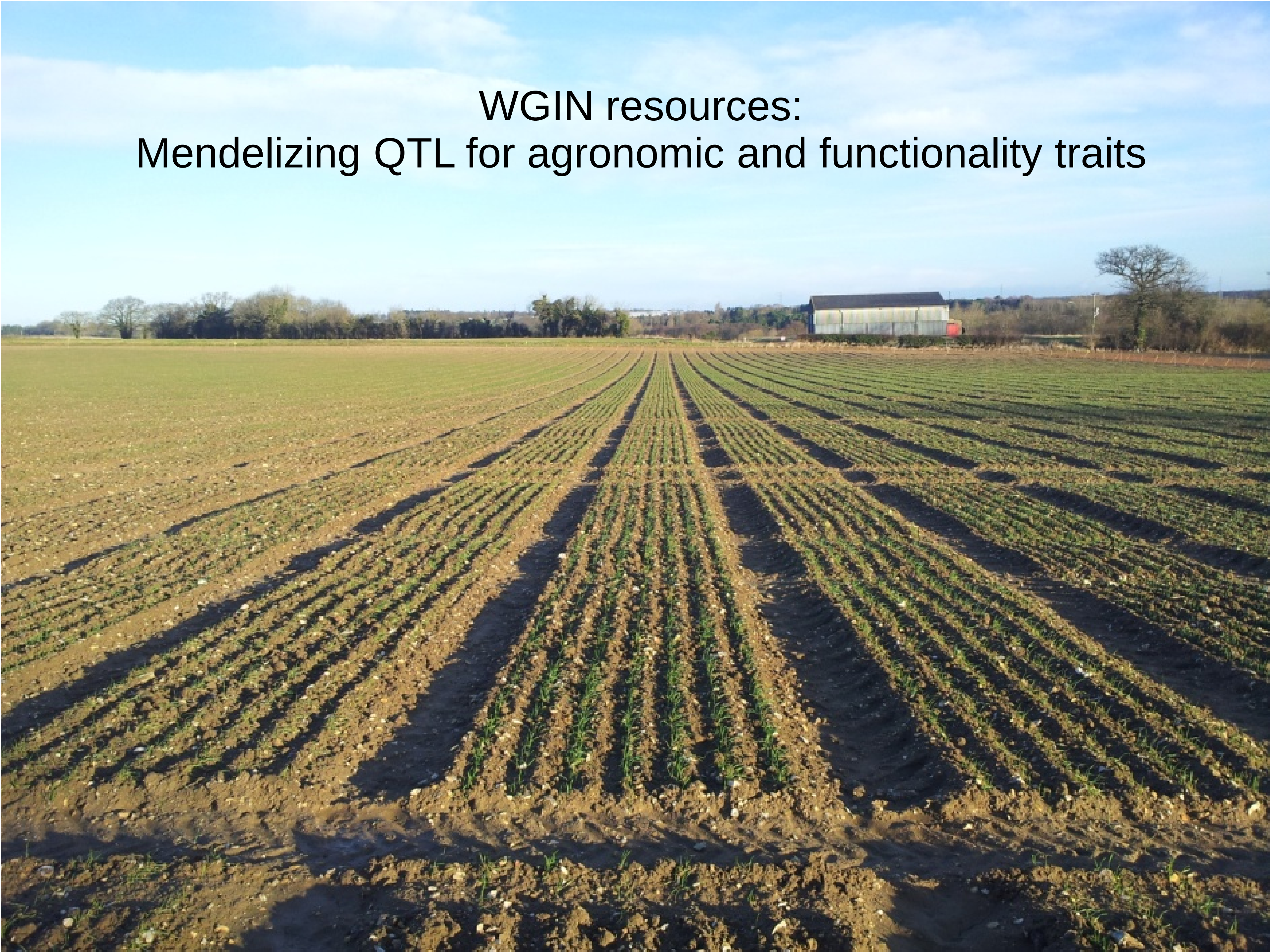
WGIN resources:
Mendelizing QTL for agronomic and functionality traits



WGIN Dissection of genetic gain in UK winter wheat

crosses

Spark x Rialto

Avalon x Cadenza

Buster x Charger

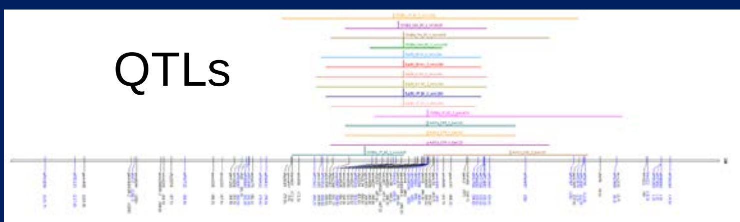
Charger x Badger

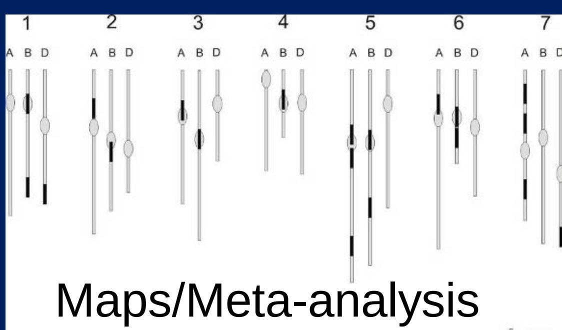
Savannah x Rialto

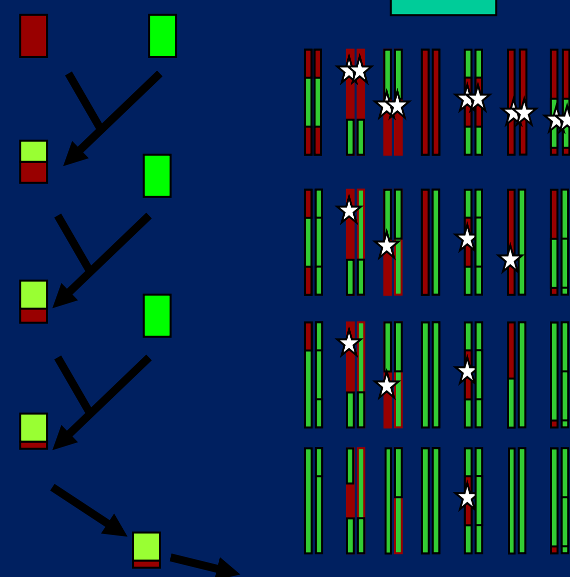
Shango x Shamrock

- Malacca x Charger
- Savannah x Renesansa
- Lynx x Cadenza
- Beaver x Soissons
- Weebil x Bacanora
- Milan x Catbird

What genes control these traits?
How do alleles
work in combination for genetic gain and
trait stability?







Isogenics

More specifically:

Germplasm Collections

- AE Watkins
- Gediflux

- **Segregating Populations**
  - Avalon x Cadenza
  - Paragon x Chinese Spring
  - Paragon x synthetic
  - Paragon x Garcia

Markers

- COS
- Allele mining

Mutant Populations

- EMS
- Gamma

- **Near Isogenic Lines**
  - A x C (height, heading, yield)
  - *Agropyron elongatum* 7
  - *Aegilops uniaristata* 3N
  - Seed axes (SxS, AxC, BxS)
  - Bread making functionality (MxH)

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  - **Bread making functionality (MxH)**

Emphasis today

DEFRA-LINK FQS23

Investigating Wheat Functionality through Breeding and End Use

Who was involved with QTL work?

JIC
Breeders
RAGT
Syngenta
Nickerson-Advanta

Millers & Bakers
CCFRA
ATC
RHMT
ADM
NABIM

- QTL prioritisation through project meetings
- For WGIN:
  - Can we control quality, at lower protein?
  - Group 1 wheat for less N?

Data: 05 and 06 harvests

			Cross	
		M x C	**S x S**	**M x H**
	Milling	ATC	ADM	CCFRA
Product	**Wholemeal**	RHMT	RHMT	RHMT
	White CBP	ATC	ATC	ATC
	Spiral White	CCFRA	CCFRA	CCFRA
	Puff Pastry	ADM	ADM	ADM

Data: 05 and 06 harvests

WGIN needed a population and process focus →

			Cross	
		M x C	S x S	M x H
	Milling	ATC	ADM	CCFRA
Product	Wholemeal	RHMT	RHMT	RHMT
	White CBP	ATC	ATC	ATC
	Spiral White	CCFRA	CCFRA	CCFRA
	Puff Pastry	ADM	ADM	ADM

Trait data sets: Spiral White 05

Loaf mass (g)	gumminess (g)	Bottom Concavity / %	Volume of Holes
Loaf volume (ml)	chewiness (g)	Left Break / %	Wall Thickness / px
Specific volume (ml/g)	resilience	Right Break / %	Cell Diameter / px
L*	firmness(g)	Left Break Height / px	Cell Vol Range (map)
a*	adhesiveness	Right Break Height / px	Relative Vol Range (map)
b*	springiness	Left Break Depth / px	Cell Volume (map)
X	cohesiveness	Right Break Depth / px	Coarse / Fine Clustering
Y	gumminess (g)	Left Break Position / px	Non-Uniformity
Z	chewiness (g)	Right Break Position / px	Cell Volume
firmness(g)	resilience	Top Left Shoulder	Coarse Cell Volume
adhesiveness	Slice Area / px	Top Right Shoulder	Average Cell Elongation
springiness	Height (max) / px	Bottom Left Roundness	Net Cell Elongation
cohesiveness	Height (avg) / px	Bottom Right Roundness	Cell Angle to Vertical / °
gumminess (g)	Breadth / px	Slice Brightness	Cell Alignment
chewiness (g)	Height / Breadth	Cell Contrast	Vertical Elongation
resilience	Wrapper Length / px	Number of Cells	Degree of Circulation
firmness(g)	Total Concavity / %	Number of Holes	Circulation Horiz Offset / %
adhesiveness	Left Concavity / %	Area of Cells / %	Circulation Vert Offset / %
springiness	Right Concavity / %	Area of Holes / %	Curvature
cohesiveness	Top Concavity / %	Volume of Holes	

Correlations Spiral White Data 05-06

All Tough traits:

	MxC		MxH		SxS	
	Corr	**Signif**	**Corr**	**Signif**	**Corr**	**Signif**
Loaf volume (ml)	0.060	NS	0.438	***	0.578	***
L*	0.467	***	0.458	***	0.340	**
firmness(g)	0.455	***	0.496	***	0.620	***
firmness(g)	0.465	***	0.446	***	0.675	***
Height (max) / px	0.496	***	0.39	***	0.543	***
Number of Cells	0.310	**	0.448	***	0.403	**
Wall Thickness / px	0.236	*	0.359	***	0.319	**
Cell Diameter / px	0.330	***	0.347	***	0.350	**
Coarse Cell Volume	0.393	***	0.442	***	0.352	**

Development of the Hereward and Malacca Near Isogenic Lines (NILs)

NIL creation was continued with the Hereward x Malacca crosses to BC_3F_2:

4 selected Hereward x Malacca lines backcrossed into Malacca

3 selected Malacca x Hereward lines backcrossed into Hereward

Malacca x Hereward breadmaking functionality NILs

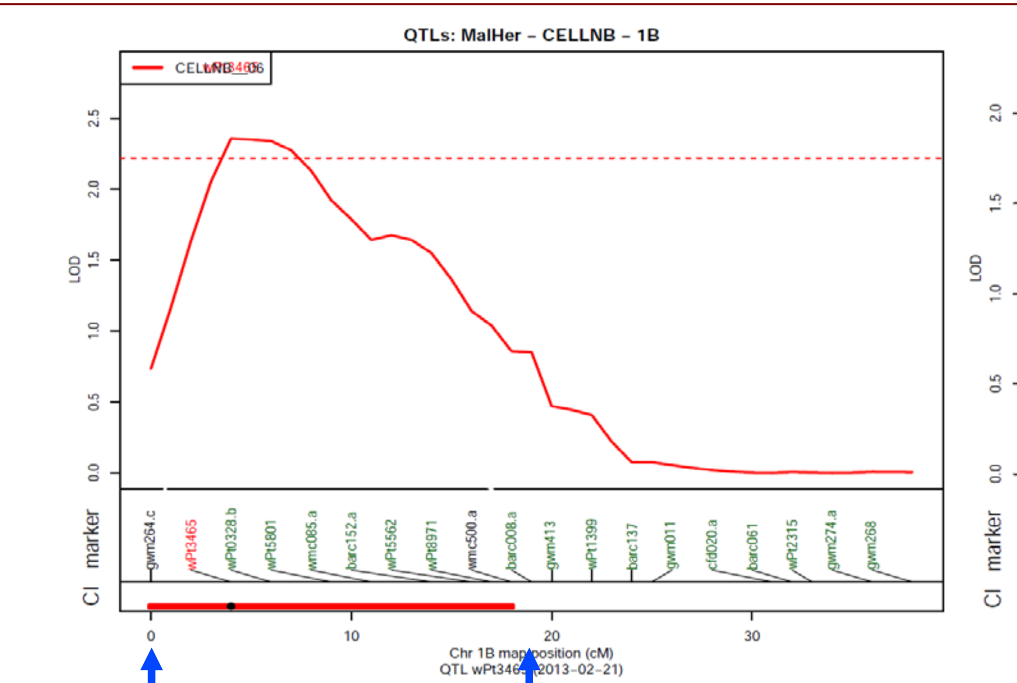
Cross	Chr	Trait	Markers used BC3F2	Number of plants		Notes	QTL	
				Hom a	Hom b			
MH100 x Malacca^4	1B	Number of cells	gwm264, barc8	11	25		x	
MH58 x Hereward^4	2B	Firmness	wmc257, wmc317	5	3*	* all plants wmc257 H Null	(x)	
MH9 x Malacca^4	2D	Loaf volume	gwm102, wmc18, gwm539	3	4*	* all plants gwm102 H/Het	x	
MH1 x Malacca^4	4D	No cells L*	barc98, gdm129	18	10		x	
MH19 x Hereward^4	4D	L*	barc98, gdm129	10	14		(x)	
MH70 x Malacca^4	6A	No of cells	gwm334	34	26	gdm36 (18cM) and barc3 (26cM) fixed as Mal last time	x	
MH60 x Malacca^4	7A	Wall thickness,cell diameter,volume,loaf volume	psp3001	14	31		?	
MH39 x Hereward^4	7B	loaf vol	gwm537, gwm577, barc182	6	3	barc182 fixed as Her	no	

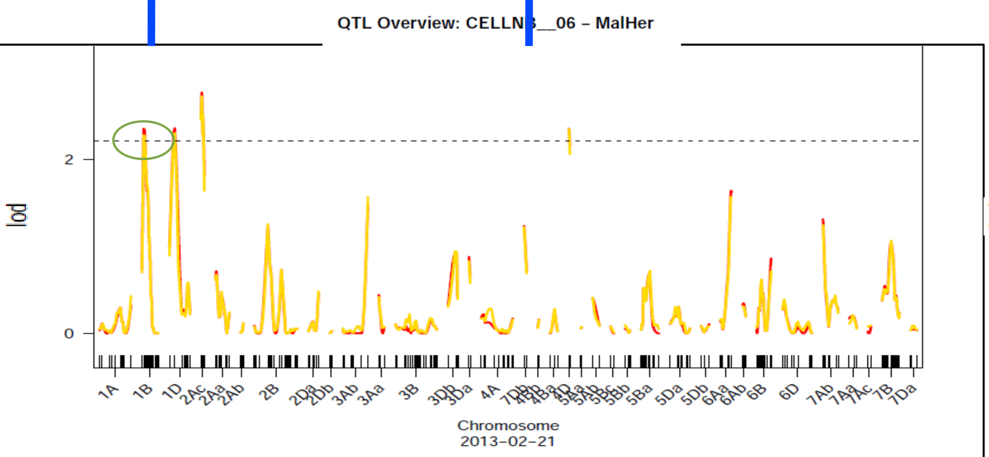
1m² plot field sown from each plant 2012-13, multiplication for replicated sowings 2013-14 for test baking.

1B – Number of Cells

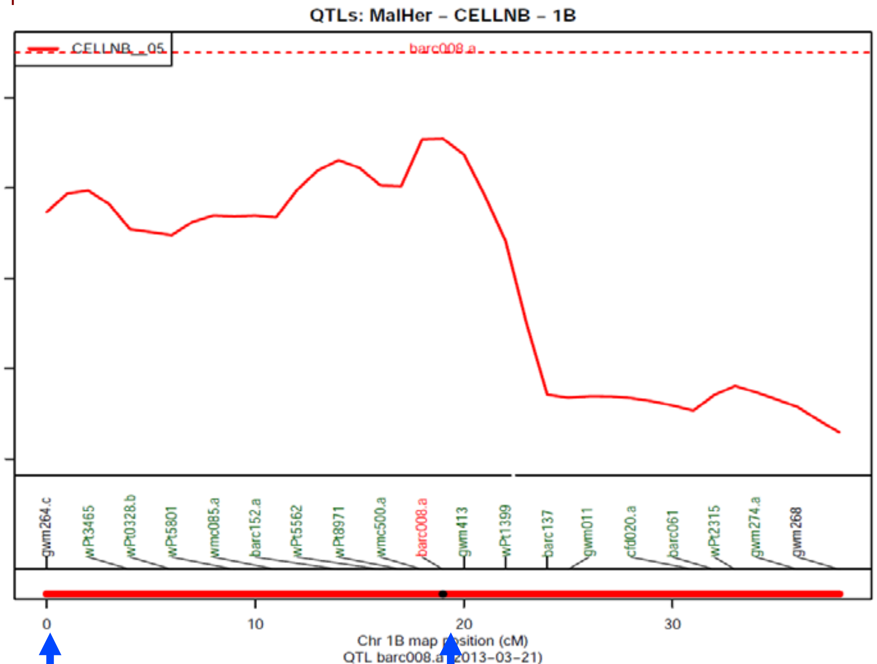
2006

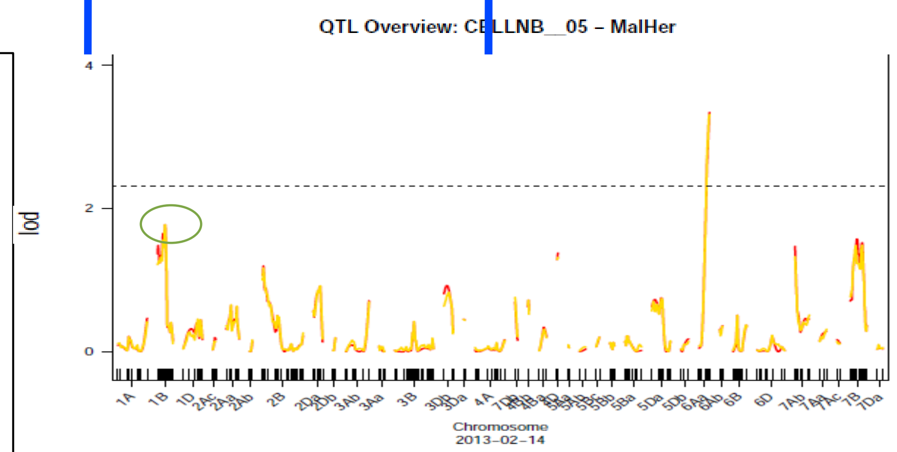
(also associated with 1B: Loaf volume.)





2005

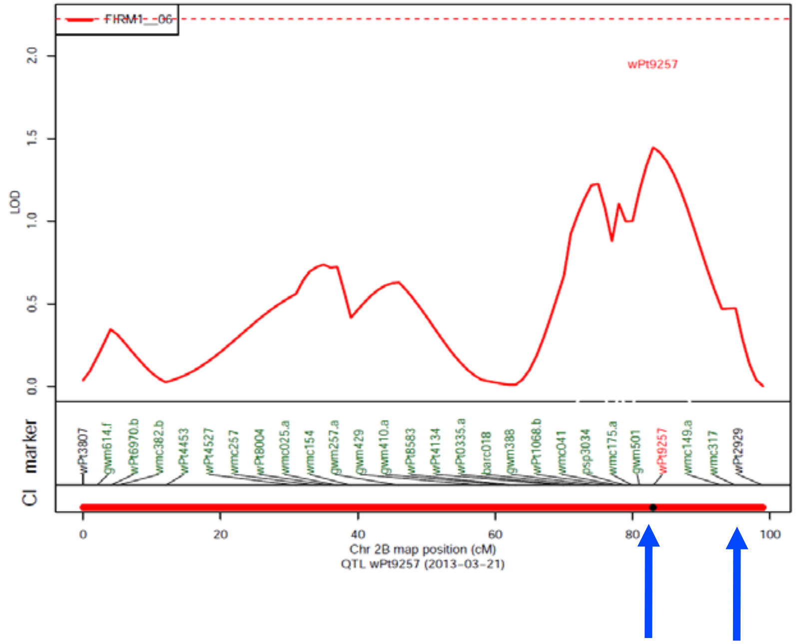




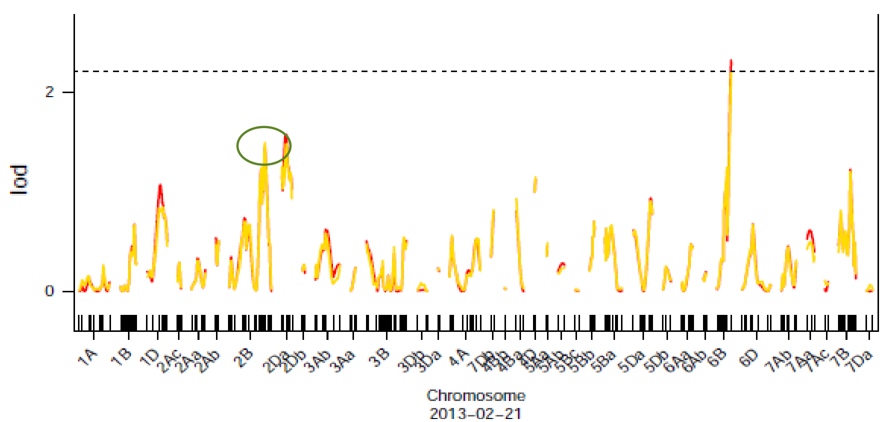
2B – Firmness (Day 1)

2006

QTLs: MalHer – FIRM1 – 2B



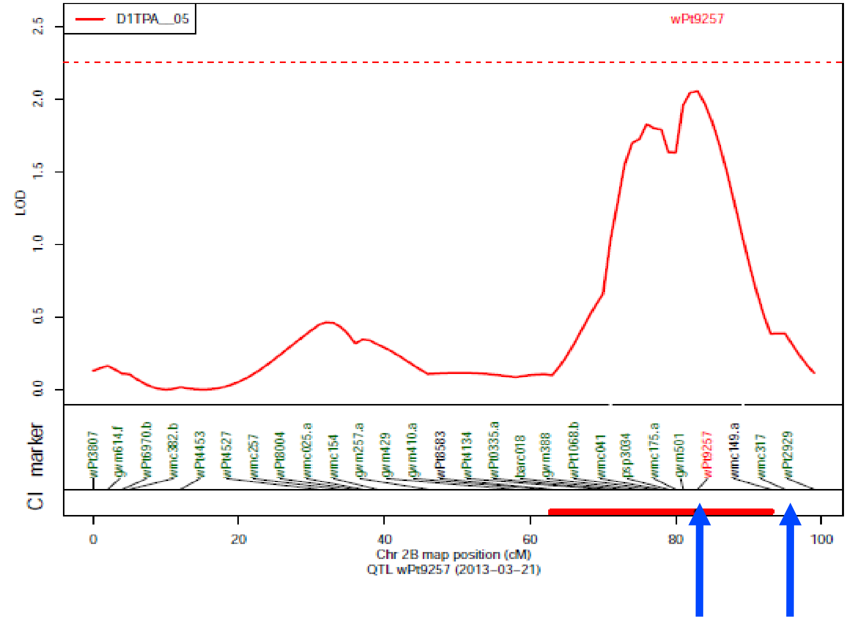
QTL Overview: FIRM1__06 – MalHer



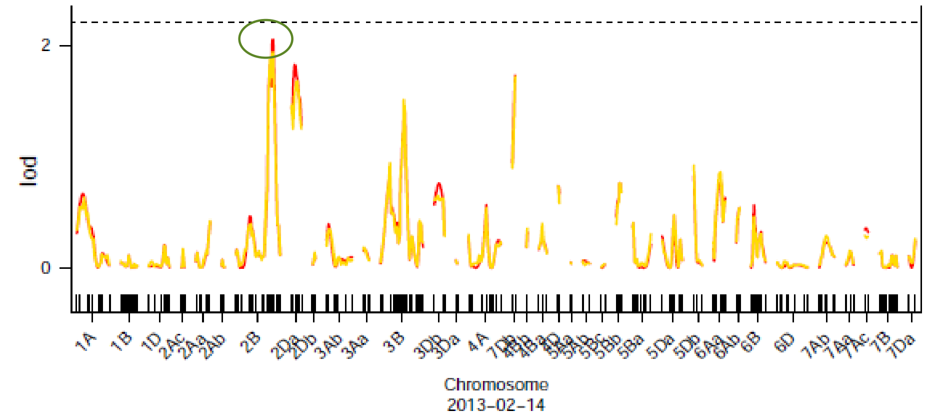
2005

(Also associated with 2B: Adhesiveness day 1, Average height (mm), Cell alignment,Chewiness day 1, Chewiness day 3, Day 3 TPA, Gumminess day 3, Height/ breadth ratio,Loaf height,Net cell elongation,Top left shoulder, Total concavity, Top right shoulder, Vertical cell elongation,Wrapper length.)

