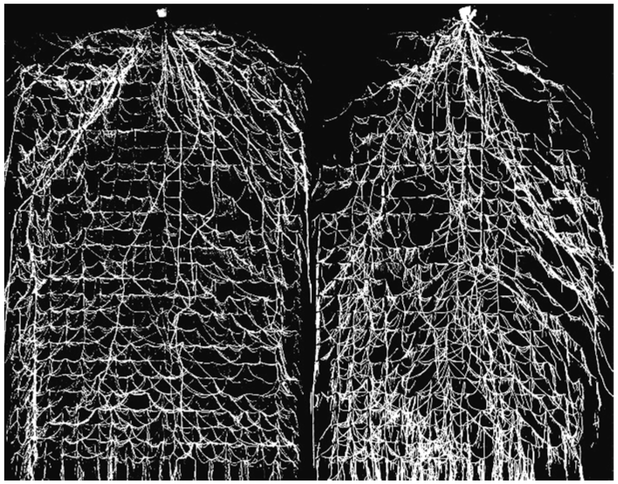




Veyradier, Chritopher & Chenu, 2013

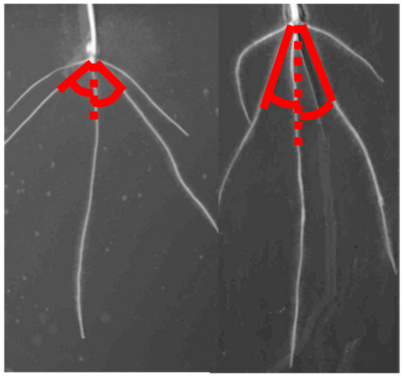
Genetic controls for Better occupancy at depth (Trait 2)

Phenotypic variability
- Better occupancy at depth -
(rhizotron - plants at flowering)



Proxy trait
(Seedling root angle)

Hartog SeriM82



Manschadi A M, et al (2008) Plant and Soil
Christopher et al (2013) TAG 126:1563

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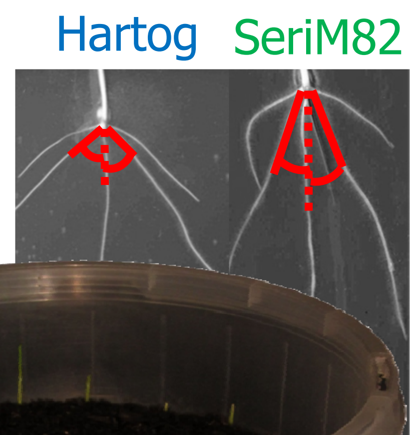

High-throughput:
- ✓ Time 5 - 10 days
- ✓ Space 600 plants / m2
- ✓ Cost-effective Material
- ✓ Labour 1,000 lines = 10h (1 person)

Richard et al (2015) Plant Methods 11:13

Genetic controls for Better occupancy at depth (Trait 2)

Phenotypic

- Better occupa

(rhizotron - plar

High-throughput:

✓ Time 5 - 10 days

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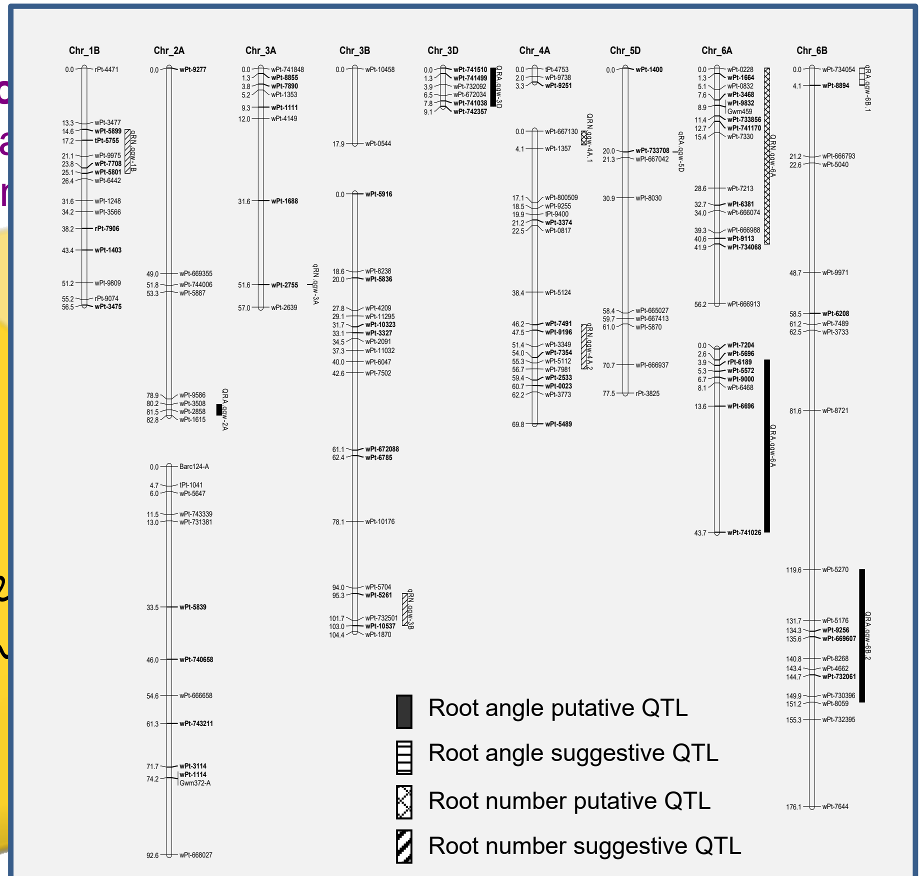
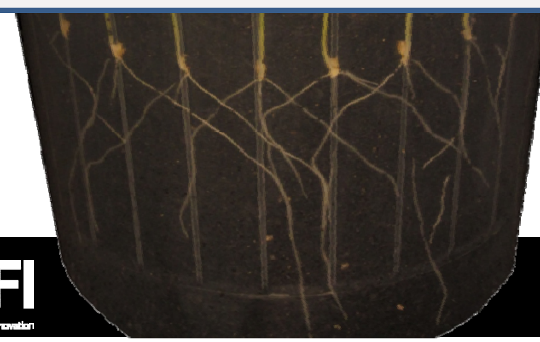
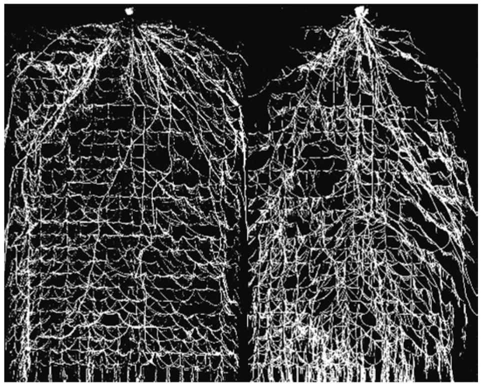




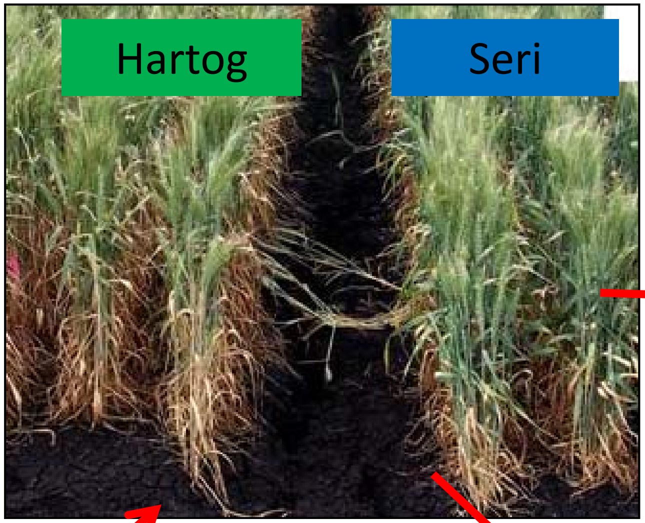
Christopher, et al. 2013. Theoretical and Applied Genetics.