QTLs: MalHer – D1TPA – 2B

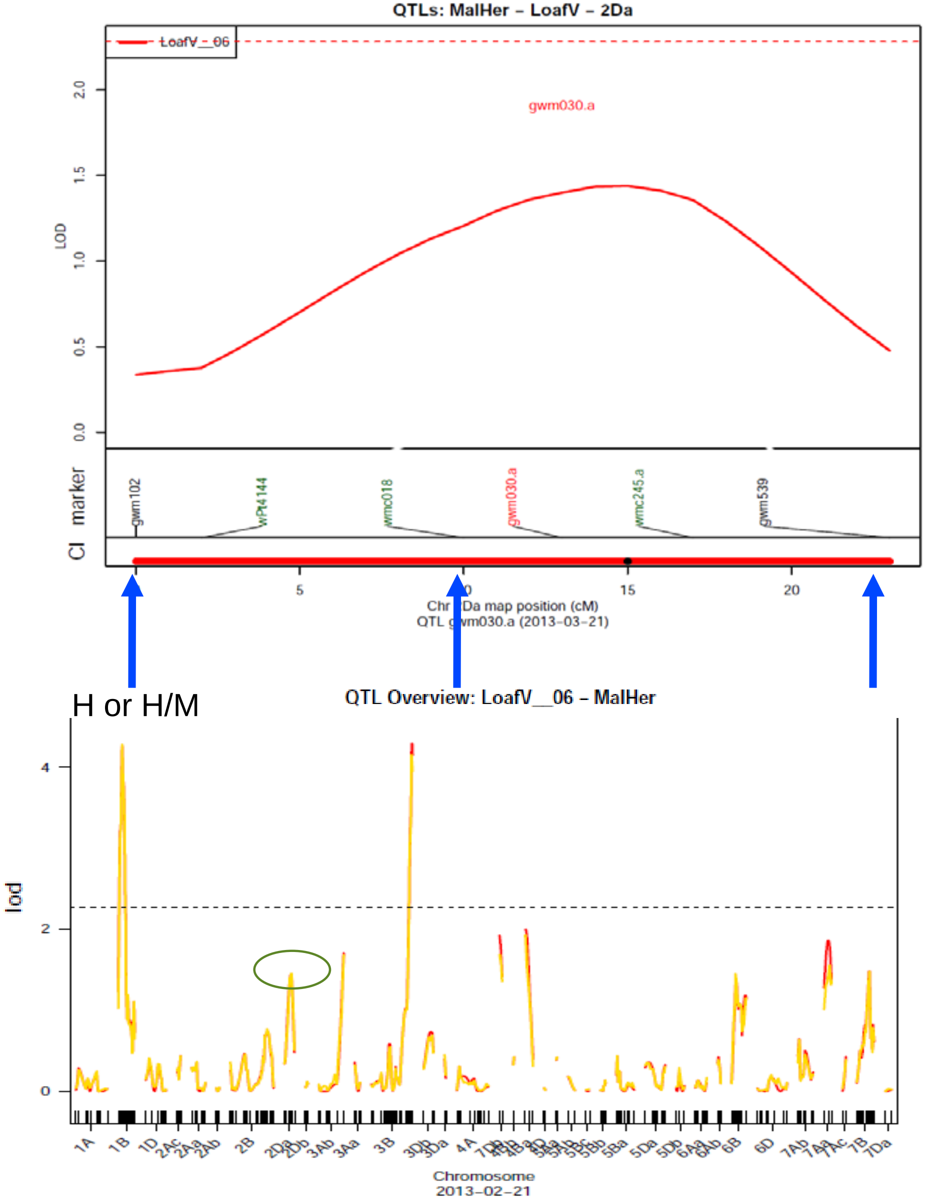


QTL Overview: D1TPA__05 – MalHer ?

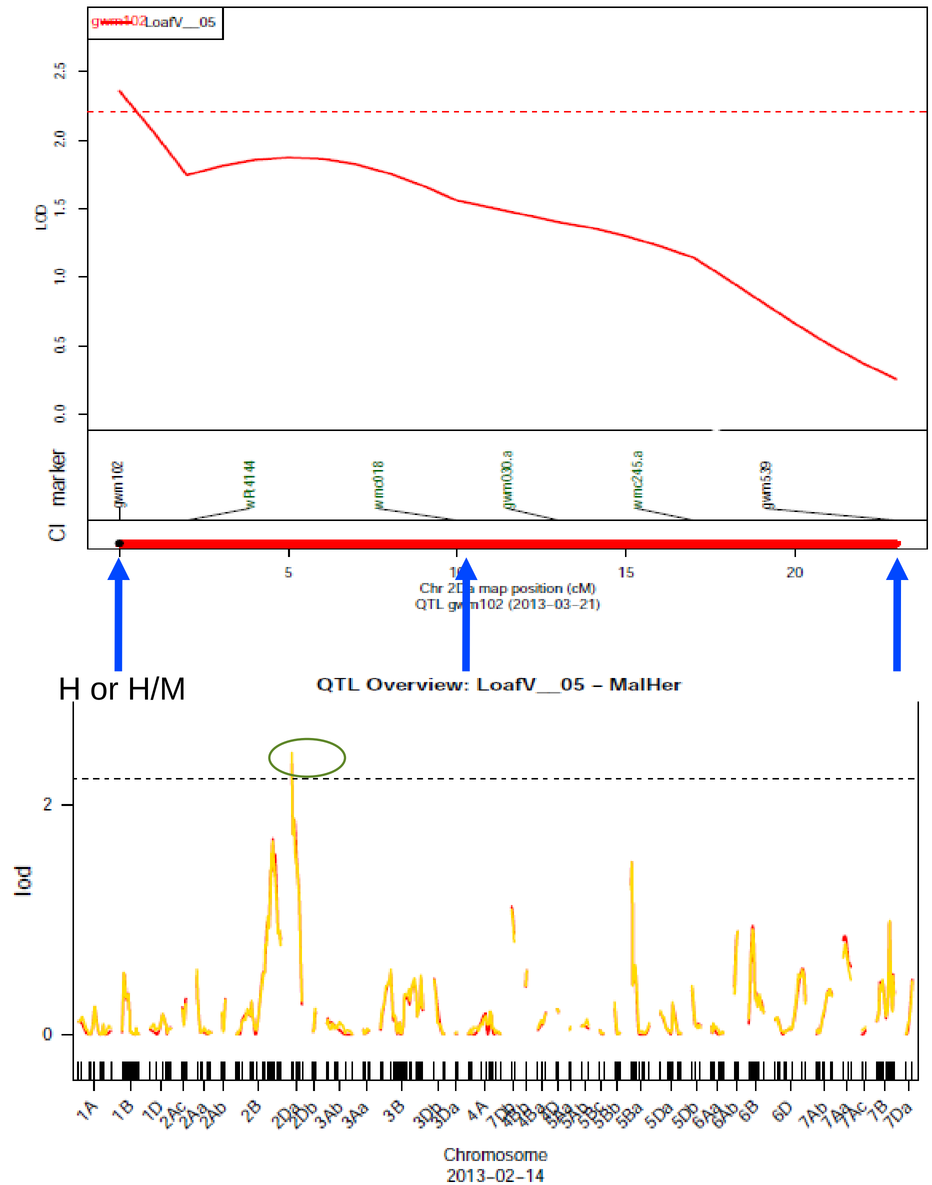


2D – Loaf Volume

2006



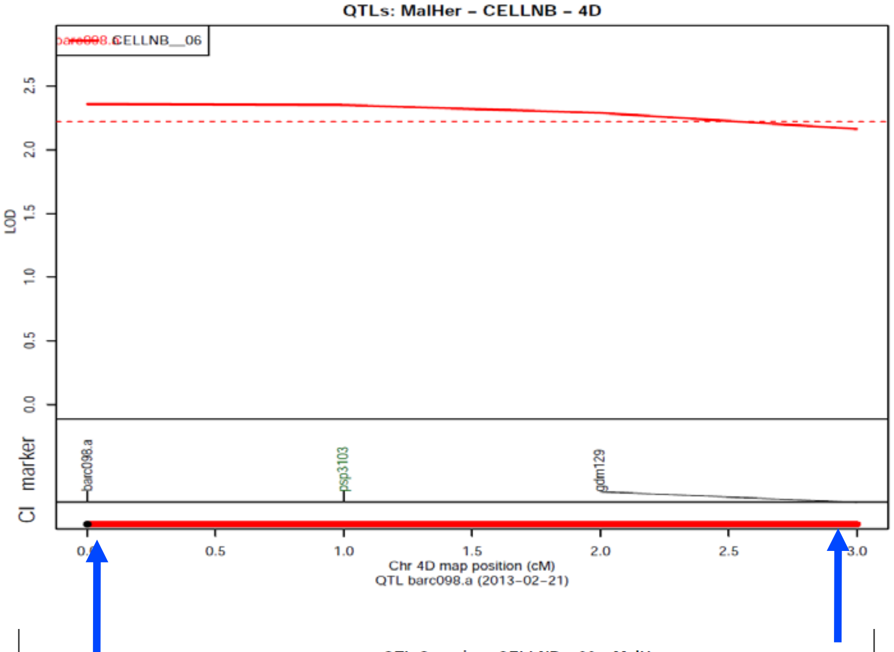
2005

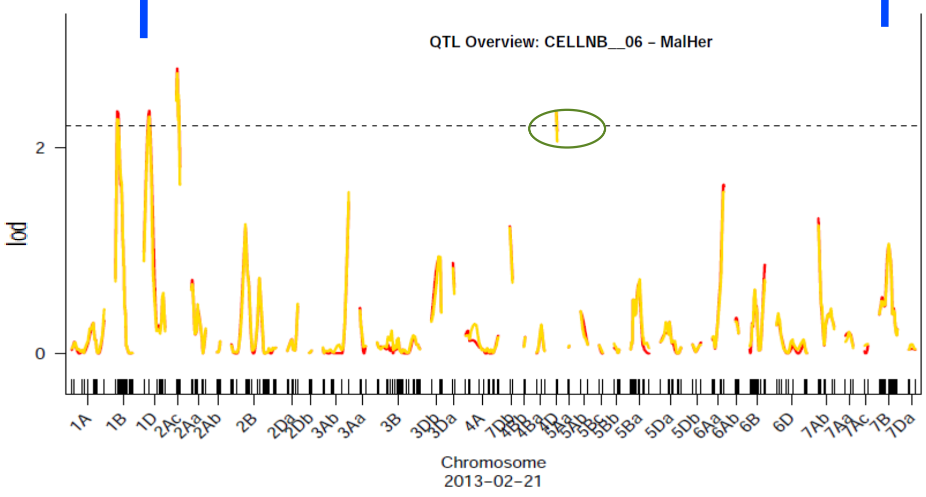


4D – Number of Cells

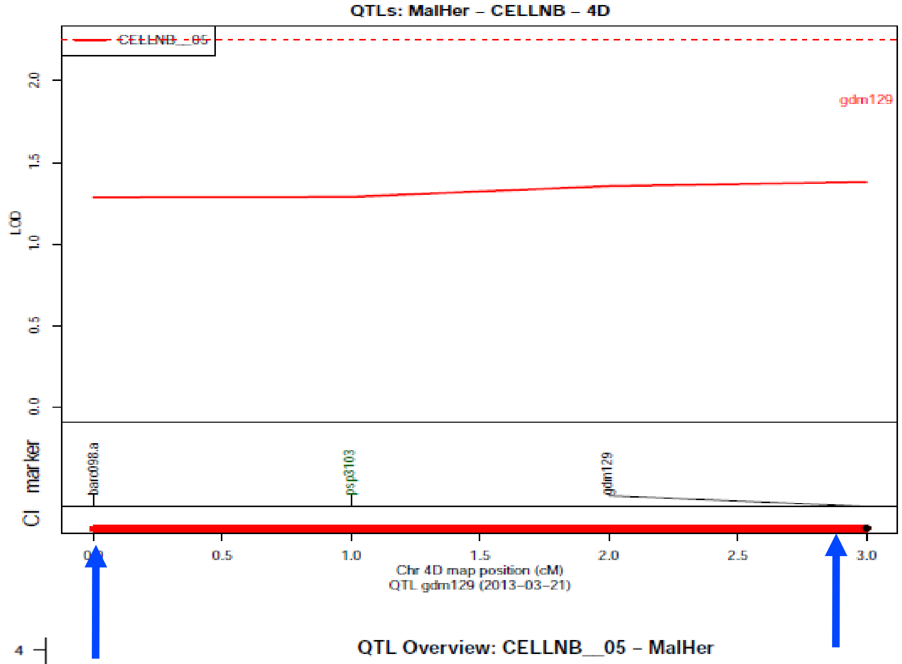
2006

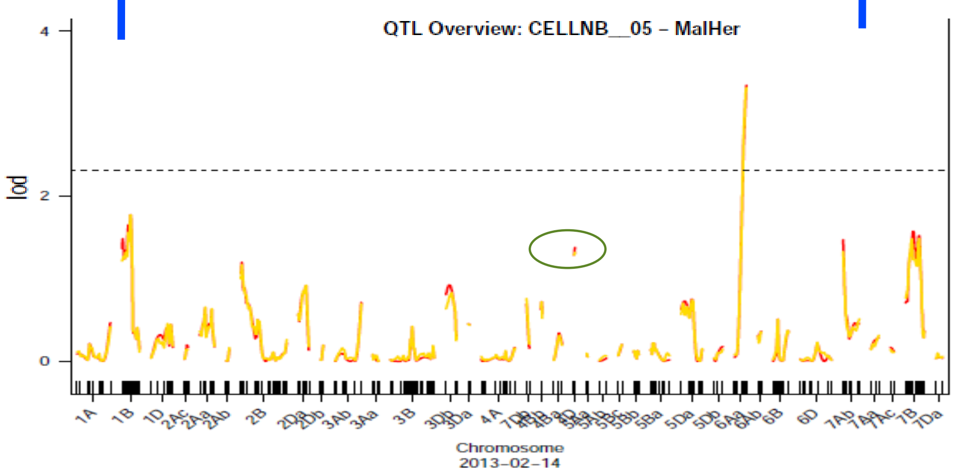
(also associated with 4D: Wall thickness, Cell diameter, Coarse cell volume)





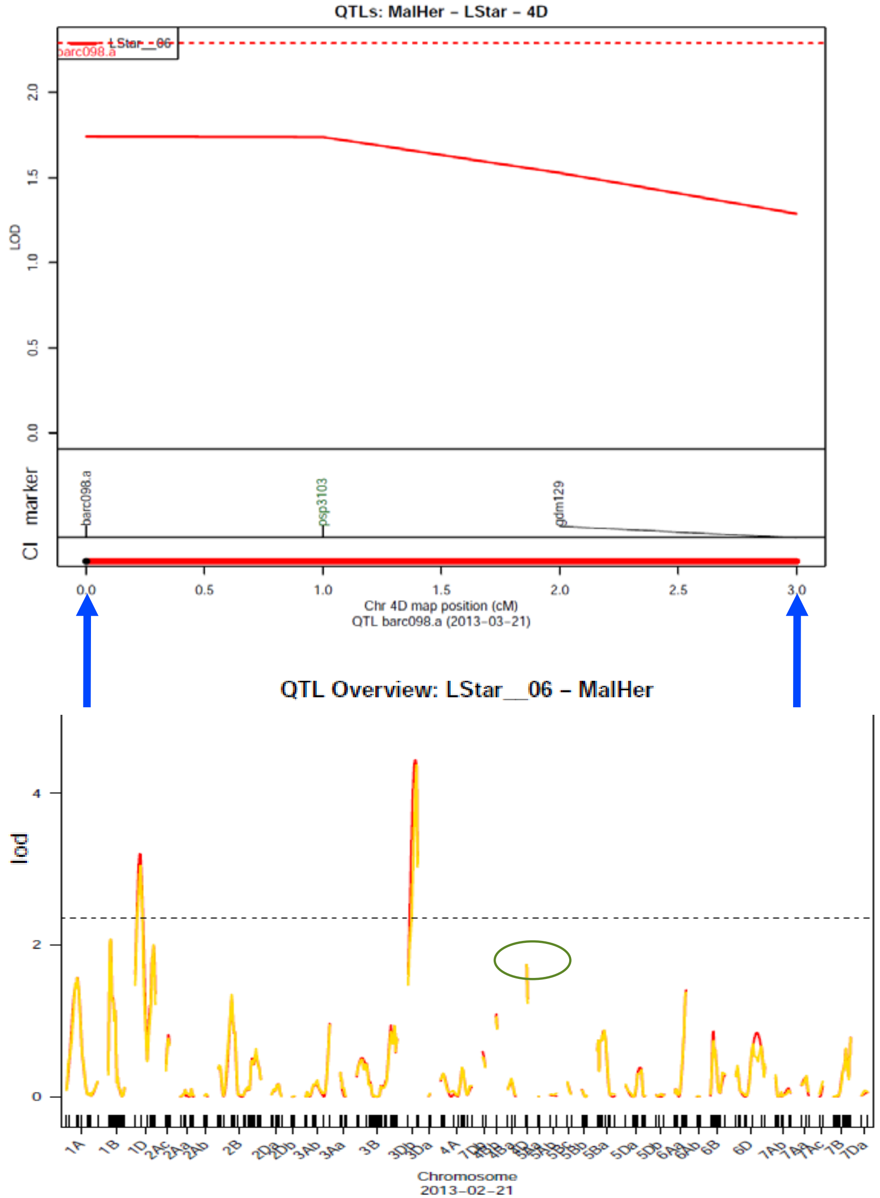
2005



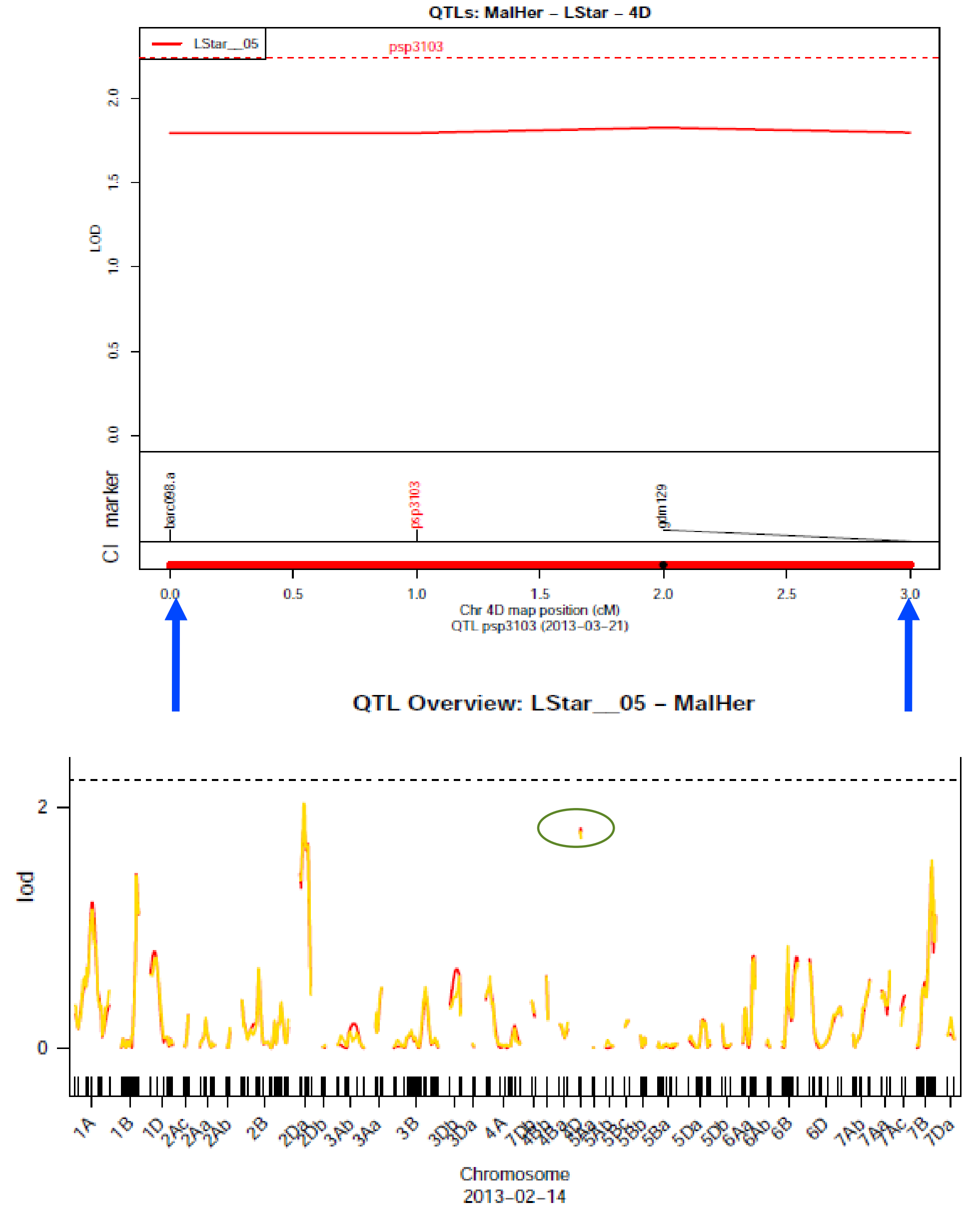


4D – L*

2006



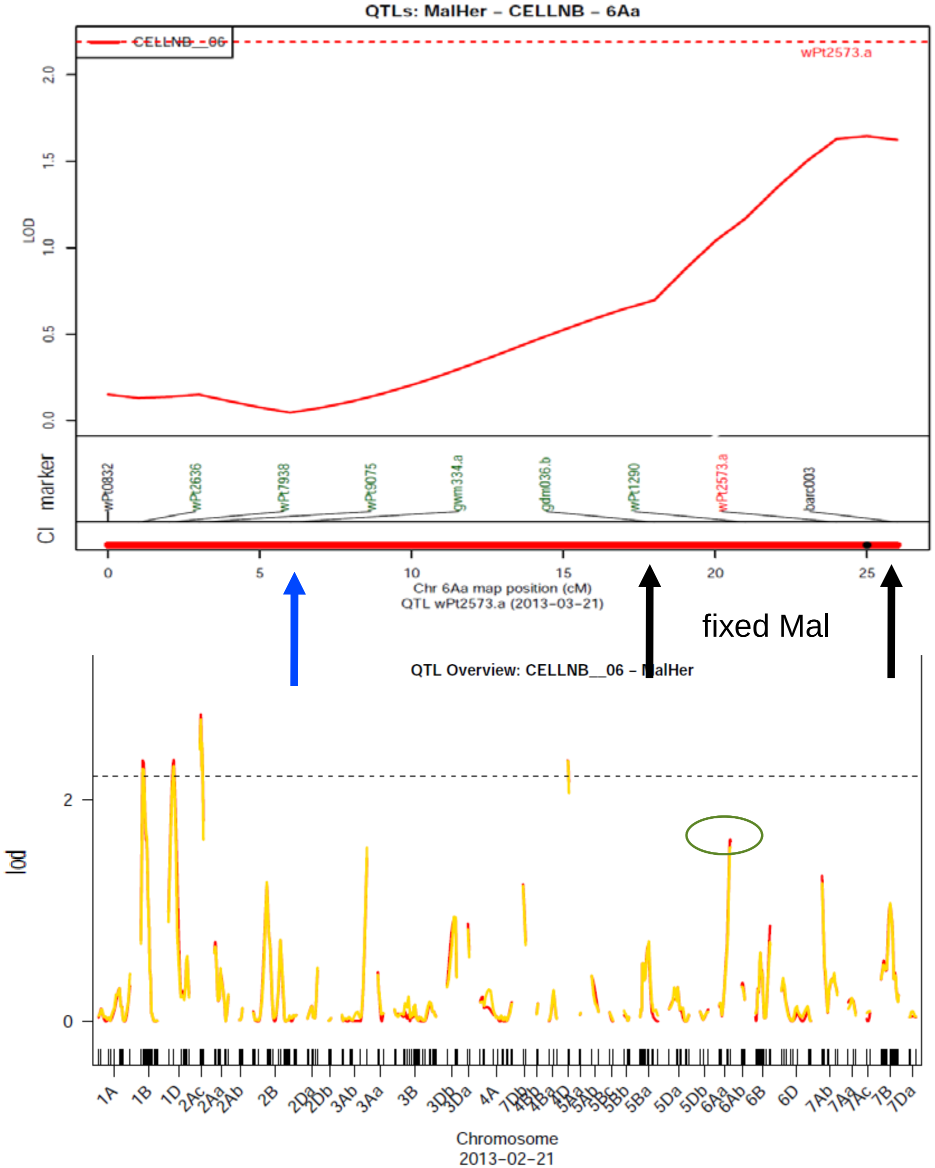
2005



6A – Number of Cells

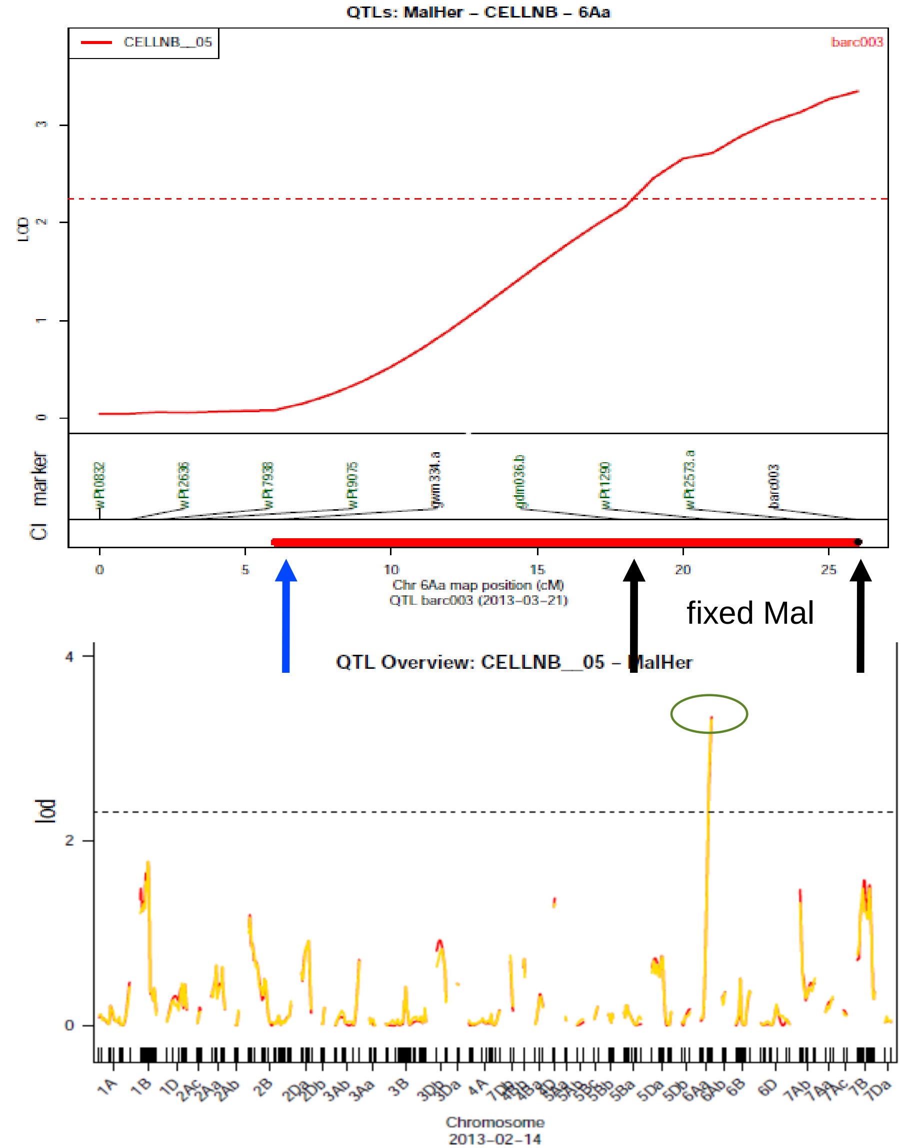
2006

(also associated with 6A: Coarse cell volume.)



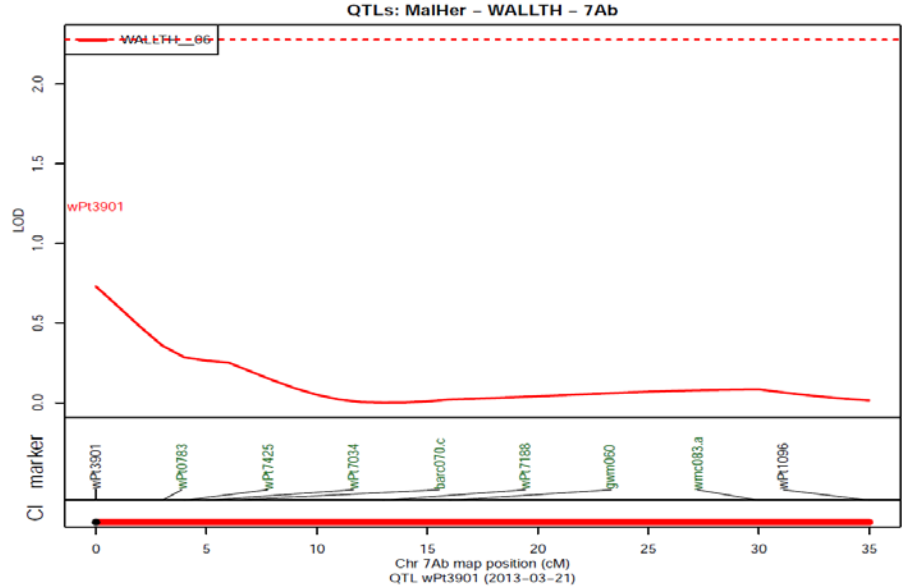
2005

(also associated with 6A: Coarse cell volume, Cell contrast, Cell non-uniformity, Cell volume, Cell volume map, Cell volume range, Relative volume range, Wall thickness.)

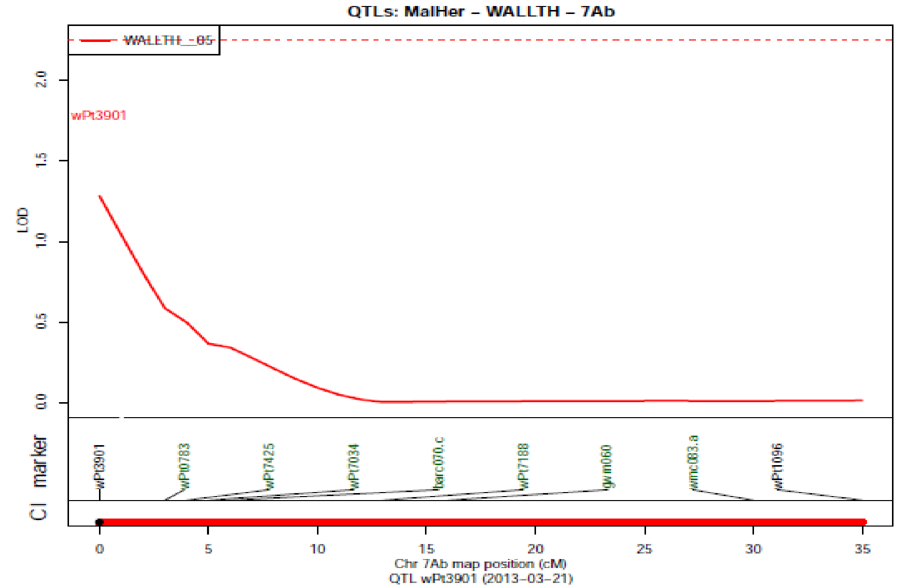


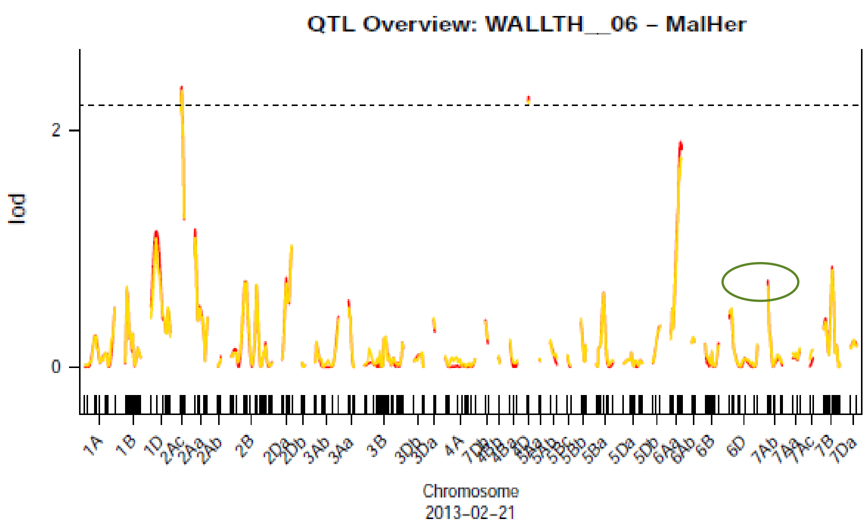
7A – Wall Thickness

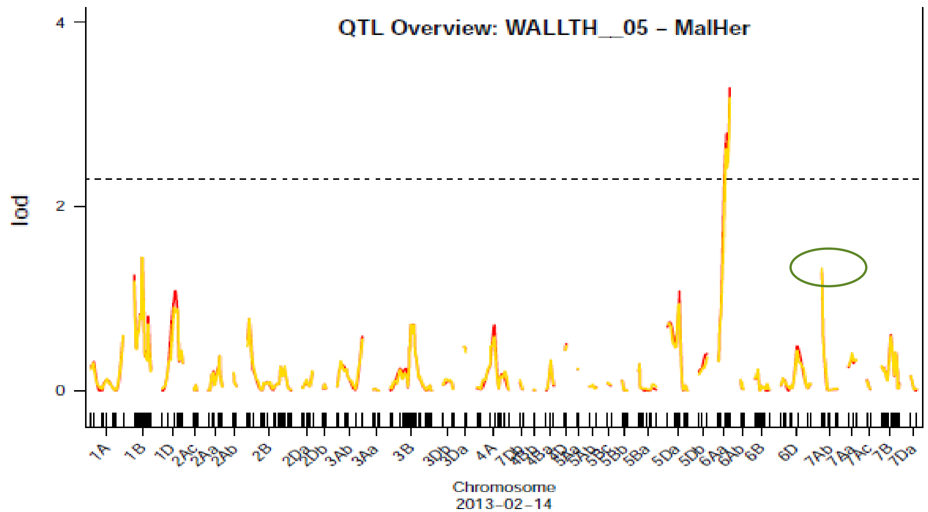
2006



2005

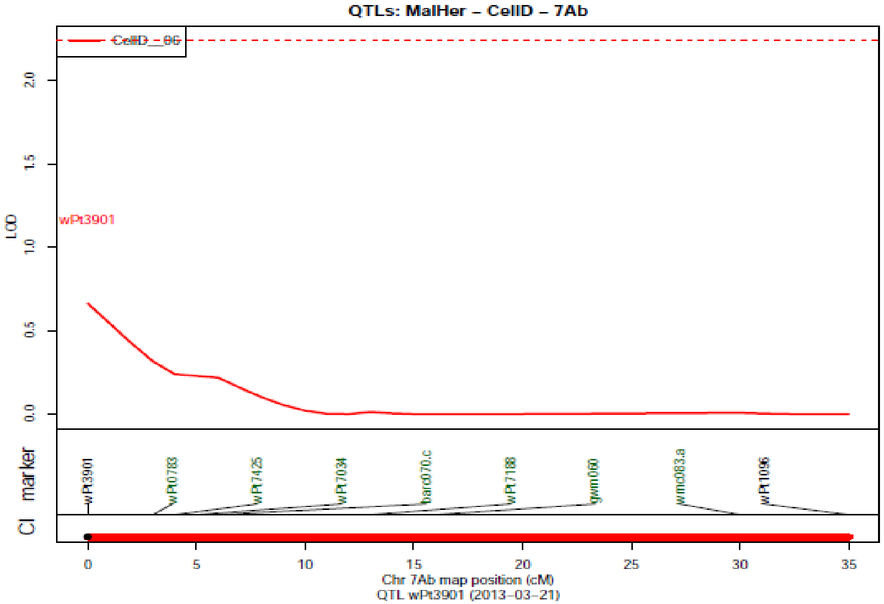






7A – Cell Diameter

2006



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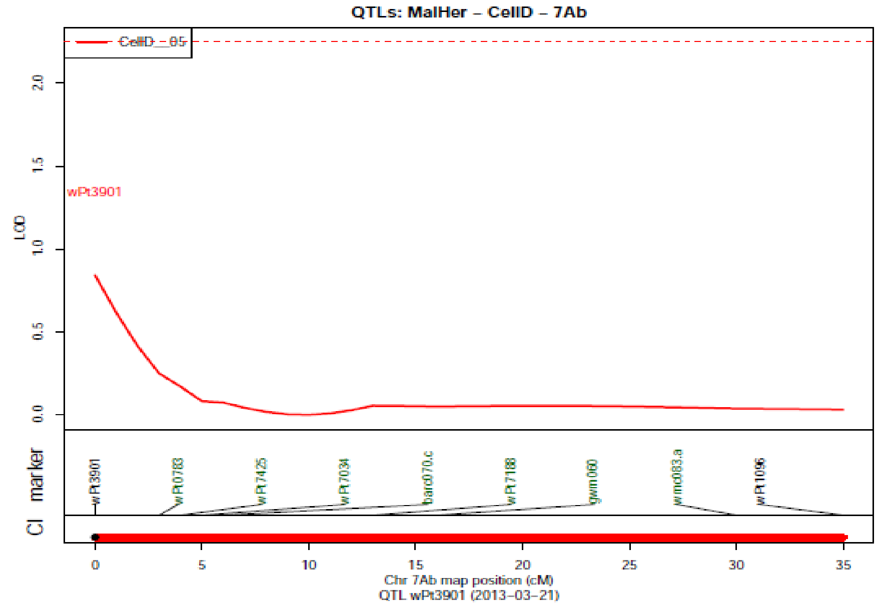
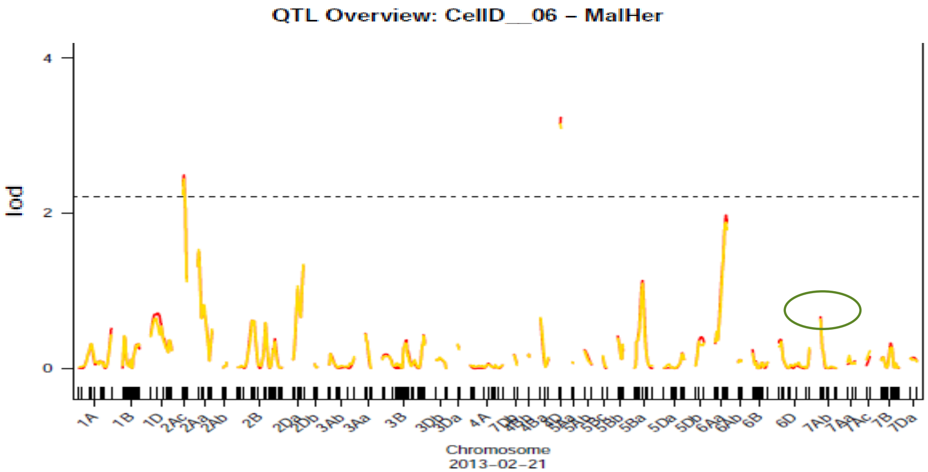
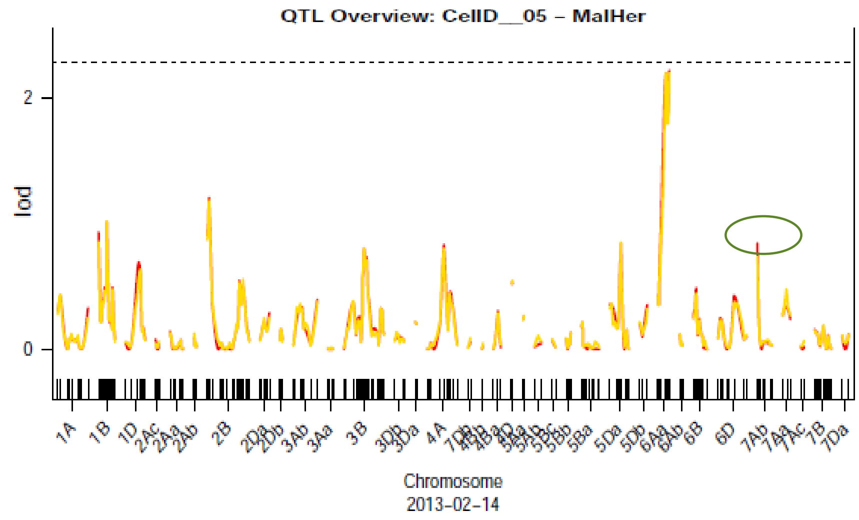
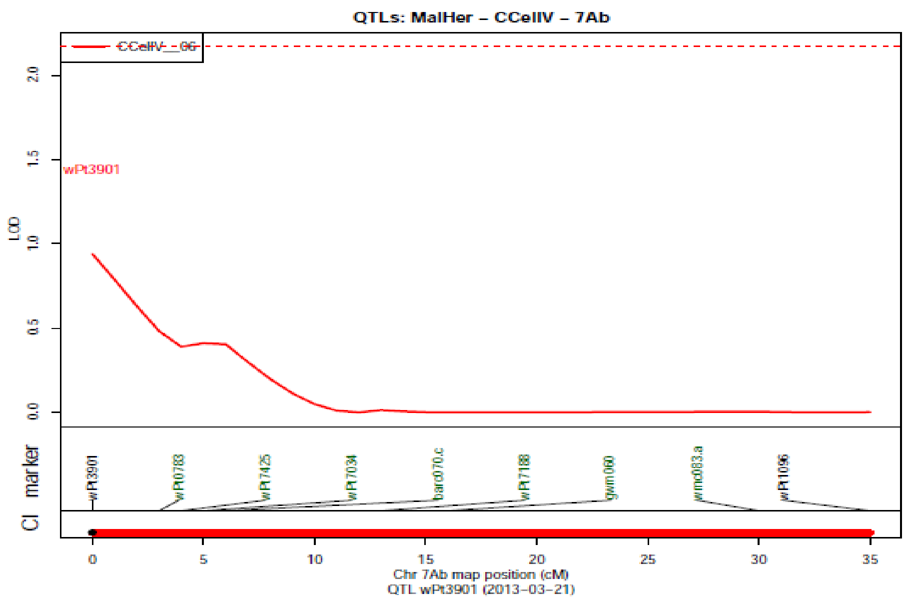


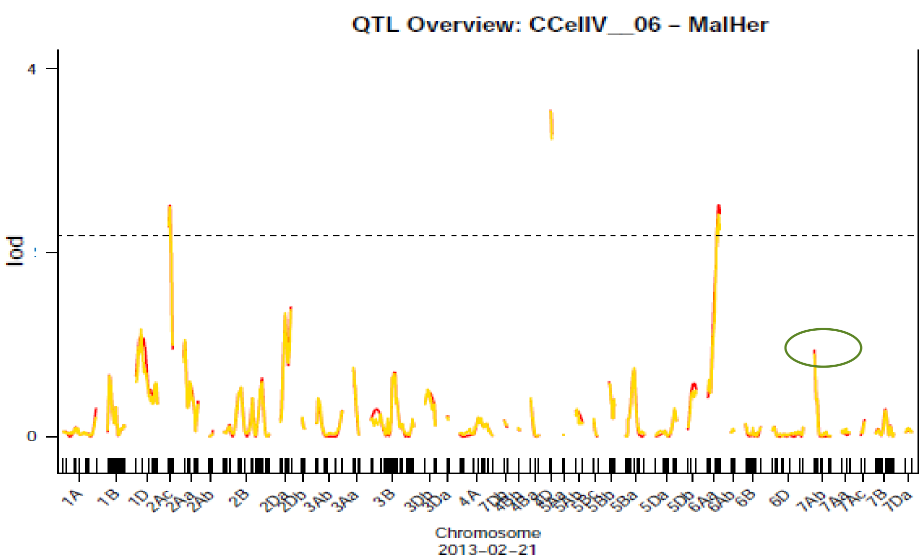




7A – Coarse Cell Volume (& Cell volume)