Involvement of roots in staygreen

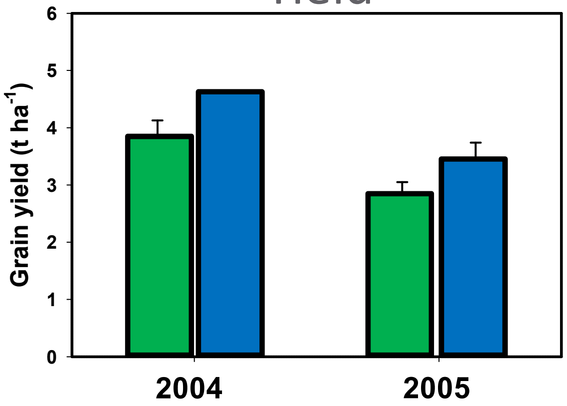
Trait 2- Better occupancy at depth

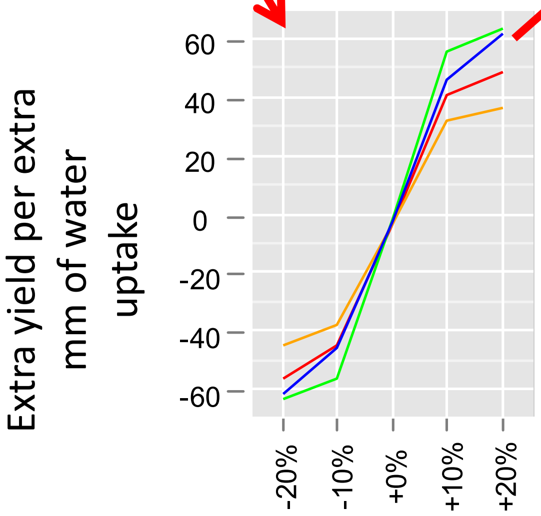


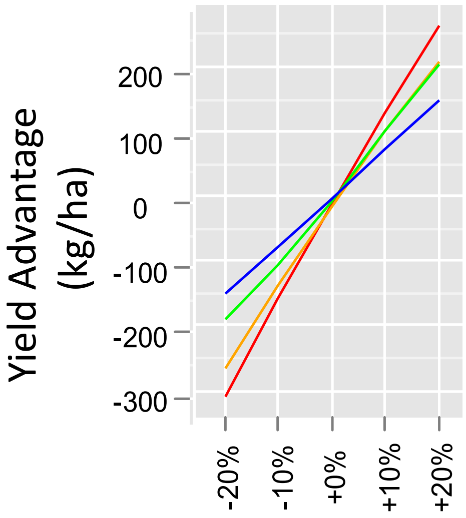
Staygreen



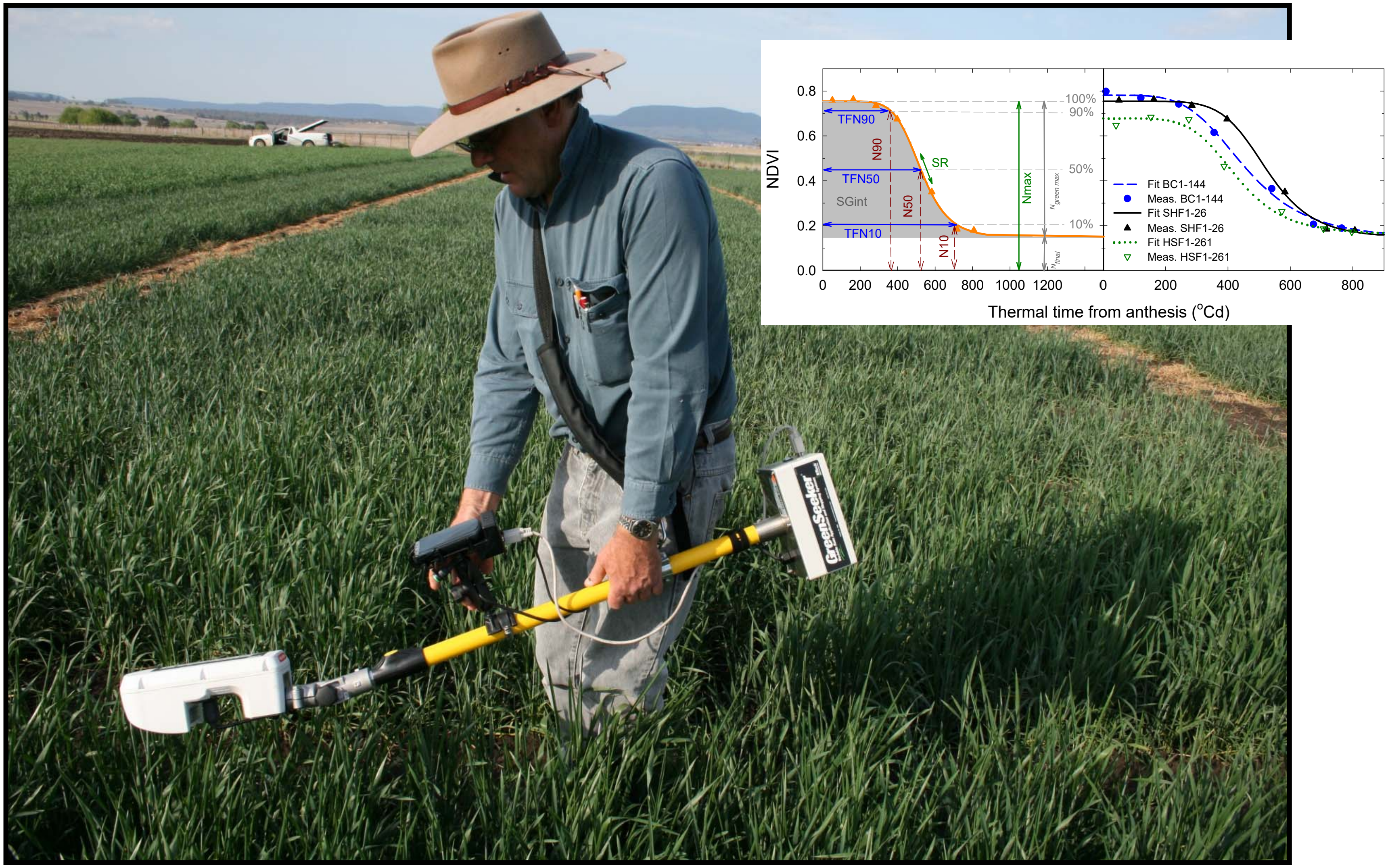
Yield







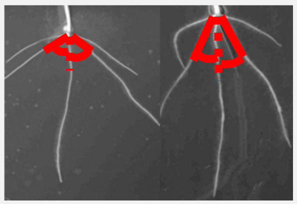
Phenotyping for staygreen



Christopher et al (2014) Functional Plant Biology.

Involvement of roots in staygreen

Roots



- Root angle putative QTL
- Root angle suggestive QTL
- Root number putative QTL
- Root number suggestive QTL

Staygreen

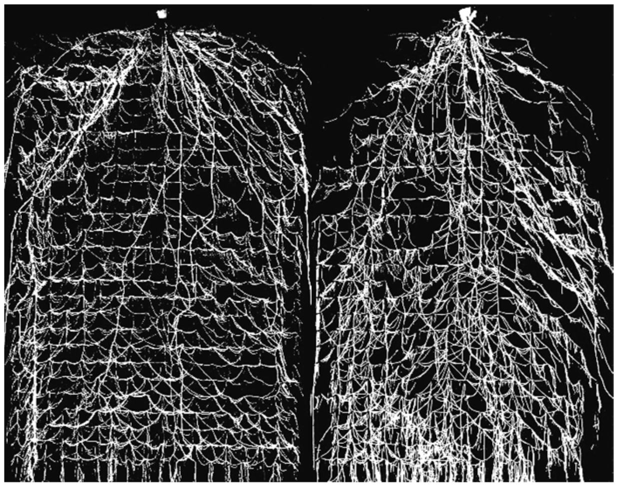
Staygreen & Yield QTL

Christopher et al (2013) TAG 126:1563
Christopher et al (in preparation)