2006





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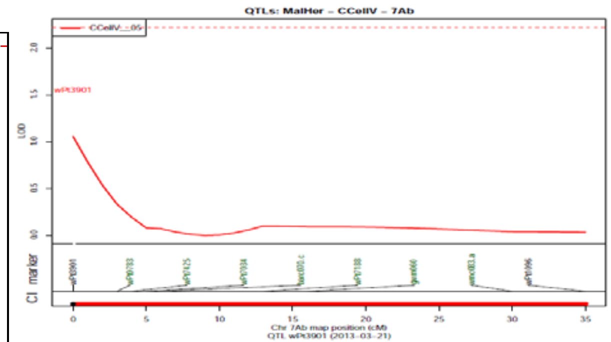
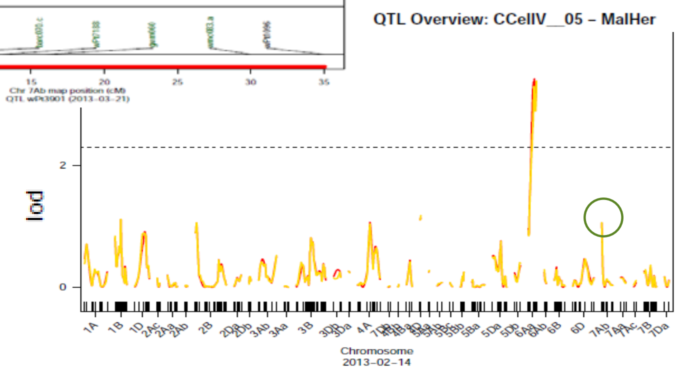
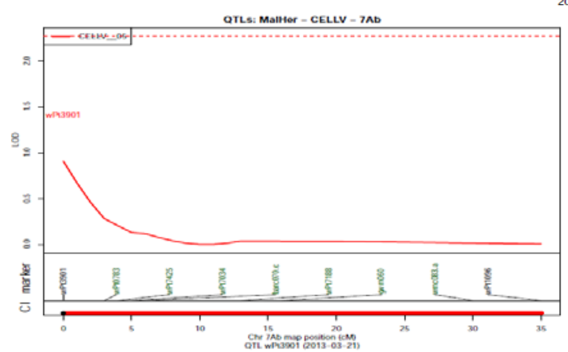
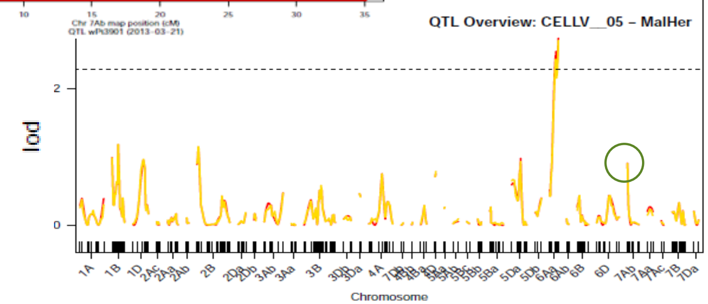


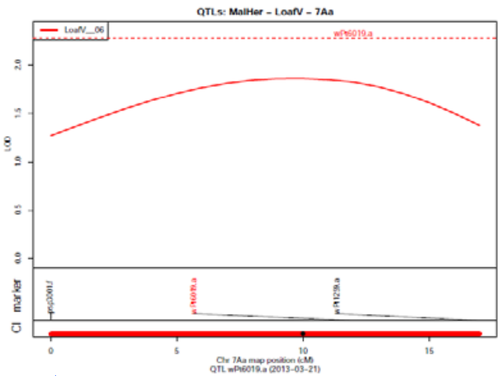


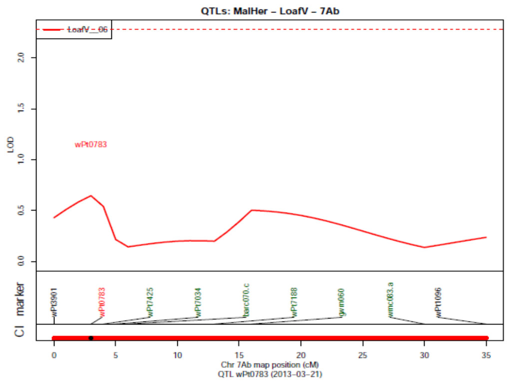


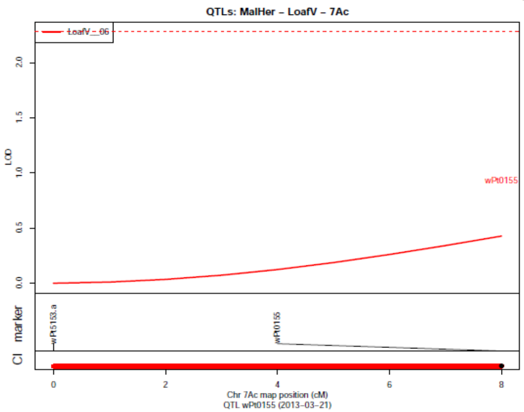


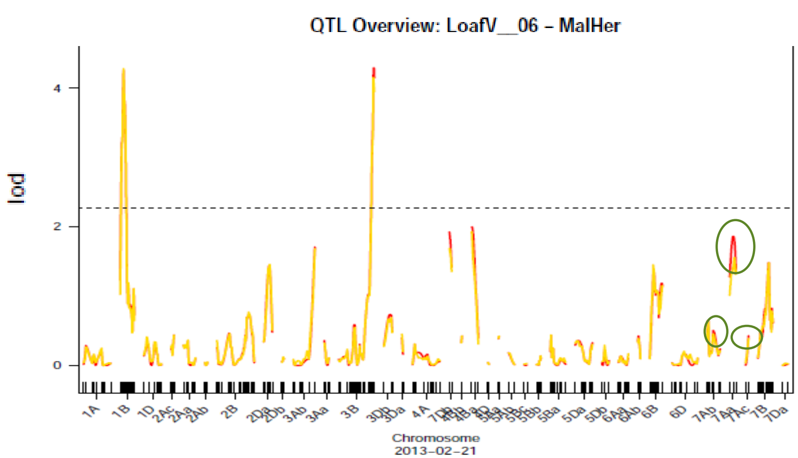
7A – Loaf Volume

2006

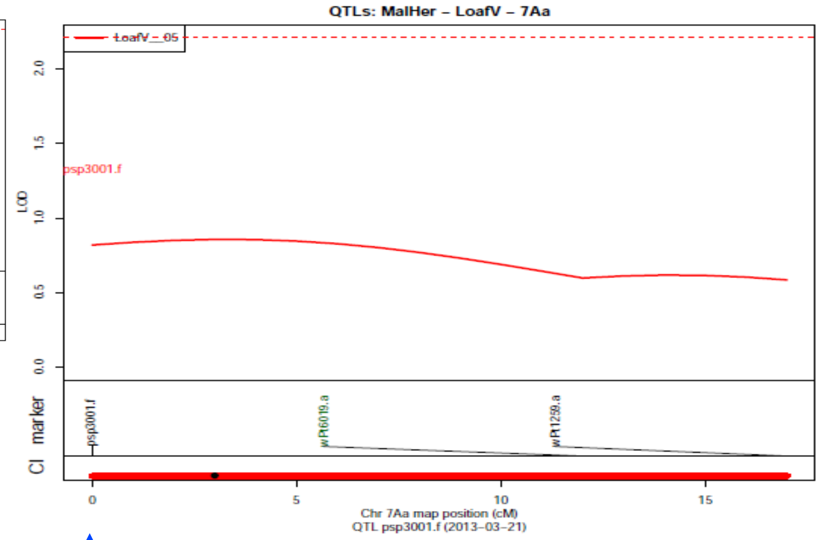


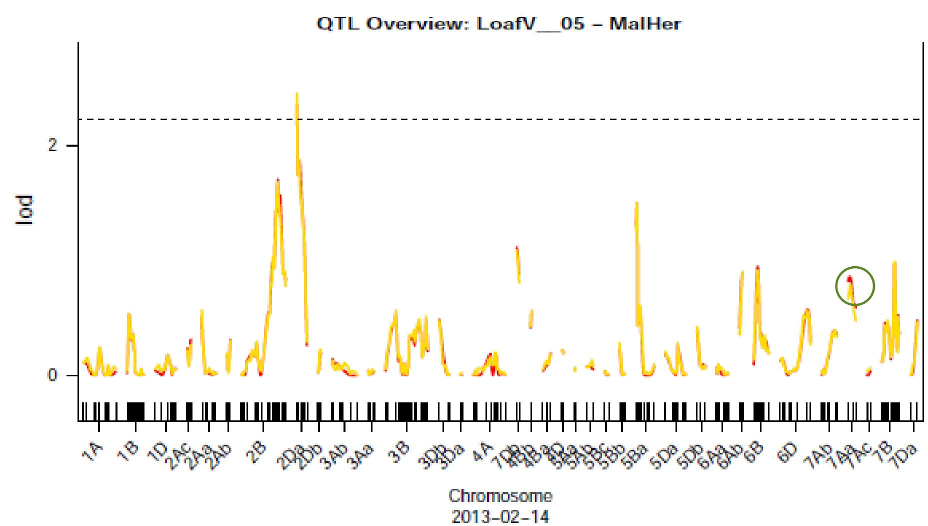






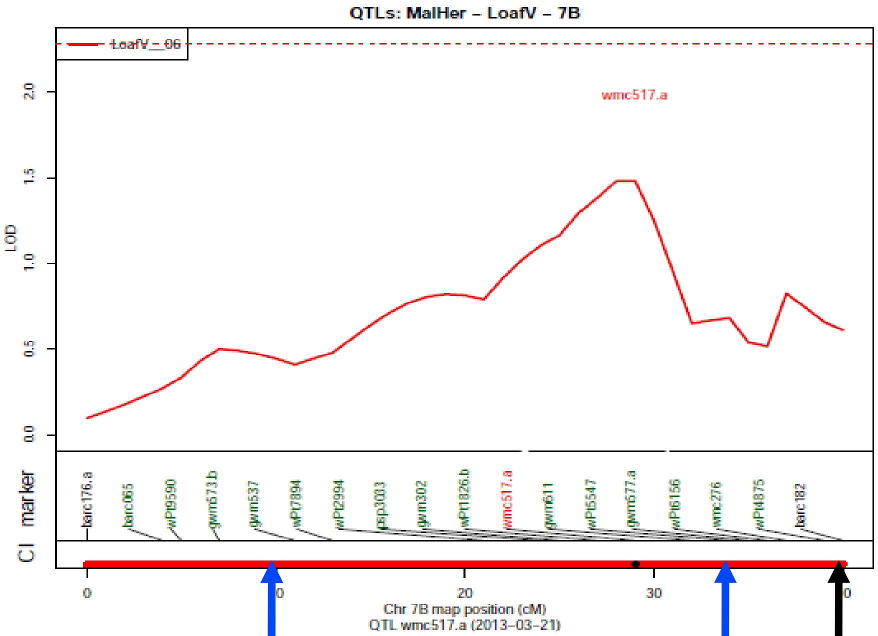
2005

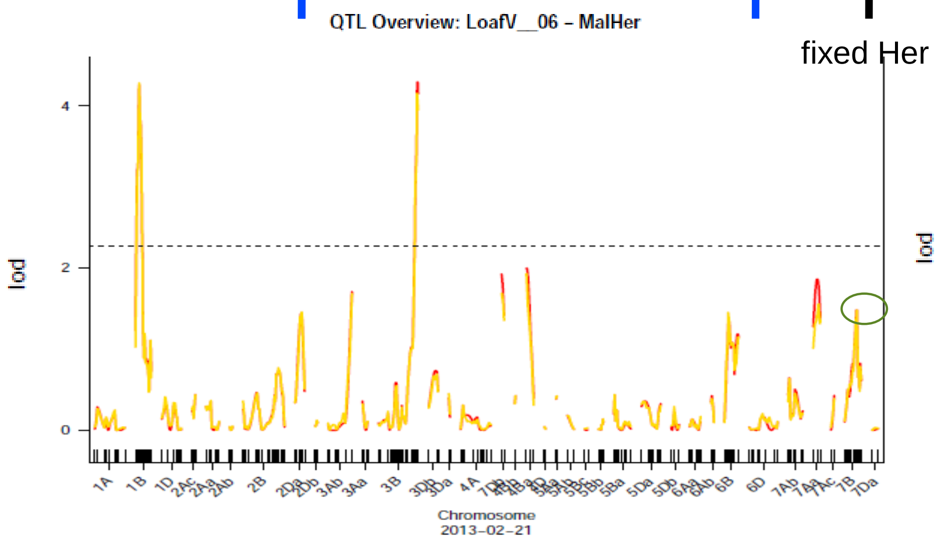




7B – Loaf Volume

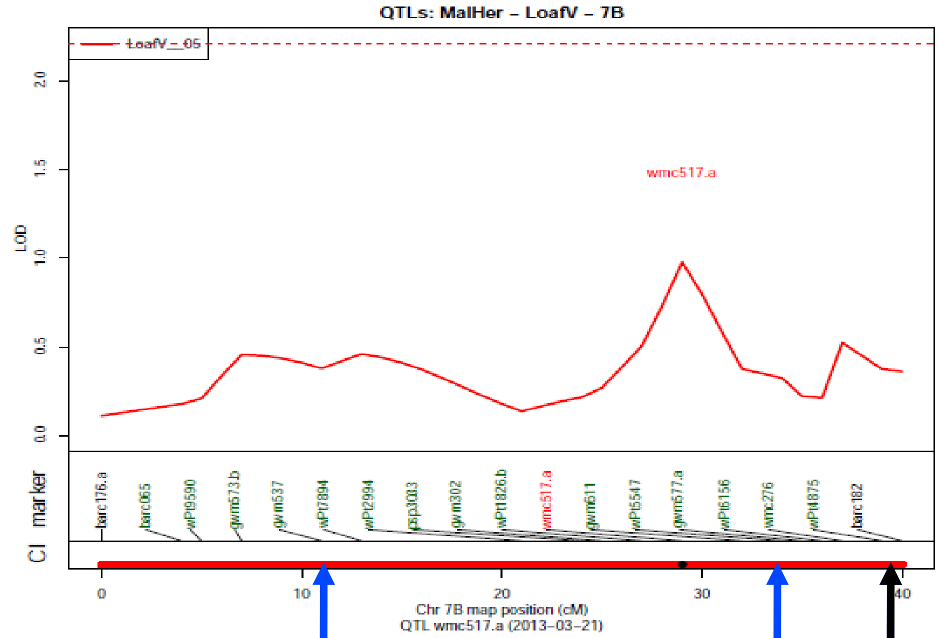
2006

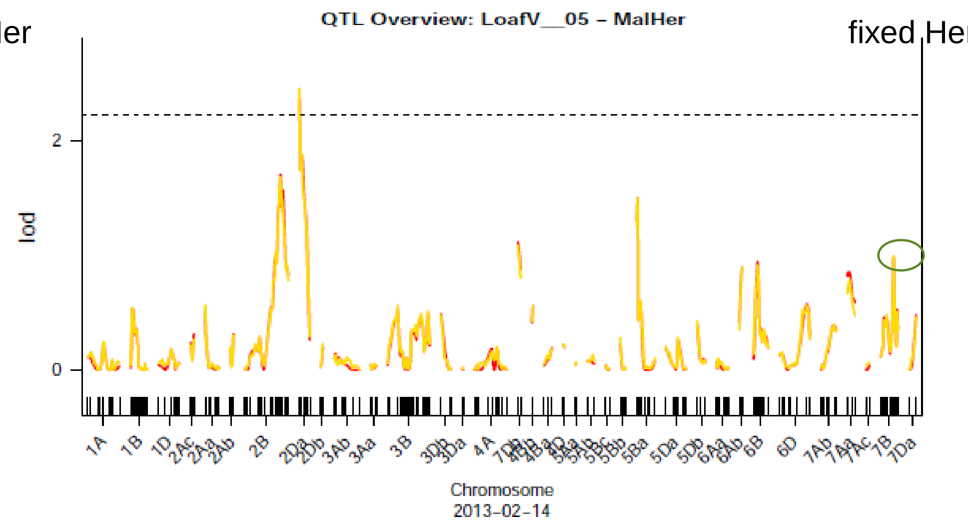




2005

(also associated with 7B: a*, Left break height)





Acknowledgements

JIC current

Cathy Mumford

Sue Freeman

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JIC WGIN past

Simon Orford

Michelle Leverington Waite

Lesley Fish

John Snape

Wheat functionality team

22/03/13

WGIN SavannahXRialto Drought Trial: Sutton Bonnington

2011: irrigated (U) and unirrigated (U)

- grain yield (GRYLD) : I/U
- thousand grain weight (TGRWT) : I/U
- grains per square meter (GRpsqm): I/U
- ear per square meter (EARpsqm): I/U
- above ground dry mass per square meter (AGDM): I/U
- harvest index (HI): I/U
- days to anthesis date (DTAD): U
- normalised vegetative index (NDVI): U
- leaf rolling score (LFCURL): U
- Canopy temperature (CTEMP): U
- dry mass of stem water soluble carbohydrate (StemWSC): U - not done
- C^{13} discrimination for grain (Cdelta): U - not done

WGIN SavannahXRialto Drought Trial: Norwich

2011 and 2012: very dry and very wet, resp.

- grain yield (GRYLD): 11/12*
- days to ear emergence (DTEM): 11/12**
- thousand grain weight (TGRWT) : 11*
- height (Ht): 11/12
- grain length (GRLG) : 11
- grain width (GRWD) : 11
- grain surface area (GRSA) : 11
- leaf senescence (LFSEN): 11 - in progress

* Traits shared with Sutton Bonnington trial.

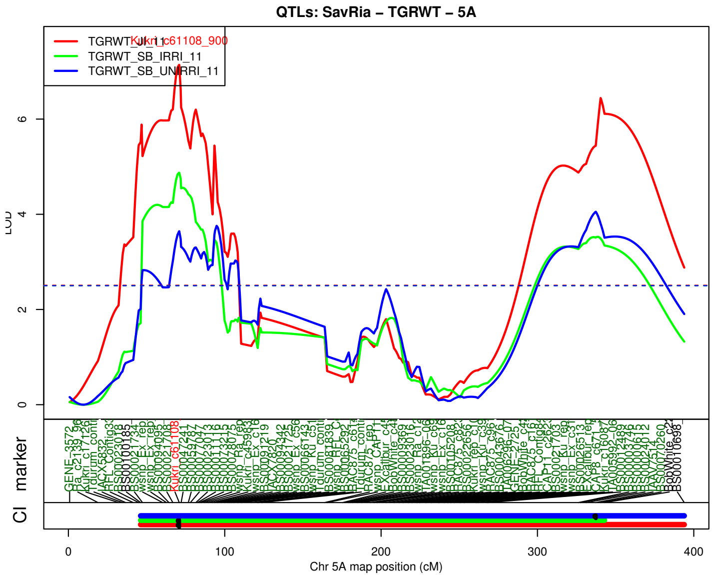
** Trait can be compared to DTAD in Sutton Bonnington trial.

Genetic Map

NIMBLEGEN SavXRia Map, provided by Keith Edwards, Bristol

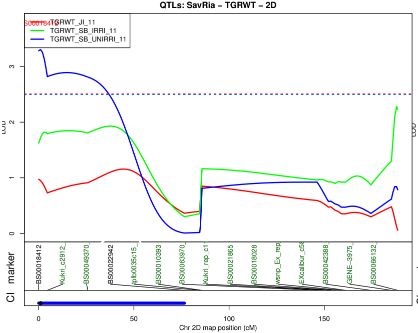
- 9239 markers on the original map
- reduced to 779 markers by discarding markers <1 cM.
- a map including SSR markers and SNP markers is in progress.

Comparison of QTLs from trials: TGRWT

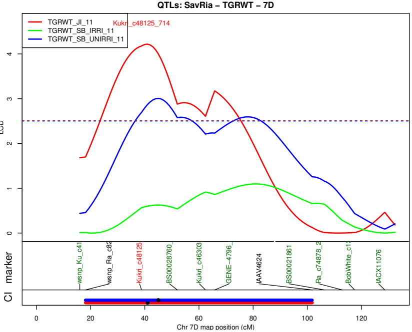


'singing from the same hymn sheet'

More TGRWT

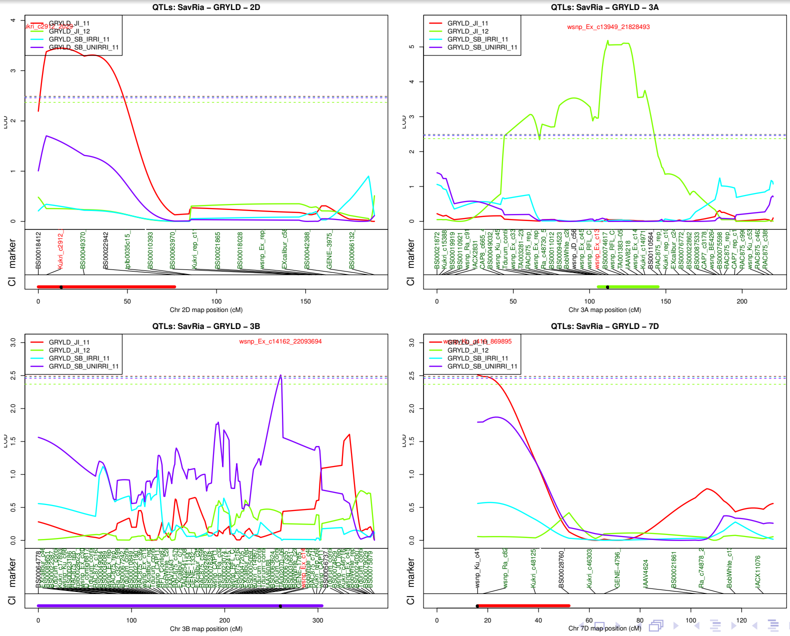


just SB 'drought'



both 'drought' environments

QTLs for GRYLD



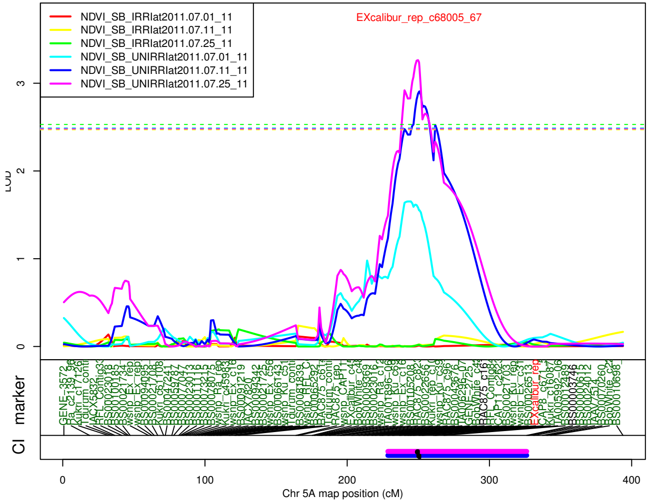
'drought' QTLs: 2D, 7D

SavXRia Sutton Bonnington QTLs

chr	pos	LOD	var	mean	add eff	on	marker	trait	env
1D	28	3.1	12.9	0.5	-0.008	S	RAC875_c78062	HI	IRRI11
4D	17.8	2.7	11.1	0.5	0.008	R	GENE-2812	HI	IRRI11
4A	191.6	2.5	7.7	50.8	-0.8	S	BS00023164	TGRWT	IRRI11
5A	70.8	5.8	20.1	50.8	-1.35	S	Kukri_c61108	TGRWT	IRRI11
6A	129	4	13.1	50.8	-1.1	S	EXcalibur_c52196	TGRWT	IRRI11
2D	3	3	12	343	12.9	R	Kukri_c2912	EARNBpsqm	UNIRRI11
7A	0	3.9	16	343	15.1	R	EXcalibur_c48636	EARNBpsqm	UNIRRI11
2D	3	4.4	17.3	16267	703	R	Kukri_c2912	GRpsqm	UNIRRI11
3B	261	3	11.3	16266	-585	S	Ex_c14162_22093694	GRpsqm	UNIRRI11
3B	260	2.4	11.3	7.6	-0.19	S	Ex_c14162_22093694	GRYLD	UNIRRI11
3A	144.9	2.6	7.2	47	1.2	R	BS00110564	TGRWT	UNIRRI11
5A	337.3	2.8	7.7	47	-1.3	S	IAAV7514	TGRWT	UNIRRI11
7D	45	2.9	8.1	47.2	-1.1	S	Kukri_c48125	TGRWT	UNIRRI11
2D	34	8.2	30.3	4.4	0.28	R	BS00049370	LFCURL	UNIRRI11
2B		3.0	17.5	4.4	0.18	R	BS00098024	LFCURL	UNIRRI11
5A	119.8	1.4	4.2	4.4	0.18	R	RAC875_c61493	LFCURL	UNIRRI11
5A	249.8	3.2	15.1	0.32	-0.011	S	EXcalibur_rep_c68005	NDVI	UNIRRI11

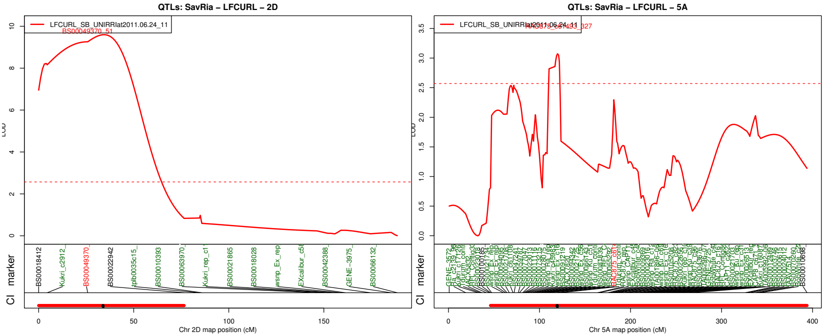
- both environments: TGRWT (5A)
- irrigated: HI (1D, 4D), TGRWT (4A,6A)
- unirrigated: EARpsqm (2D, 7A), GRpsqm (2D,3B), GRYLD (3B), LFCURL (2B, 2D, 5A), NDVI (5A)
- no qtls: AGDM, CTEMP
- not done: StemWSC, Cdelta

QTL 5A for NDVI



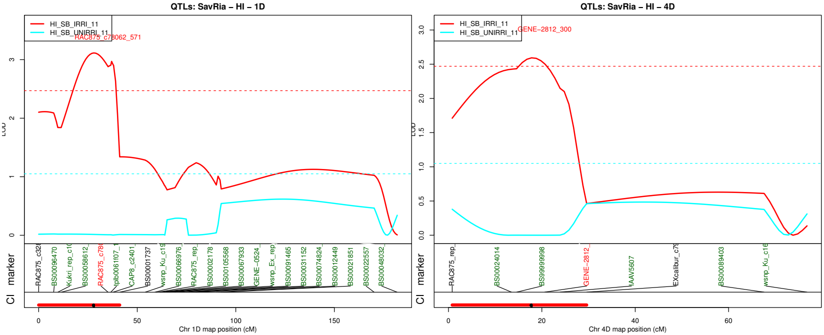
NDVI QTL 5A only under 'drought'.

QTLs for LFCURL



LEAFCURL QTL 2D coincides with GRpsqm, 5A NOT with NDVI.

QTLs for HI



HI QTLs (1D, 4D) only found under irrigated conditions.

SavXRia JIC QTLs

chr	pos	LOD	var	mean	add eff	on	marker	trait	env
4A	163	4.1	15.5	300	0.7	R	BS00080927	DTEM	JI11
7D	21	3.5	13.4	300	0.6	R	Ra_c8297_14095831	DTEM	JI11
3A	74.6	3	8.8	41.3	-0.6	S	TA003281-2379	DTEM	JI12
4A	136.4	5.4	16.9	41.3	0.7	R	RAC875_c95150	DTEM	JI12
7D	128.6	4	12.1	41.3	0.5	R	IACX11076	DTEM	JI12
1A	54.8	4.2	7.4	6.9	0.09	R	IAAV3168	GRLG	JI11
3A	146	7.3	13.9	6.9	0.08	R	BS00110564	GRLG	JI11
5A	46.8	8.1	15.9	6.9	-0.1	S	BS00100185	GRLG	JI11
7A	295	3.1	5.4	6.9	0.1	R	BS00009995	GRLG	JI11
7D	40	7.7	15	6.9	-0.11	S	Kukri_c48125	GRLG	JI11
2D	13	3.8	14.8	4.7	0.19	R	Kukri_c2912	GRYLD	JI11
7D	16	2.7	10.2	4.7	-0.16	S	Ku_c416_869895	GRYLD	JI11
3A	112	5.1	21.5	8.6	0.5	R	Ex_c13949_21828493	GRYLD	JI12
1B	134.3	2.7	5.6	52.3	-1.7	S	CAP12_c6629	Ht	JI11
2A	295	5.3	11.4	52.3	-1.8	S	EXcalibur_c35919	Ht	JI11
3A	82	5.7	12.6	52.3	2.4	R	Ex_rep_c106152_90334299	Ht	JI11
6A	47.6	7.5	17.1	52.3	-2.4	S	RFL_Contig2954	Ht	JI11
2A	293.5	2.6	5.6	86.1	-2.7	S	EXcalibur_c35919	Ht	JI12
3A	85	11.4	29.8	86.1	4.4	R	Ex_rep_c106152_90334299	Ht	JI12
6A	82	7.5	17.8	86.1	-3.8	S	RFL_Contig2523_2130662	Ht	JI12
5A	70.8	6.9	20.8	53.6	-2.3	S	Kukri_c61108	TGRWT	JI11
7D	41	3.9	10.9	53.6	-1.8	S	Kukri_c48125	TGRWT	JI11

QTL summary

	JI11	JI12	SB11 IRRI	SB11 UNIRRI	JI11	SB11 IRRI	SB11 UNIRRI	SB11 UNIRRI	SB11 UNIRRI	SB11 IRRI	SB11 UNIRRI	SB11 UNIRRI	JI11	JI12	JI11	JI12	JI11	JI11
Trait:	GRYLD	GRYLD	GRYLD	GRYLD	TGRWT	TGRWT	TGRWT	EARNBpsqm	GRNBpsqm	HI	Leaf curl	NDVI	DTEM	DTEM	Height	Height	Grain length	Grain surface
Chr																		
1A					R												R	R
1B															S			
1D							S			S					R			
2A															S	S		
2B																		
2D	R						S	R	R		R							
3A		R					R							S	R	R	R	
3B				S					S									
3D																		
4A						S							R	R				
4B																		
4D										R								
5A					S	S	S				R	S					S	S
5B																		S
5D																		
6A						S									S	S		
6B																		
6D																		
7A								R									R	
7B																		
7D	R				S		S						R	R			S	S

Summary

- TGRWT 5A QTL (Sav) found in all environments tested.
- TGRWT 7D QTL (Sav) only found under 'drought'.
- GRYLD QTLs 2D (Ria) and 7D (Ria) only found under 'drought'.
- 2 QTLs for leaf rolling (LFCURL) on 2D (Ria) and 5A (Ria).
- LFCURL 2D coincides with EARNBpsqm and GRNBpsqm and GRYLD (all Ria).
- LFCURL 5A does not coincides with 5A TGRWT (Sav).
- HI QTLs 1D (Sav) and 4D (Ria) only found if irrigated.

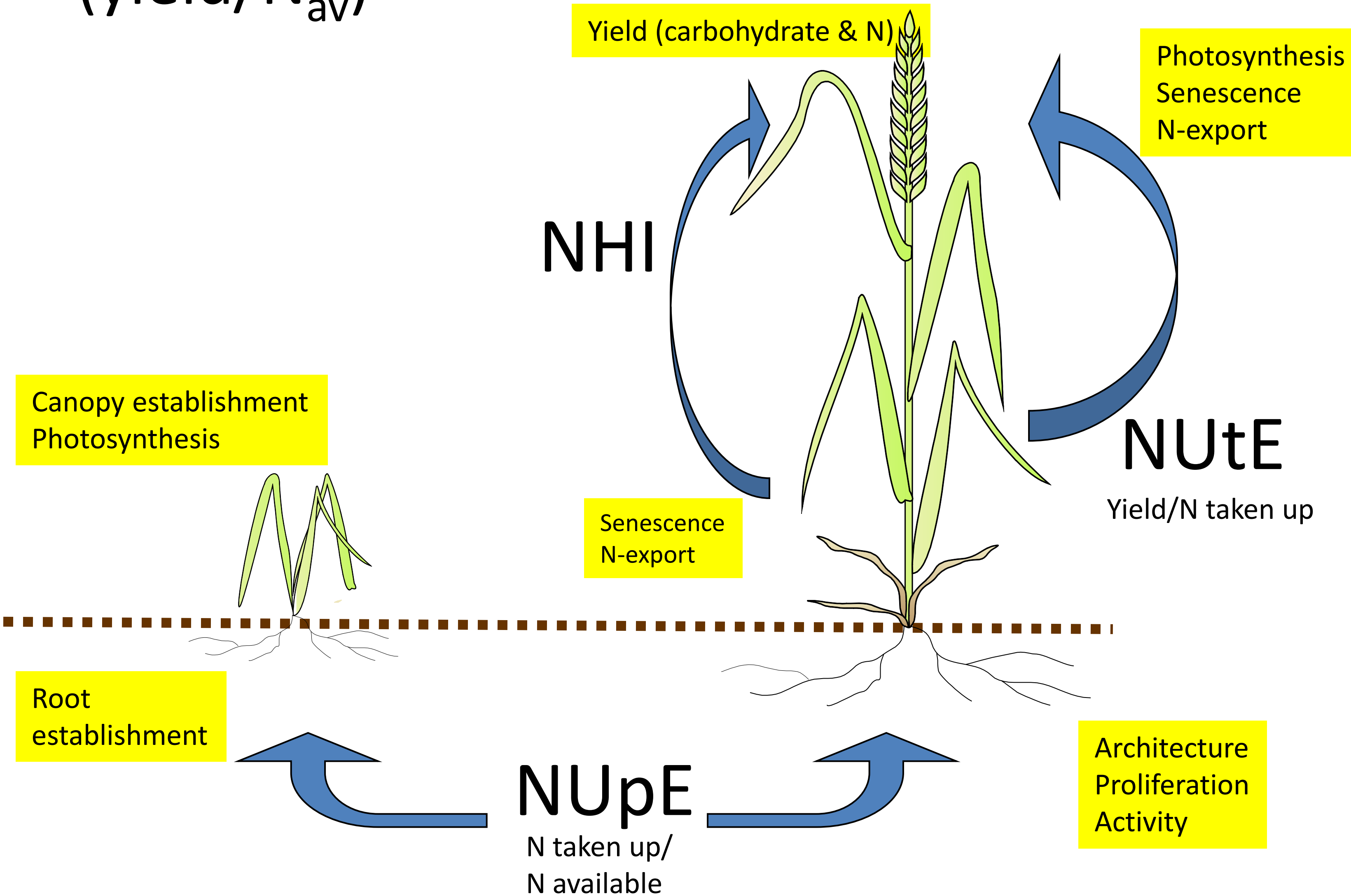
Objective 8 – Nitrogen update

M J Hawkesford

WGIN Management Meeting

25th March 2013

$NUE = NUpE \times NUtE$
$(yield/N_{av})$

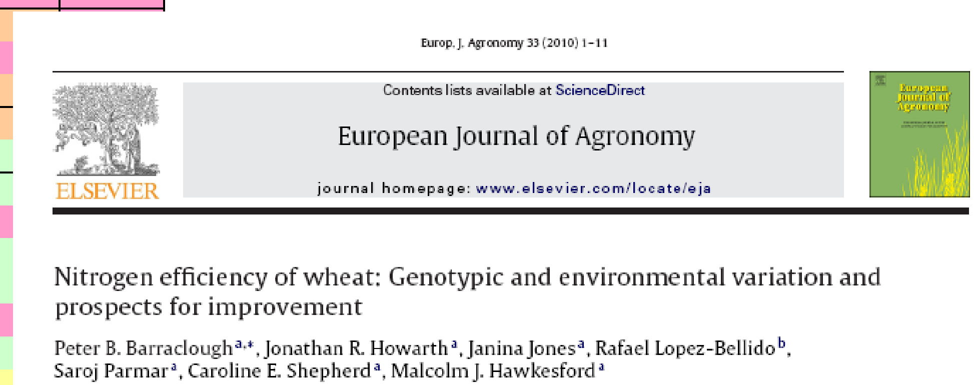


Variety Performance at 200 kg-N/ha (2004-08)

Variety	Code	Nabim	Years	Yield	%N	Uptake	Utilisation
Avalon	AV	1	5				
Flanders	FL	1	1				
Hereward	HE	1	5				
Hurley	HU	1	5				
Malacca	MA	1	5				
Mercia	ME	1	4				
Maris Widgeon	MW	1	5				
Shamrock	SH	1	4				
Solstice	SL	1	5				
Spark	SP	1	1				
Xi 19	XI	1	5				
Cadenza	CA	2	5				
Cordiale	CO	2	3				
Einstein	EI	2	1				
Lynx	LY	2	5				
Rialto	RL	2	1				
Scorpion	SC	2	1				
Soissons	SS	2	5				
Beaver	BE	3	4				
Claire	CL	3	4				
Riband	RI	3	5				
Robigus	RO	3	4				
Istabraq	IS	4	4				
Napier	NA	4	3				
Savannah	SA	4	4				
Paragon (spring)	PA	1	5				
Chablis (spring)	CH	2	1				
Arche	AR	F	1				
Batis	BA	G	5				
Caphorn	CP	F	1				
Cappelle Desprez	CD	F	1				
Enorm	EN	G	1				
Isengrain	IG	F	1				
Monopol	MO	G	5				
Opus	OP	G	1				
PBis	PB	G	1				
Petrus	PE	G	1				
Sokrates	SK	G	5				
Zyta	ZY	P	1				

Upper-Q
Inter-Q
Inter-Q
Lower-Q

Summary of variety performance (quartile rankings) based on 2004-07 WGIN datasets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journal homepage: www.elsevier.com/locate/eja

Nitrogen efficiency of wheat: Genotypic and environmental variation and prospects for improvement

Peter B. Barraclough[a,*], Jonathan R. Howarth[a], Janina Jones[a], Rafael Lopez-Bellido[b], Saroj Parmar[a], Caroline E. Shepherd[a], Malcolm J. Hawkesford[a]

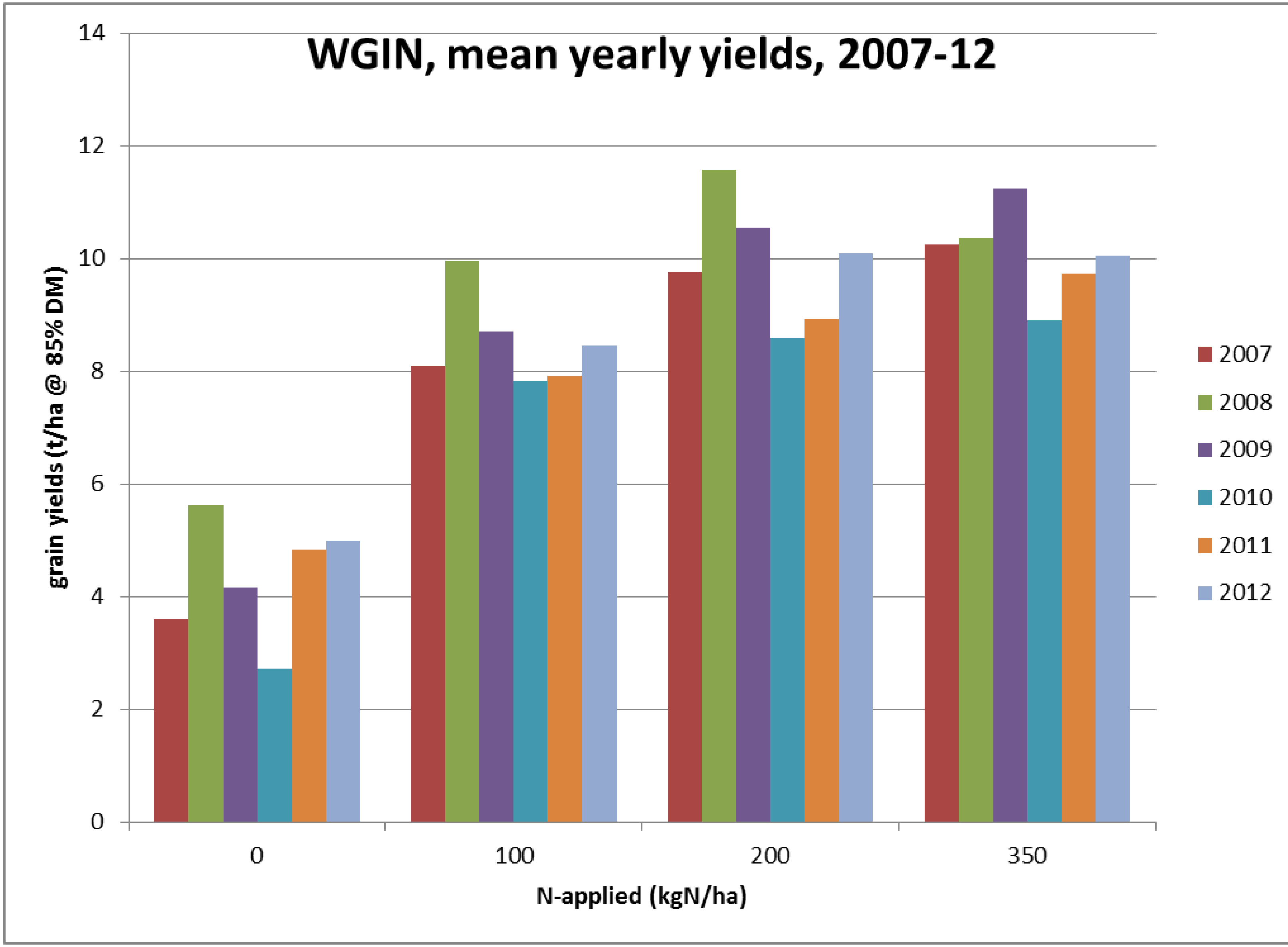
EJA (2010) 33, 1-11

2013

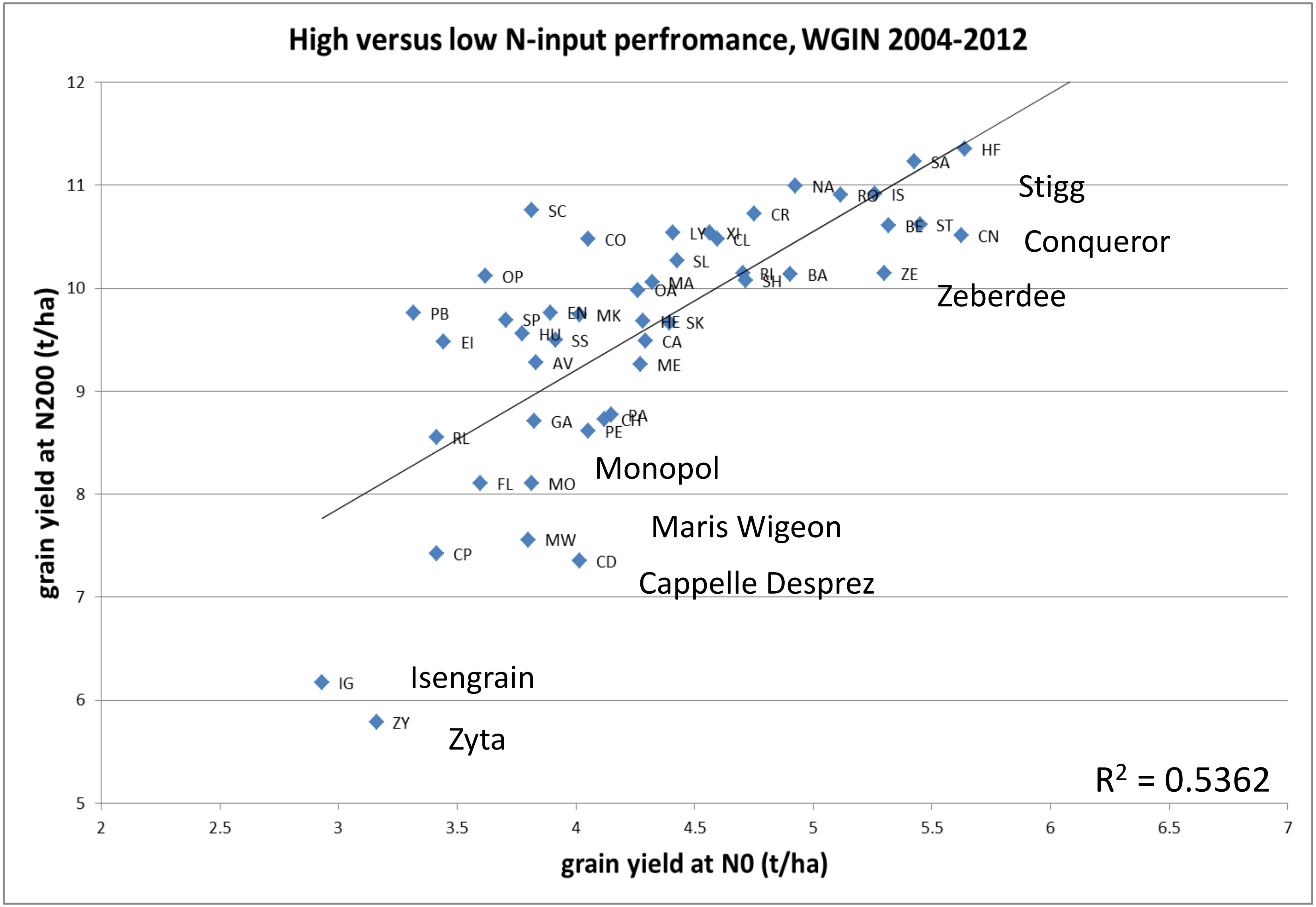
2012 Diversity Trial

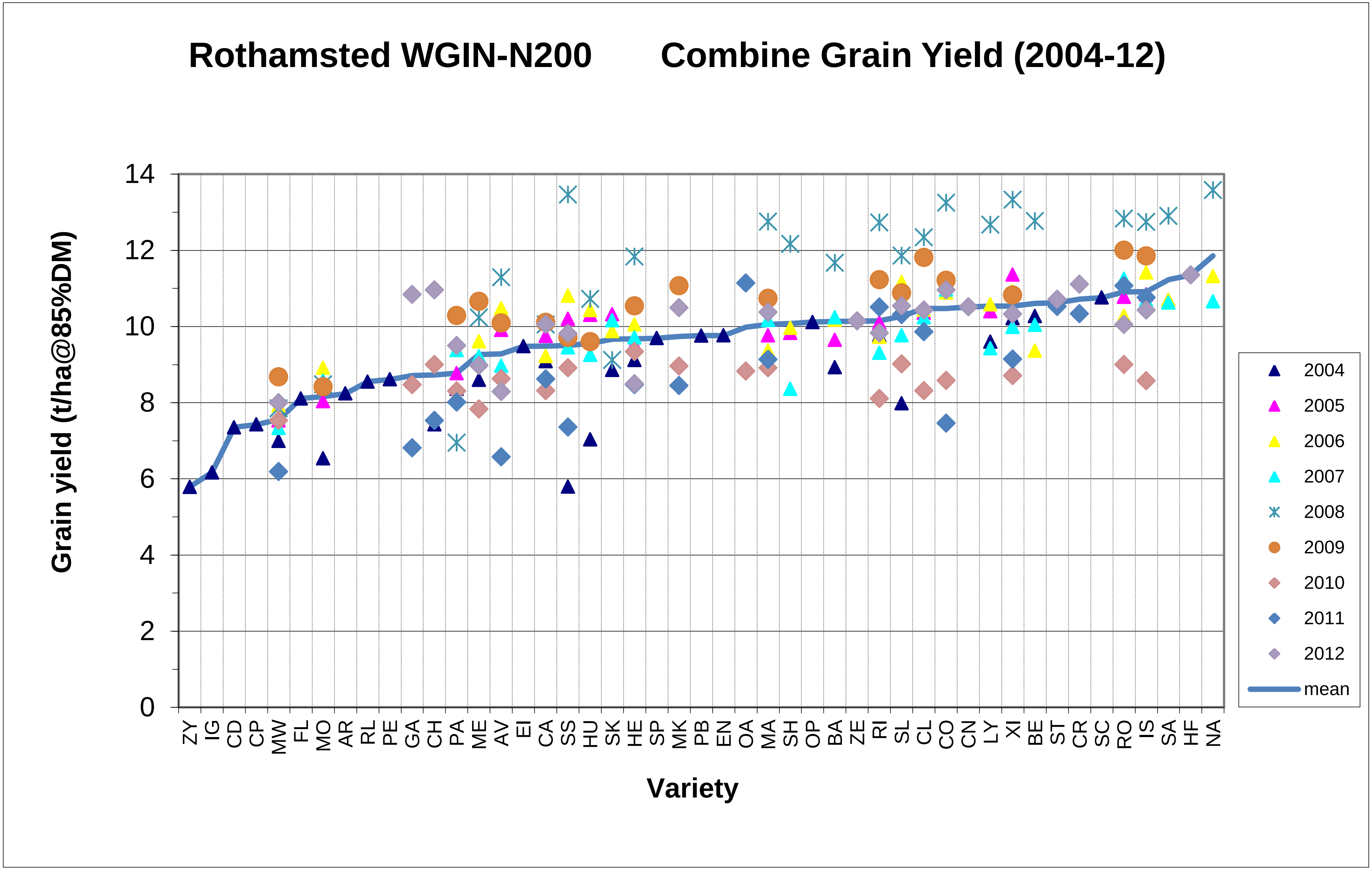
Diversity trial history

Trial	Year	Varieties (core of 9)	N-levels	kg N/ha	
1	2004	32	4	0,50,200,350	Blackhorse
2	2005	20	2	0,200	Fosters
3	2006	24	3	0,100,200	Meadow
4	2007	24	4	0,100,200,350	Blackhorse
5	2008	24	4	0,100,200,350	Meadow
6	2009	24 (include 6 x A x Cs)	4	0,100,200,350	Summadells
7	2010	25 (include 6 x A x Cs)	4	0,100,200,350	Blackhorse
8	2011	25 (include 4 x A x Cs)	4	0,100,200,350	Meadow
9	2012	25 (include WUE/take-all lines)	4	0,100,200,350	Summardell
10	2013	25 (include WUE/take-all lines)	4	0,100,200,350	Blackhorse