Summary

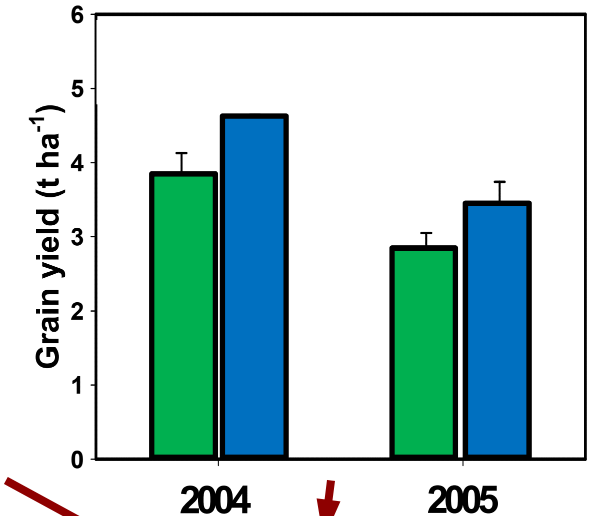
Model → **Target trait**
- trait of interest
in silico -

Genotypic variability
- Better occupancy at depth -
(rhizotron - plants at flowering)

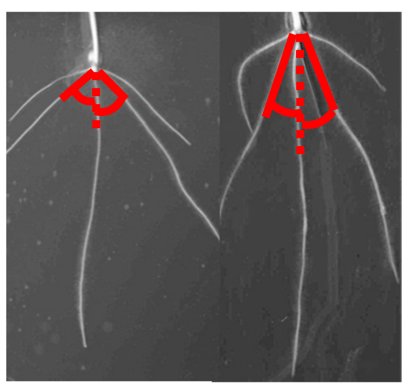


Emergent property
(staygreen)

Yield

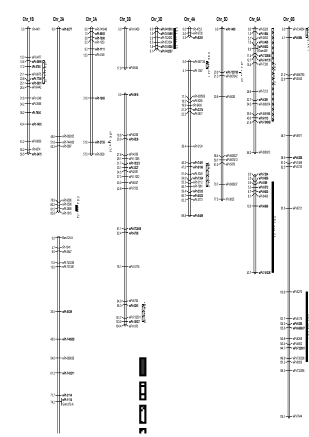


Proxy trait
(Seedling root angle)

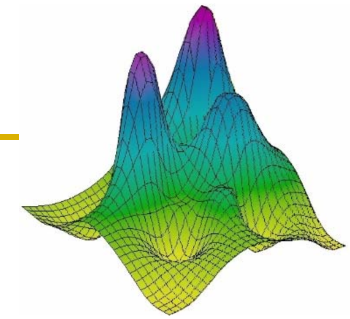


High-throughput method

Genes of interest



Summary – Dealing with GxMxE complexity



Whole-plant / Crop modelling for:

- Identification of traits of interest (e.g. wheat root architecture) with if possible reduced/removed context dependency (i.e. stable across environments, genetic background)
- Scaling up the impact of traits & gene/QTL on more integrated traits (e.g. yield) in various environmental situations (e.g. organ-level QTL in maize)
- Characterisation of the plant environment to unravel the GxE interactions (e.g. select for genotype better adapted to the target population of environments).
- Linkage with breeding models to fix more efficiently interesting genes and traits (e.g. QUGene)
- Test of the impact of genotype, management, future climatic scenarios and aid creation of future varieties, and identification of 'best' associated management

Acknowledgement

Modelling
G. Hammer (QAAFI)
S. Chapman (CSIRO)
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A. Doherty (DAFF)
G. McLean (DAFF)
P. Casadebaig (INRA)

Root - staygreen
J. Christopher (QAAFI)

Leaf elongation
F. Tardieu (INRA)
C. Weckler (INRA)