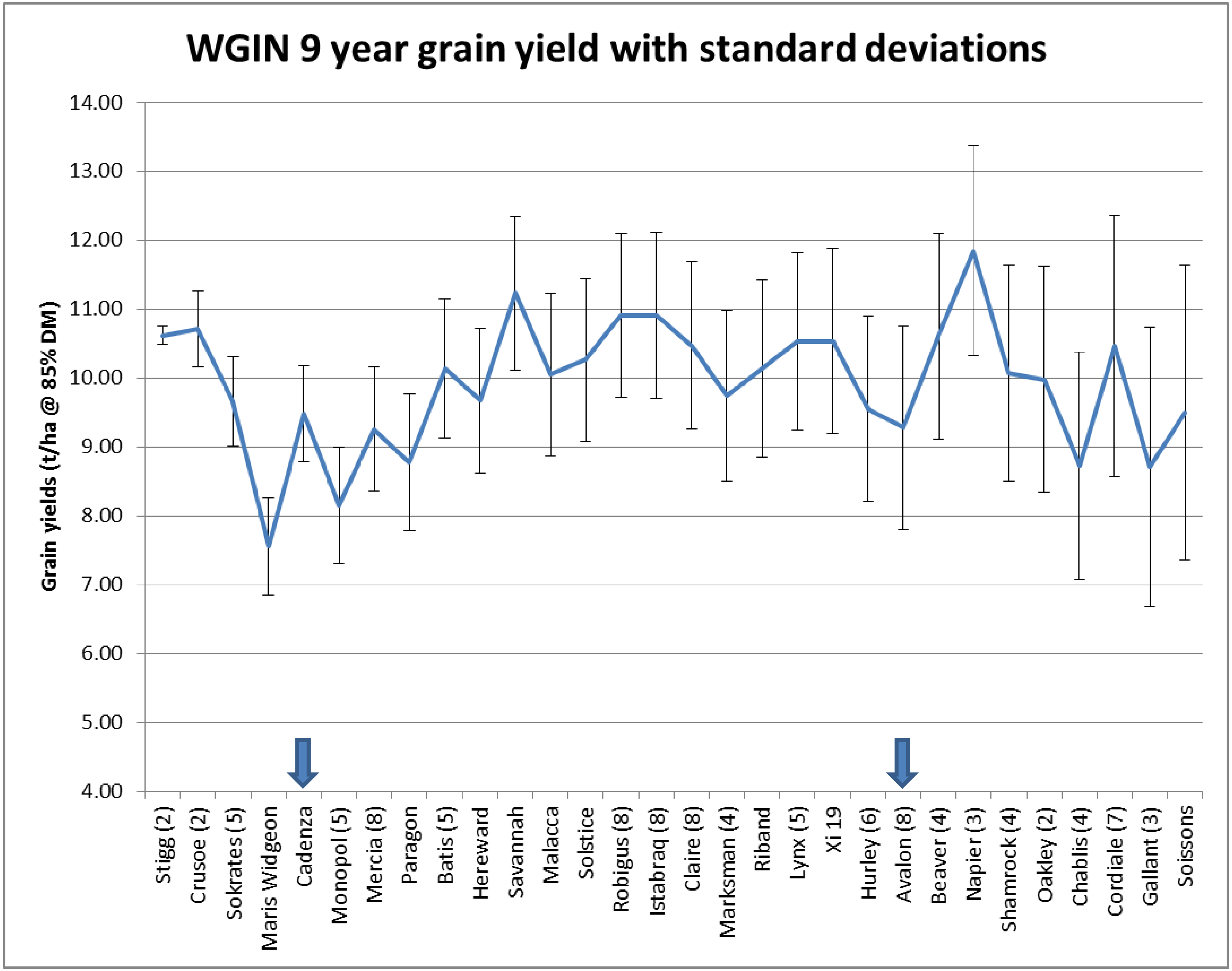

WGIN, mean yearly yields, 2007-12
grain yields (t/ha @ 85% DM)
0
2
4
6
8
10
12
14
0
100
200
350
N-applied (kgN/ha)
2007
2008
2009
2010
2011
2012

Grain yields, high v low N input performance, 2004-12





Rothamsted WGIN-N200 Combine Grain Yield (2004-12)
Grain yield (t/ha@85%DM)
0
2
4
6
8
10
12
14
ZY IG CD CP MW FL MO AR RL PE GA CH PA ME AV EI CA SS HU SK HE SP MK PB EN OA MA SH OP BA ZE RI SL CL CO CN LY XI BE ST CR SC RO IS SA HF NA
Variety
2004
2005
2006
2007
2008
2009
2010
2011
2012
mean


WGIN 9 year grain yield with standard deviations
Grain yields (t/ha @ 85% DM)
14.00
13.00
12.00
11.00
10.00
9.00
8.00
7.00
6.00
5.00
4.00
Stigg (2)
Crusoe (2)
Sokrates (5)
Maris Widgeon
Cadenza
Monopol (5)
Mercia (8)
Paragon
Batis (5)
Hereward
Savannah
Malacca
Solstice
Robigus (8)
Istabraq (8)
Claire (8)
Marksman (4)
Riband
Lynx (5)
Xi 19
Hurley (6)
Avalon (8)
Beaver (4)
Napier (3)
Shamrock (4)
Oakley (2)
Chablis (4)
Cordiale (7)
Gallant (3)
Soissons

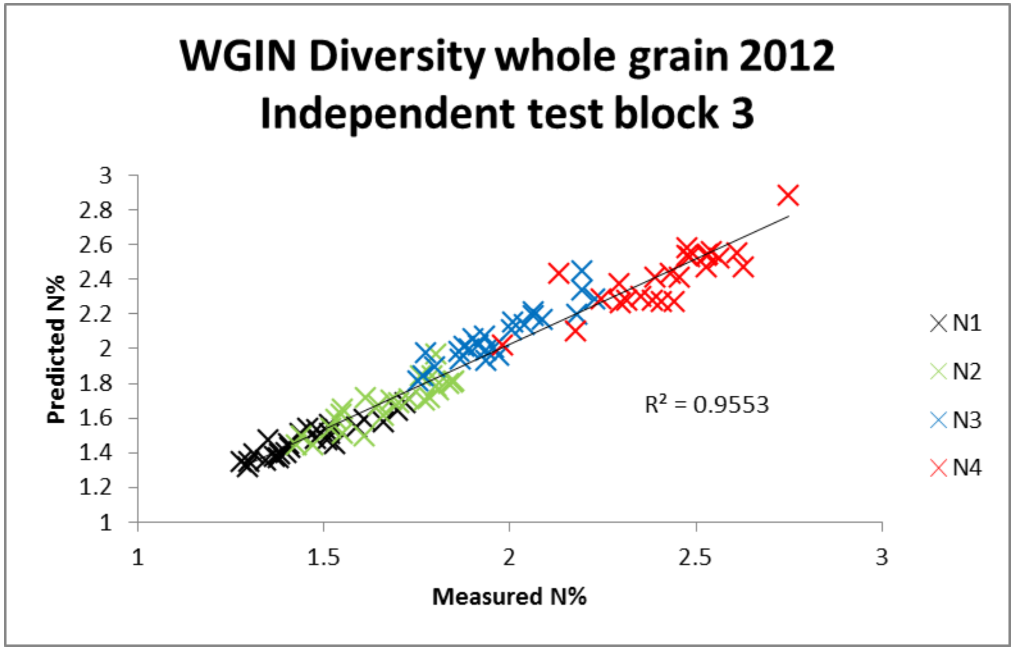
2013 harvest season (drilled 13th October)

Wheat varieties for WGIN-NUE 2012/13

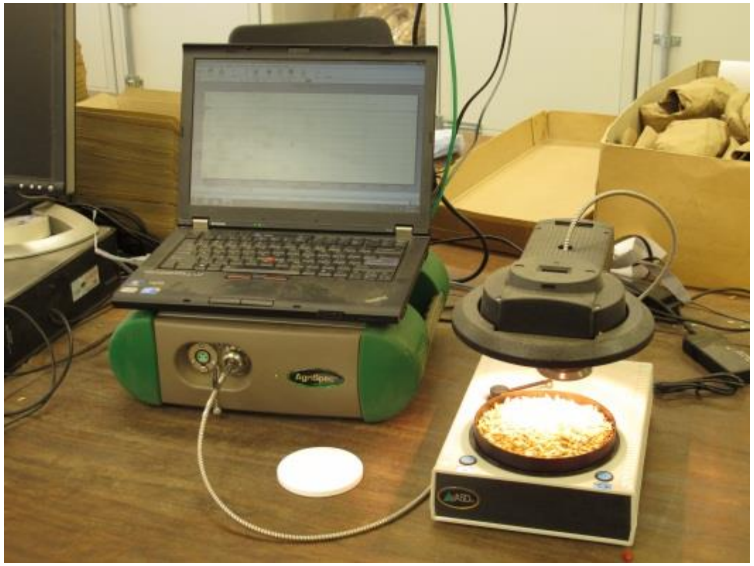
W=WGIN data, D=desk study

Variety	Source	Dressing	Code	Nabim	Rationale	inclusion in trial requested by	Previous years of trials (harvest year)
1. A C Barrie	Premium Crops		AB		Canadian re wheat. Disease sensitive. Tall. High grain N. Low yield. Spring type.	MH	new
2. Avalon		recleaned	AV	1	WGIN DH parent; Low NupE & NutE (D) WUE trial	PB, RG, MJH	05-12
3. Cadenza		recleaned	CA	2	WGIN DH parent; Best NupE (W) WUE trial	PB, RG, MJH	04-12
4. Chablis	KWS		CH	2	SPRING variety (previous grown in 2004 trial) as very N-responsive variety	MH	only in 04, 10, 11, 12
5. Claire	LIM	kinto	CL	3	Was biggest area on RL; WGIN DH parent; Good second wheat	PB,PS	05-12
6. Cocoon	Agrii/Secobra		CC	3	Tall variety. High yield. 2010 introduction. Eyespot and rust resistant.	MH	New
7. Conqueror	KWS		CN	4	New Grp 4, very high yielding	MH	12
8. Cordiale	KWS	redigo deter	CO	2	Good second wheat. BBSRC Quality project WUE trial	RG	06-12
9. Crusoe	LIM		CR	2	Carries dicoccoides. Shows the 'stay green' character		11, 12
10. Gallant	Syn		GA	1	new claimed high yield and high protein type	MH	10, 11, 12
11. Hereford	Syn		HF	4	Feed (not on RL), high yield, brown rust susceptible, possible low take-all build-up and good resistance. Multi trait.	KHK/RG	12
12. Hereward	RAGT	anchor	HE	1	Best protein on RL; benchmark bread variety. BBSRC Quality project WUE trial	PB,PS	04-12
13. Istabraq	LIM	kinto + lattitude	IS	4	Best yield on RL; Distilling cultivar; In LINK 'GREENgrain'; Good second wheat. BBSRC Quality project. WUE trial	PB,PS	05-12
14. Malacca	KWS	redigo deter	MA	1	Biggest Group 1 area; DH choice; Low NupE, high NutE (W). BBSRC Quality project	PS	04-12
15. Marksman	RAGT	redigo	MK	2	new for 2009, PRS request for BBSRC Quality project	PS	09-12
16. Maris Widgeon		sibutol	MW	1	Tall (rht), old cultivar WUE trial	PB, AM	04-12
17. Mercia		recleaned	ME	1	Low NupE & NutE (desk); Low Canopy N requirement; In IGF micro-array. WUE trial. RHT series	RG	04, 06-12
18. Paragon	RAGT	redigo twin	PA	1	Spring variety; WGIN mutagenesis population; High NupE (W)	PB	04-12
19. Riband	RAGT	recleaned	RI	3	WGIN DH parent; Distilling cultivar; In LINK 'GREENgrain'; High NutE (W)	RG	04-12
20. Robigus	KWS	redigo deter lattitude	+RO	3	Best Group 3 yield; Best NUE, high NupE & NutE (D); Good second wheat. WUE trial	PB, AM	05-12
21. Stigg	LIM		ST	?4	Carries dicoccoides. High disease resistance. Shows the 'stay green' character		11, 12
22. Soissons	Elsoms	redigo	SS	2	WGIN DH parent; Early maturing; High NupE, low NutE (W) WUE trial	PB,RG, AM	04-12
23. Solstice	LIM	beret gold lasttitude	+SL	2	Biggest Group 2 area; DH choice; Worst NupE (W)	RG	04-12
24. Xi19	LIM	redigo deter	XI	1	Best Group 1 yield; High NUE, NupE, NutE (D); Low NupE (W). BBSRC Quality project. WUE trial	PB,PS	04-12
25. Zebedee	LIM		ZE	3	High WUE, grp 3. Multi trait. WUE trial	JFoulkes	12

NIRS - Predicting Grain Nitrogen



The grain from 2 blocks was used to build a grain N prediction model, and the model was independently tested on the grain from block 3.



Whole grain is scanned on a sample turntable. Up to 240 samples can be scanned/day. Milling, weighing and measuring N conventionally would take about about 5 days per 240 samples, and be expensive.

Avalon x Cadenza 2012 trial

Avalon x Cadenza Trials

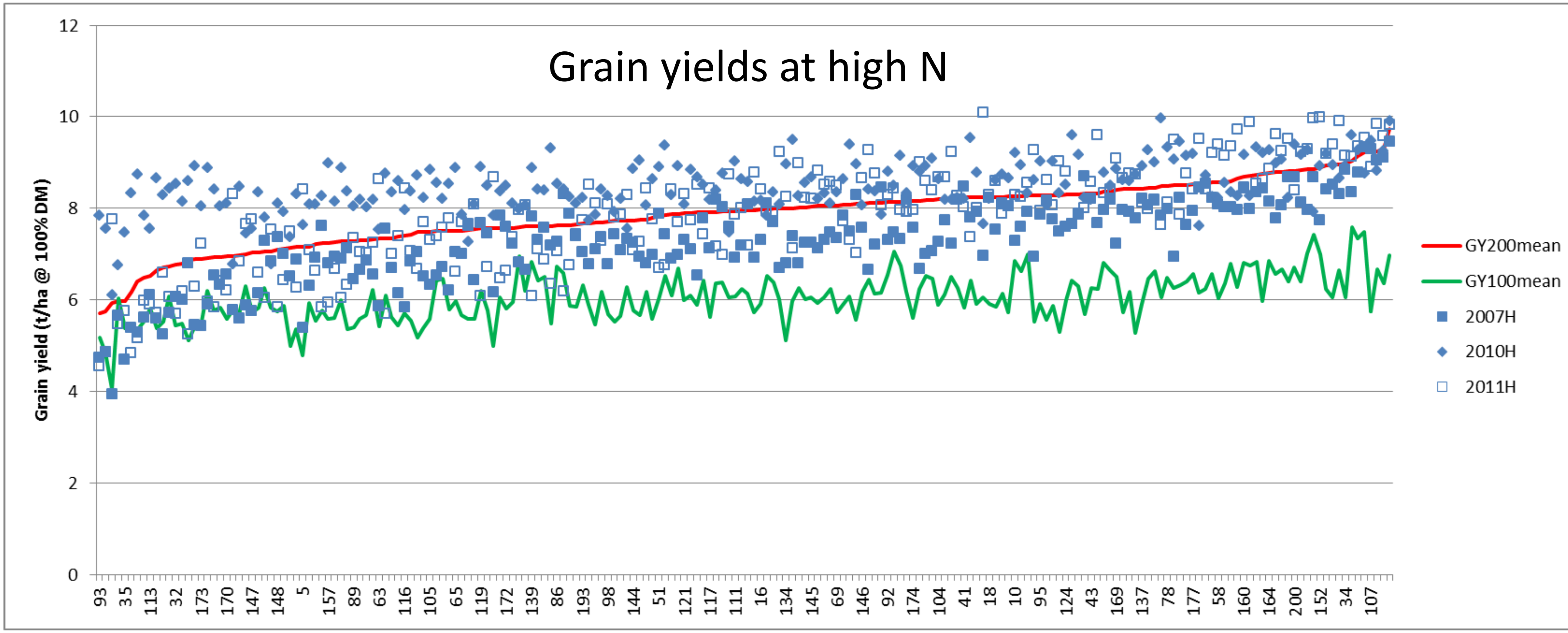
Trial	Harvest year	Sites	Notes	kg N/ha applied (+ c 50 kg/ha N_{min})	Soil N (kg/ha to 90 cm)
1 (719)	2007	Blackhorse		200	49.9
2, 3 (817; 851-3)	2008	Bones and Woburn	Woburn trial split	Both 100	78.3; 34.4,36.1, 36.7
4 (903, 904)	2009	Fosters/Summardells	Split over 2 fields (wet)	100	48.2; 40.7
5 (1035)	2010	Blackhorse	(very dry)	200	39.8
6(1103)	2011	Great Harpenden	(very dry)	200	44.0
7*(1202)	2012	Bones	(wet May/June)	50	69.5
8*(1319	2013	Blackhorse	Abandoned		

*= not directly WGIN funded

Avalon x Cadenza

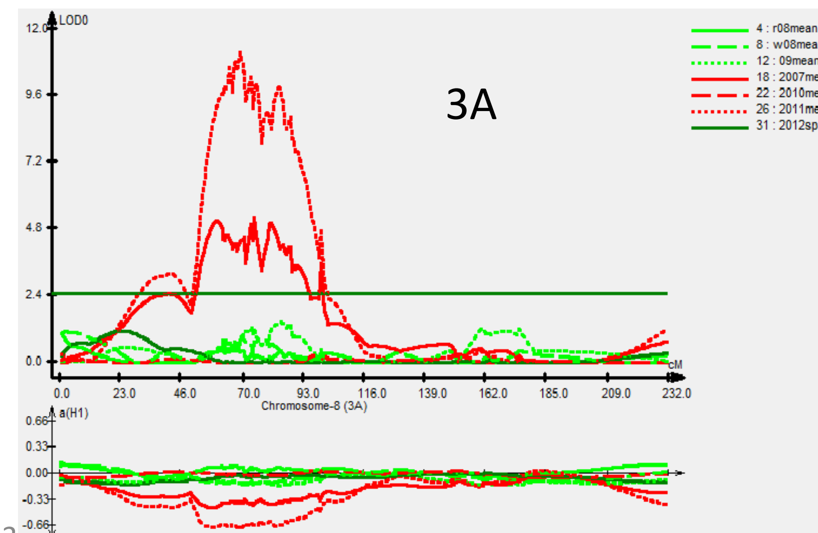
- Traits being measured

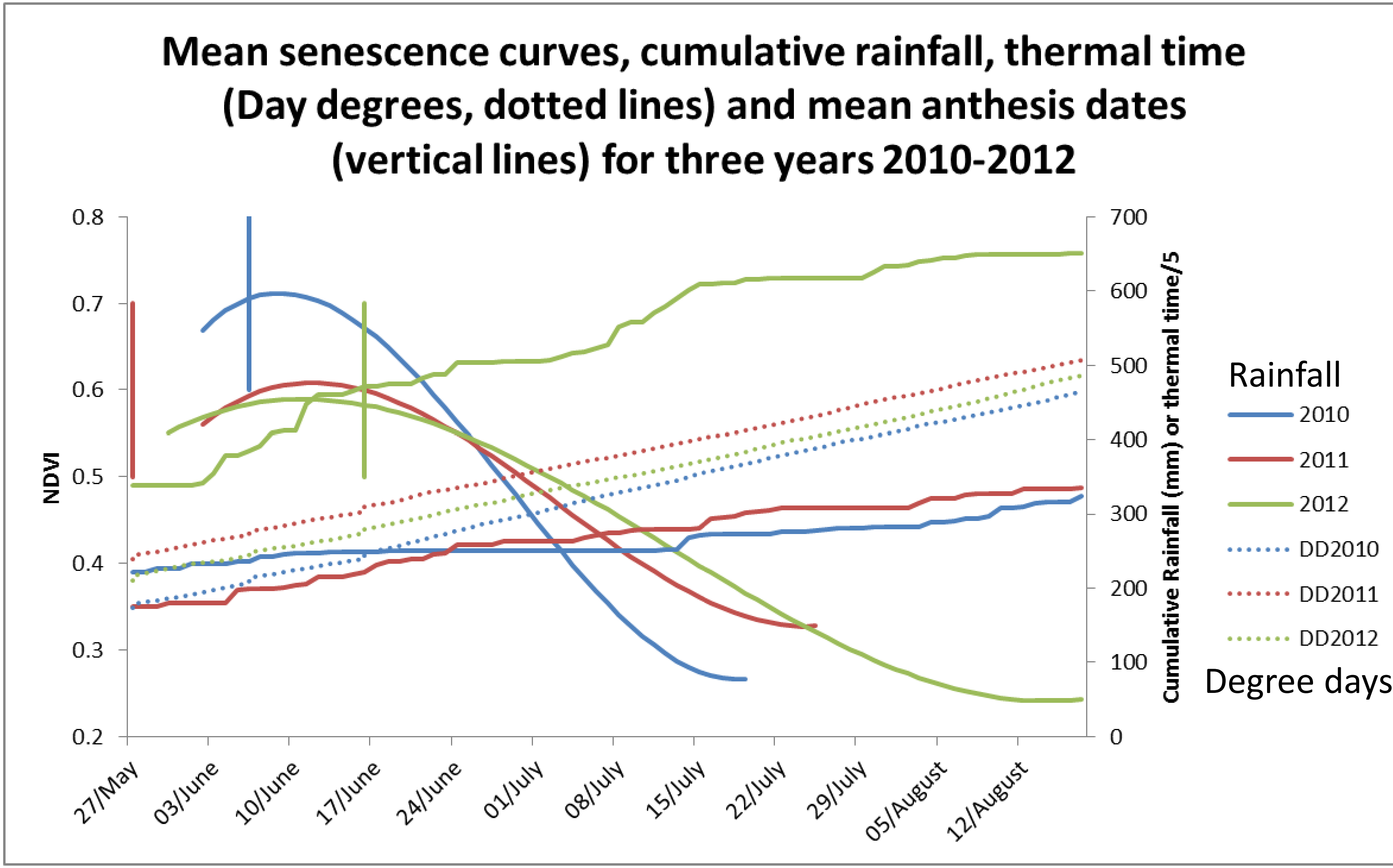
- Flowering time and height
- Yield (grain and straw) and TGW
- Nitrogen (grain and straw)
- NUtE, N uptake (final)
- Leaf N and SPAD (anthesis and 21 dpa)
- Leaf size
- Canopy longevity, reflectance, rate of senescence
- Early N uptake
- Gene expression
- Roots



Monthly rainfall in spring and summer (mm) at Rothamsted in the years 2007-2011. Six-monthly totals and 30-year averages (1971-2000) are shown.

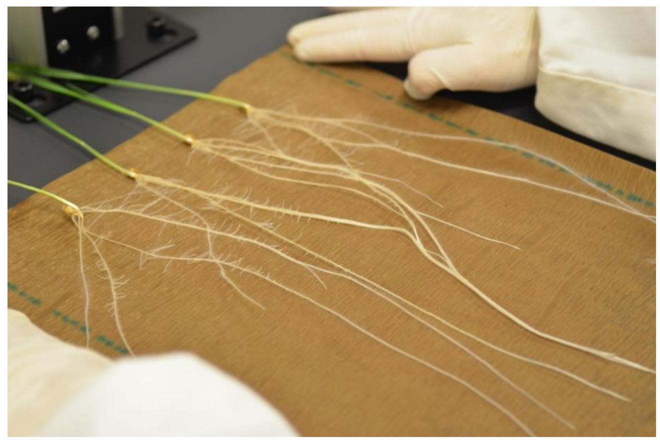
Year	Mar	Apr	May	Jun	Jul	Aug	Total
2007	57.6	2.8	135.8	72.4	86.8	64.4	**419.8**
2008	108.5	53.5	87	35.3	90.3	107.8	**482.4**
2009	37.3	46.7	24.8	68.1	73.3	63.4	**313.6**
2010	45.2	18.7	38.4	23.5	31.6	127.6	**285**
2011	10	5.2	23.6	83	44.6	81.2	**247.6**

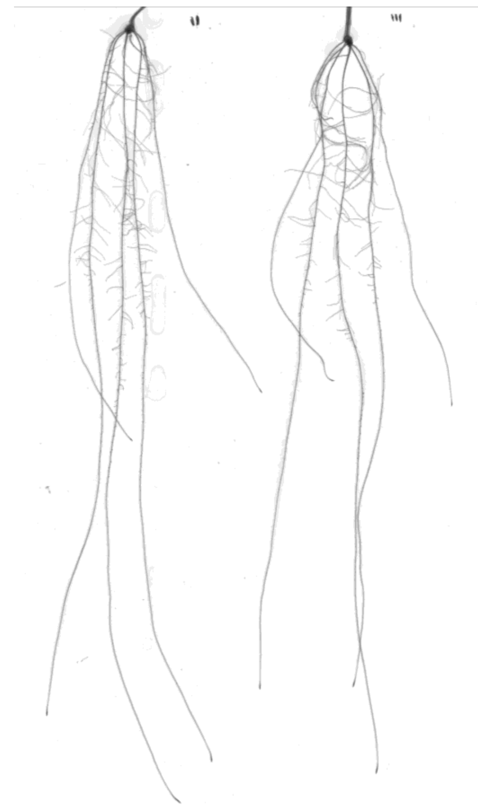




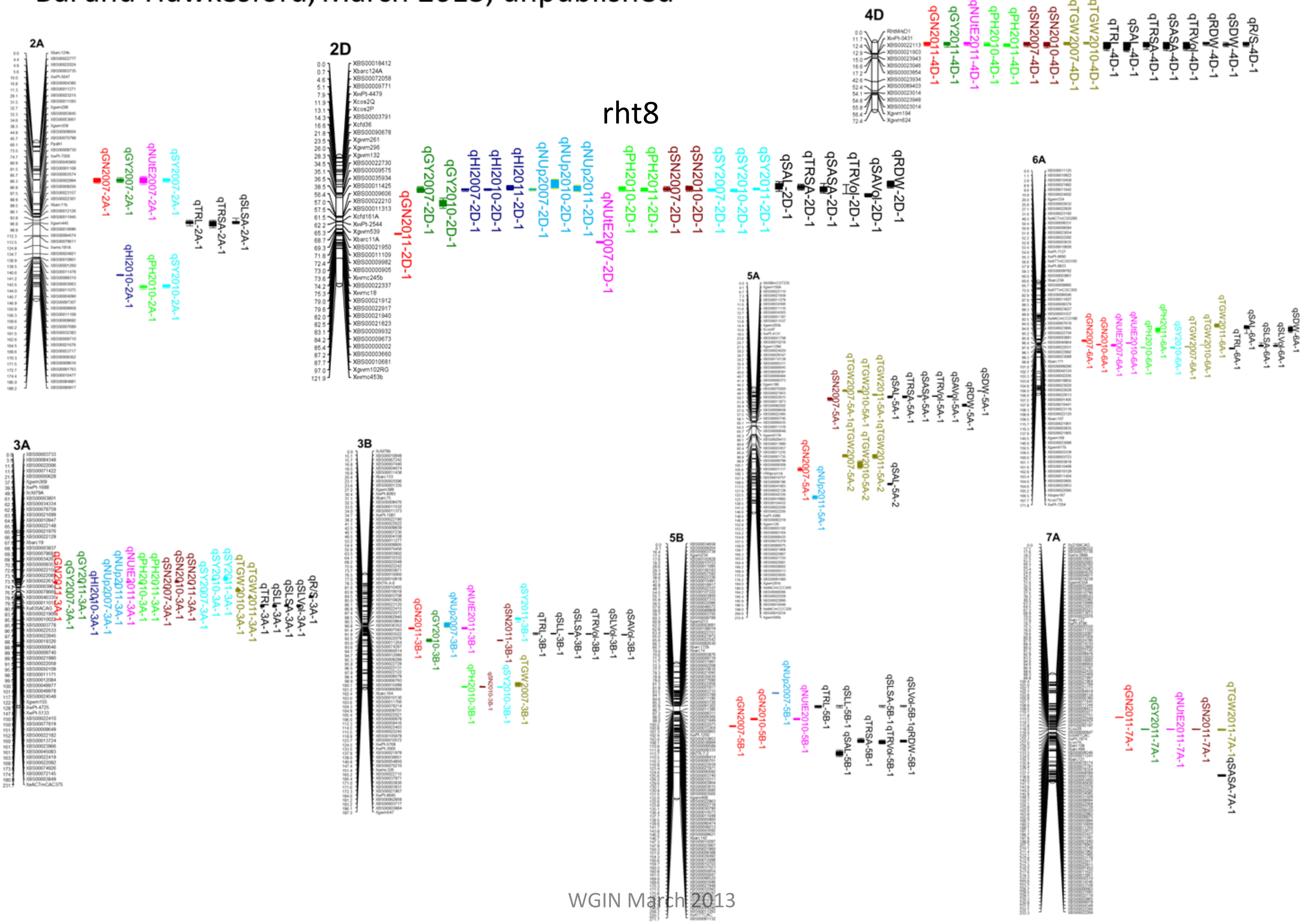
Mean senescence curves, cumulative rainfall, thermal time (Day degrees, dotted lines) and mean anthesis dates (vertical lines) for three years 2010-2012
NDVI
0.8
0.7
0.6
0.5
0.4
0.3
0.2
700
600
500
400
300
200
100
0
Cumulative Rainfall (mm) or thermal time/5
27/May
03/June
10/June
17/June
24/June
01/July
08/July
15/July
22/July
29/July
05/August
12/August
Rainfall
2010
2011
2012
DD2010
DD2011
DD2012
Degree days

Variation in root traits: mapping QTLs



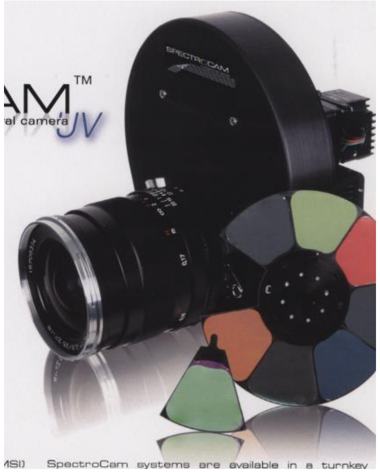


Bai and Hawkesford, March 2013, unpublished



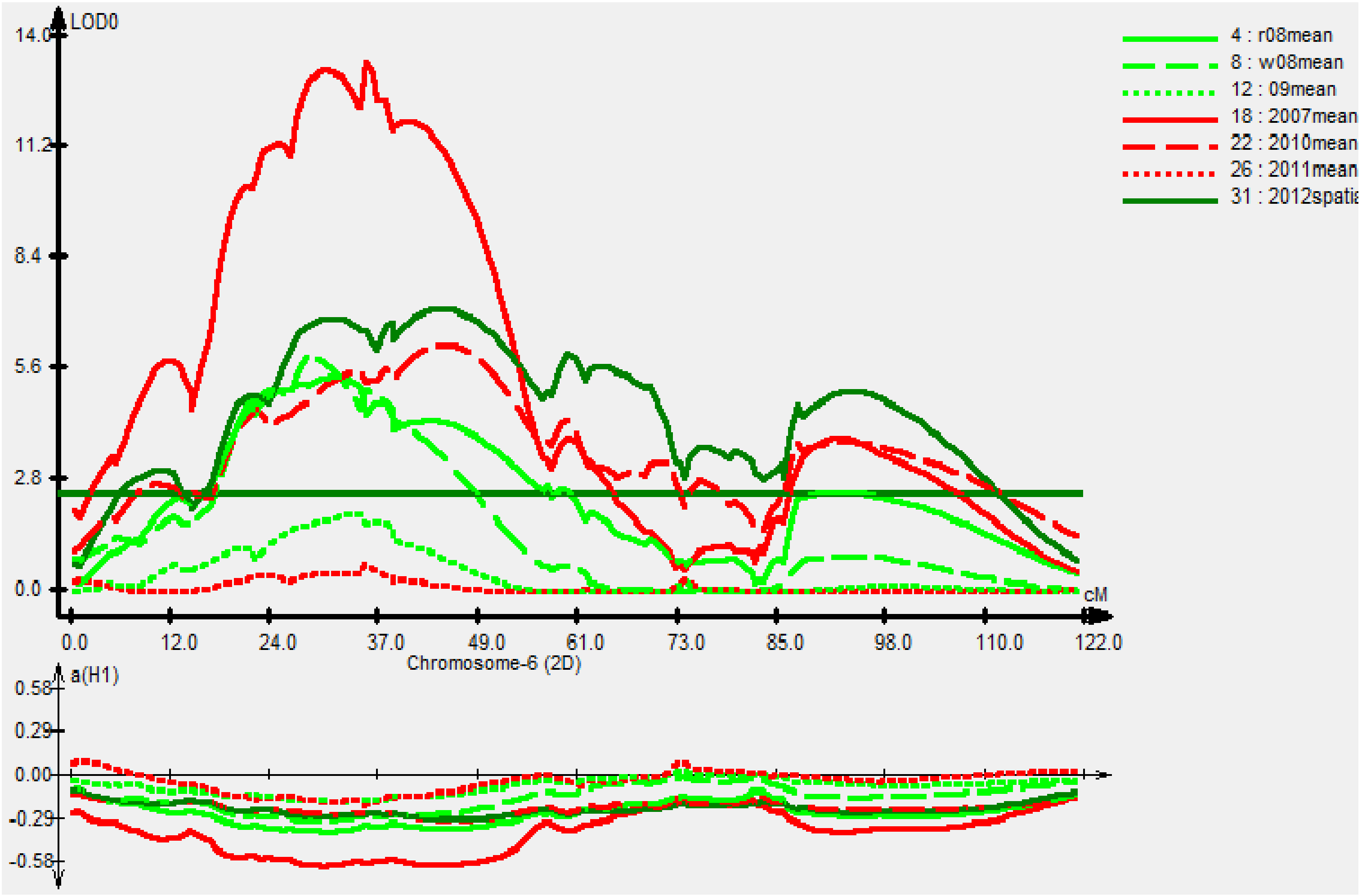
Forward plans....

- Final evaluation of modern diversity trial
- Evaluate field phenotype methodologies: NDVI, canopy multispectral data, NIRS and imaging
- Cross reference NUE/RUE/Take-all interactions

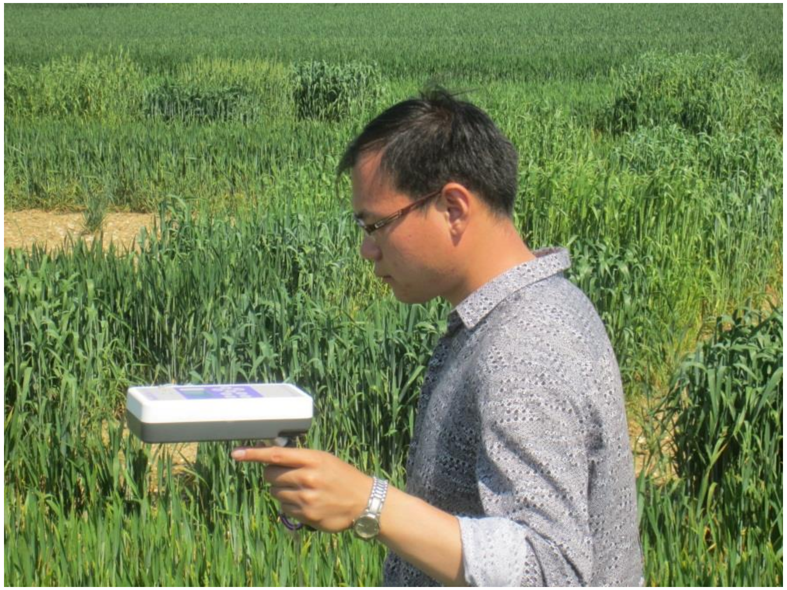


Thanks

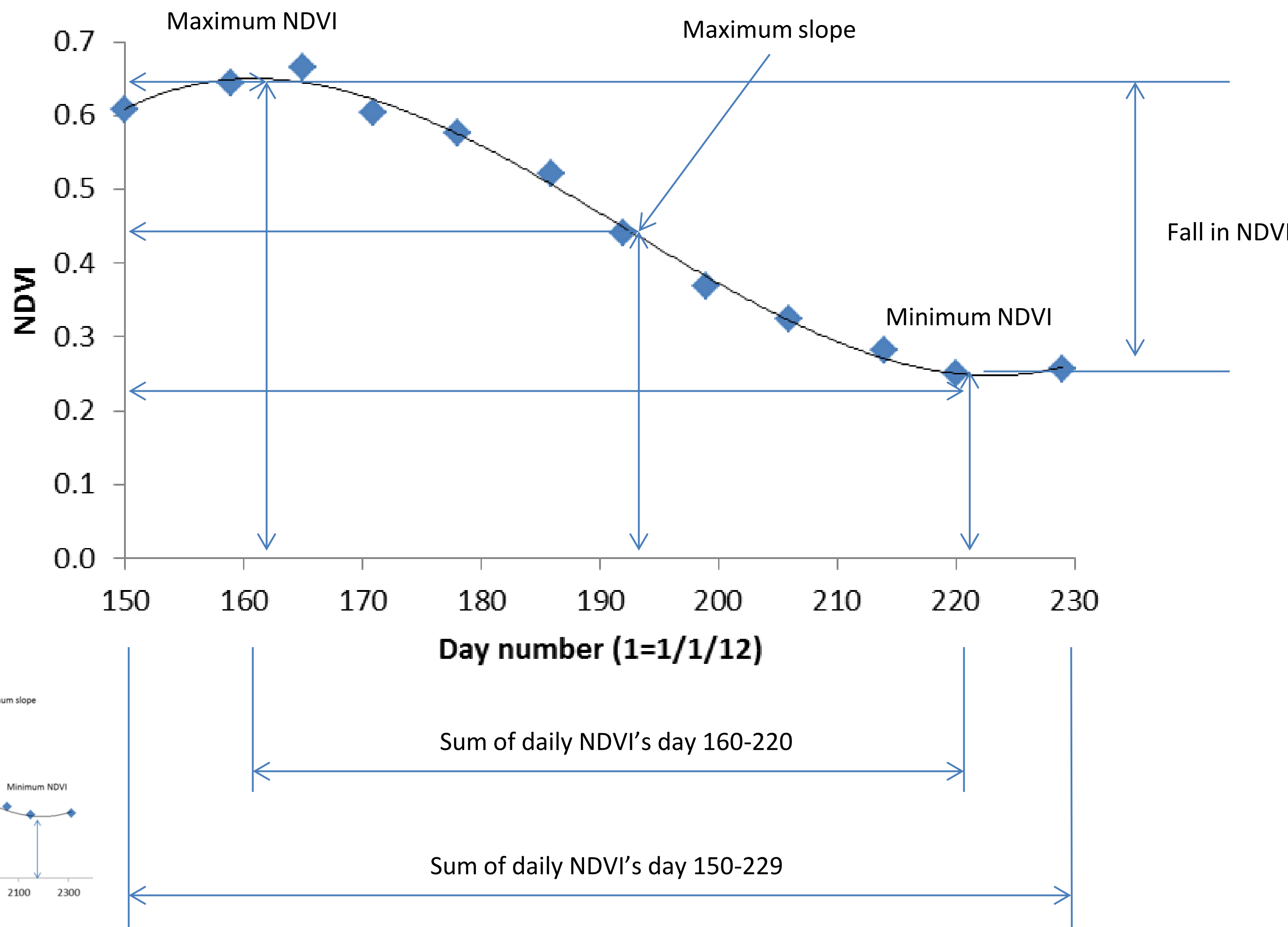
- RRes Farm staff
- Peter Barraclough
- Group and field team: Andrew Riche, Peter Buchner, Yongfan Wan, Jonathan Howarth, Mark Durenkamp, Saroj Parmar, Janina Jones, Dan Godfrey, Emmanuelle Cabannes, Adinda Derkx, Fumie Shinmachi, Caihong Bai + many summer students

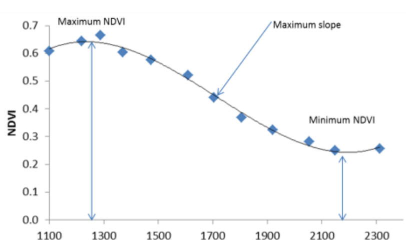

LOD0
14.0
11.2
8.4
5.6
2.8
0.0
cM
0.0
12.0
24.0
37.0
49.0
61.0
73.0
85.0
98.0
110.0
122.0
Chromosome-6 (2D)
a(H1)
0.58
0.29
0.00
-0.29
-0.58
4 : r08mean
8 : w08mean
12 : 09mean
18 : 2007mean
22 : 2010mean
26 : 2011mean
31 : 2012spatia

A x C and senescence

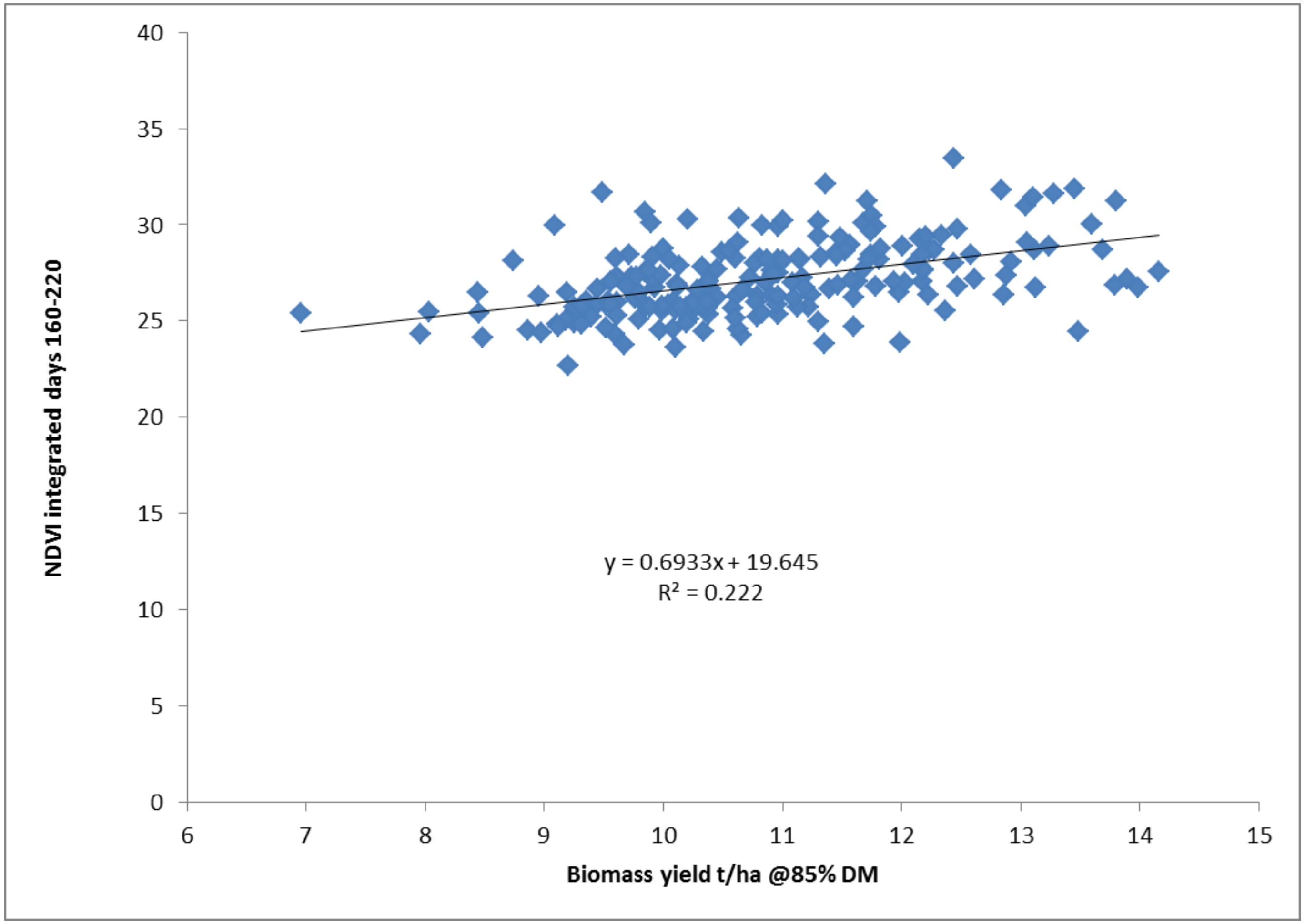


A x C senescence curve parameters

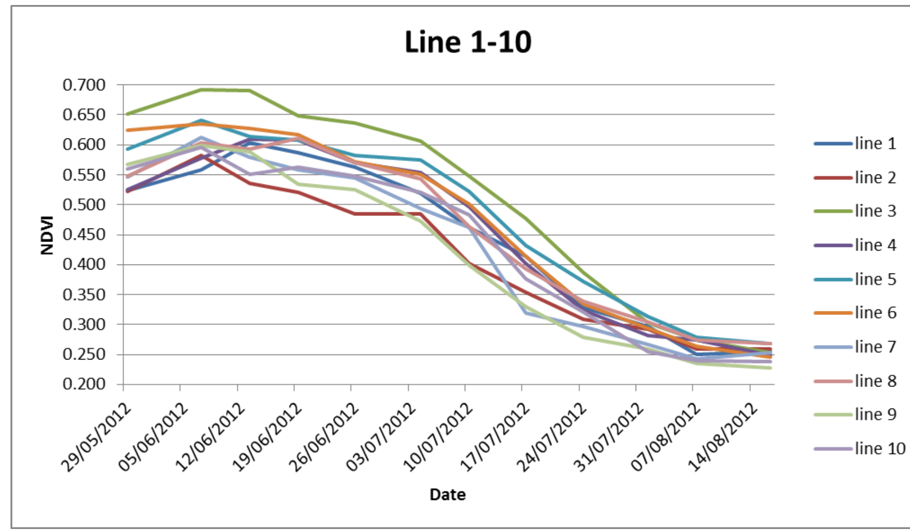




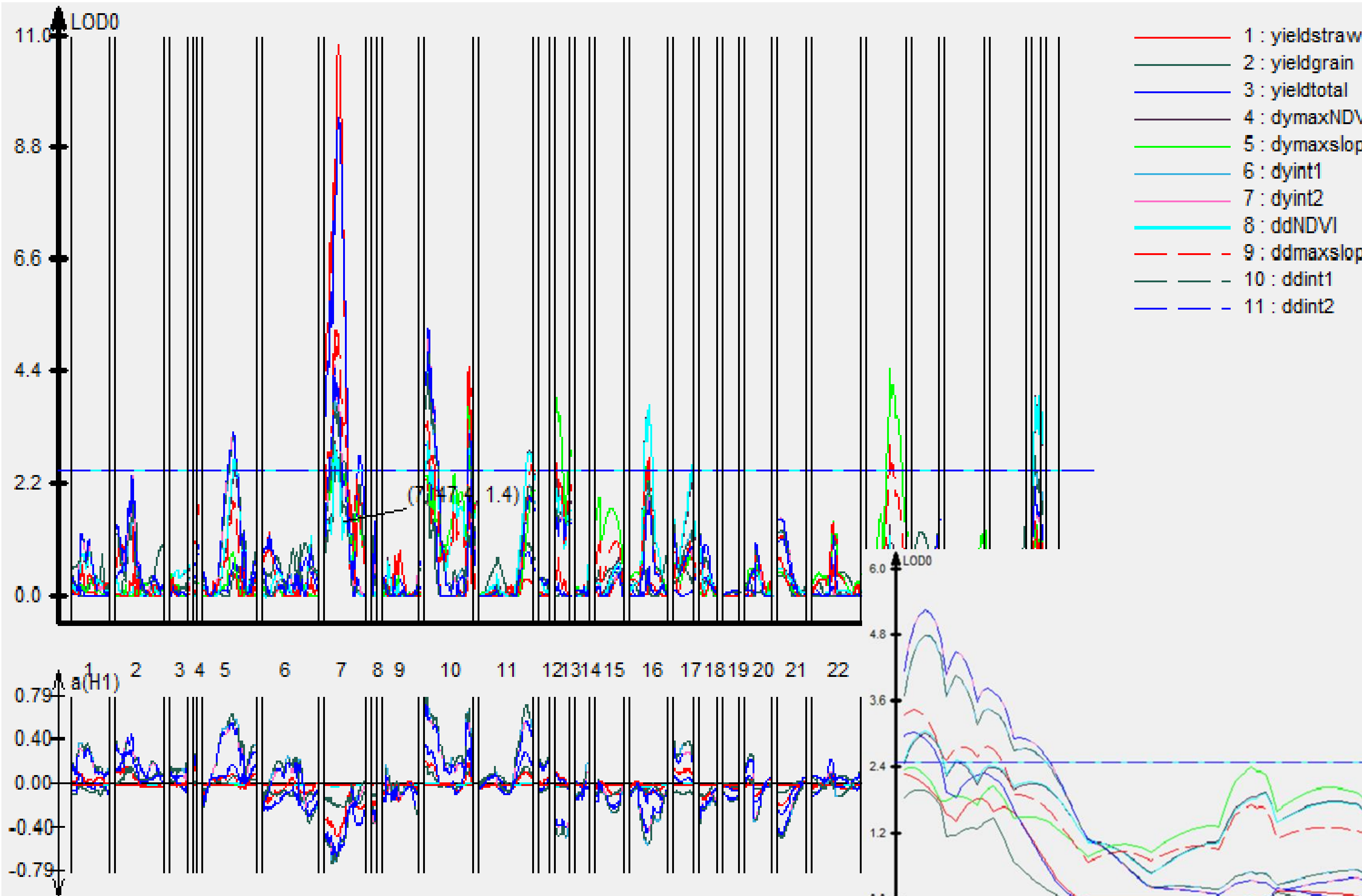
Integration relates to yield

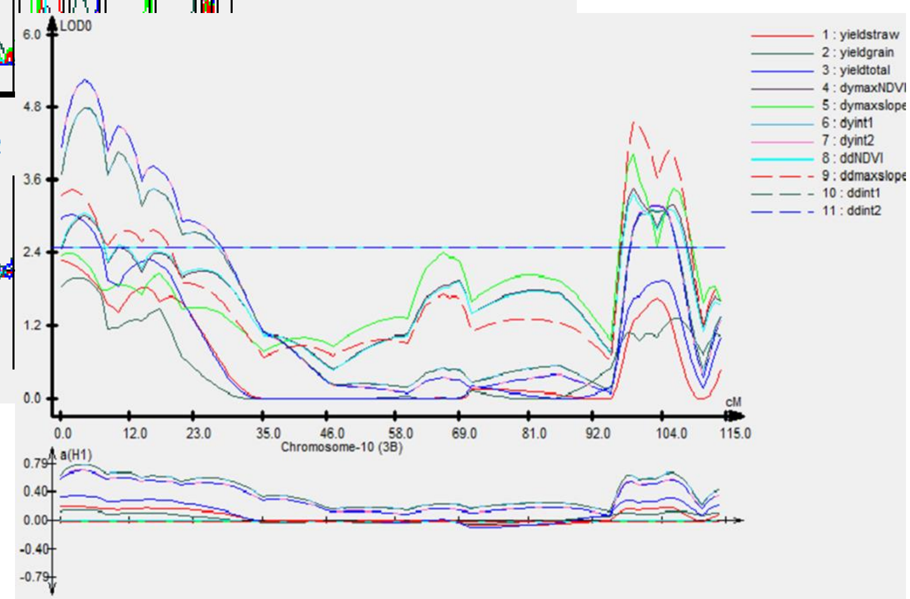


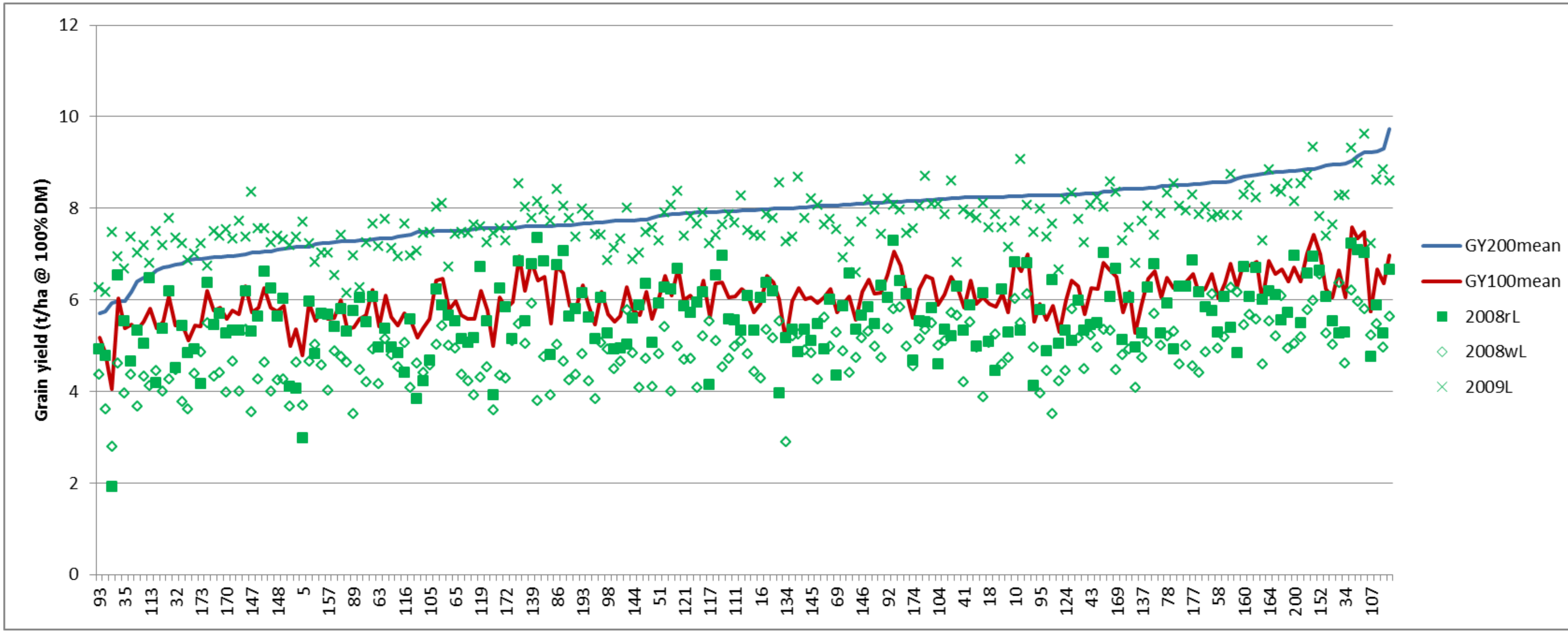
Quantifying senescence characteristics



Senescence and yield QTL

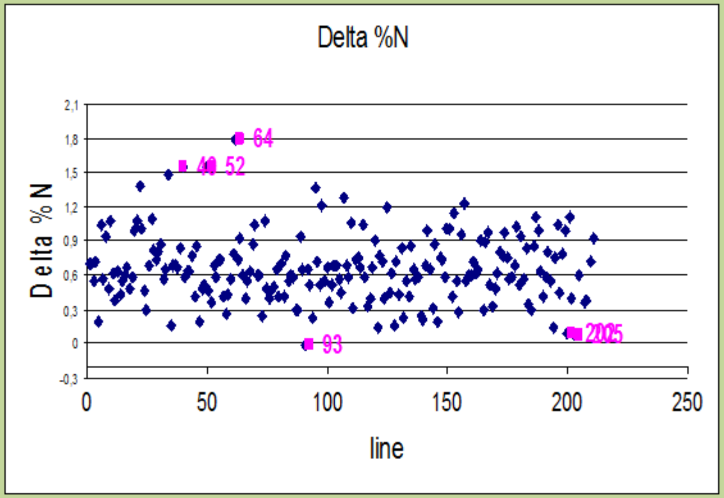


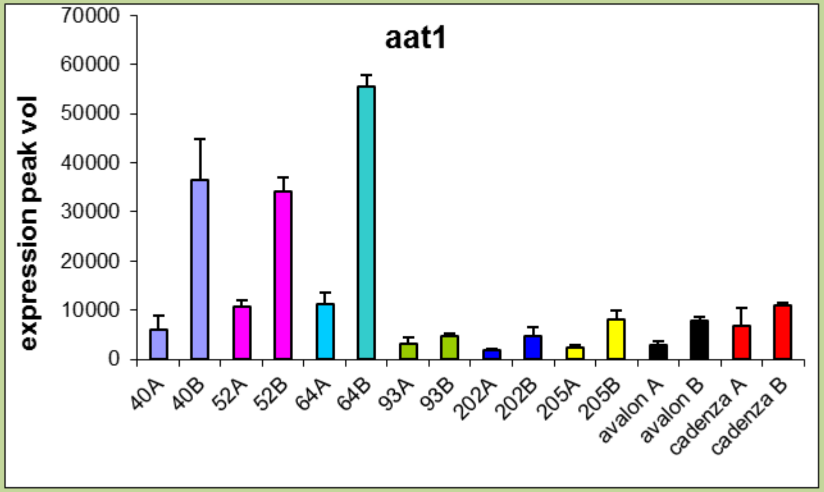



Grain yield (t/ha @ 100% DM)
12
10
8
6
4
2
0
93
35
113
32
173
170
147
148
5
157
89
63
116
105
65
119
172
139
86
193
98
144
51
121
117
111
16
134
145
69
146
92
174
104
41
18
10
95
124
43
169
137
78
177
58
160
164
200
152
34
107
GY200mean
GY100mean
2008rL
2008wL
2009L

Canopy longevity as a target

Wheat amino acid transporter TaAAT1 expression in leaf 2 of AxC double haploid lines (field grown) differing in their N-remobilisation capacity





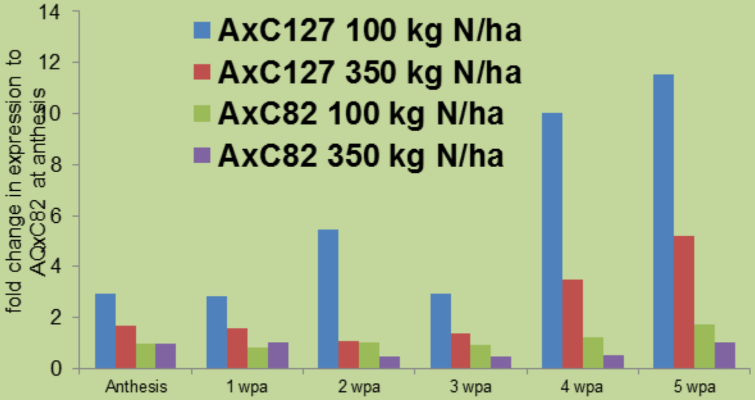
Lines 40, 52 and 64 with a high delta N and lines 93, 202 and 205 with a low delta N (red dots). Delta N was measured on leaf 2 between anthesis and day 21.

Positive correlation with increasing expression of TaAAT1 in AxC lines with high leaf 2 N-remobilisation capacity 3 weeks post anthesis compared to low expression in AxC lines with low N-remobilisation capacity.

A = anthesis; B = 3 wpa)

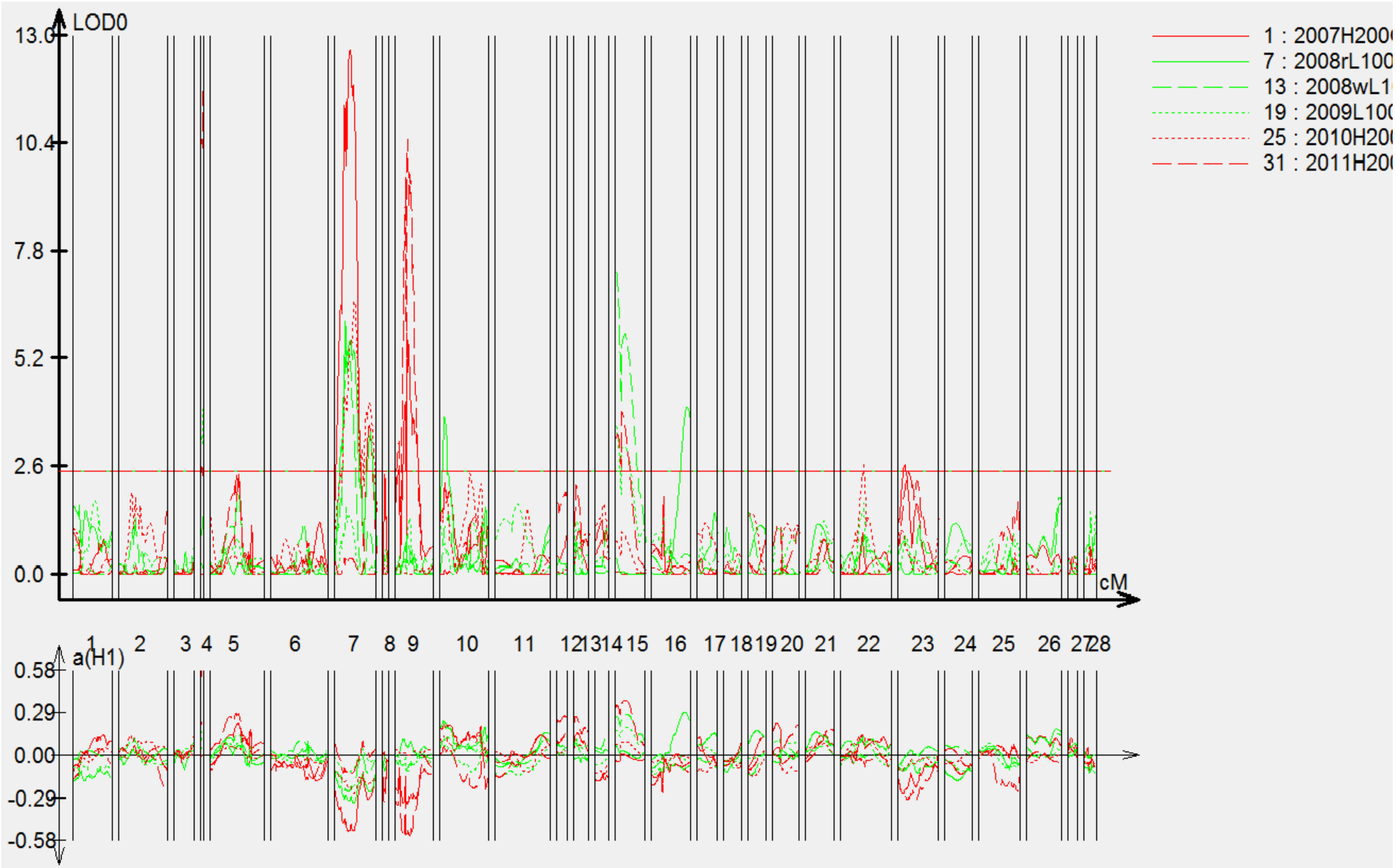
Field experiment (WGIN)

AxC lines 127 and 82 are characterised by early N export (127) compared to slow export (82). The lines where grown in the field under different nitrate fertilization (0, 100, 200, 350 kg/ha N). With anthesis leaf 2 were harvested every week until 5 weeks post-anthesis (wpa) and gene expression studies were performed.



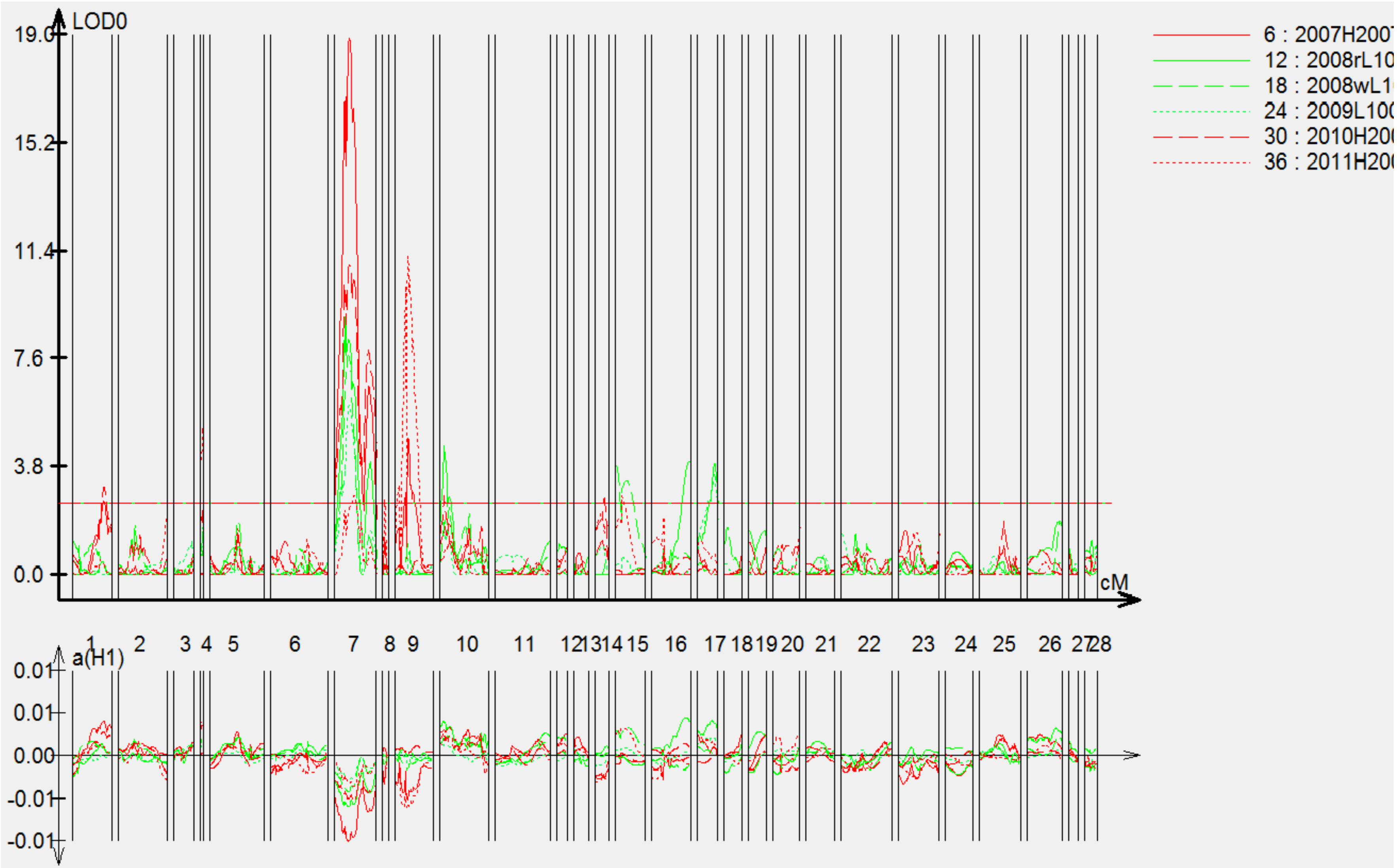
Under field conditions insufficient N-fertilization (100 kg N/ha) results already in an up-regulation of TaAAT1 gene expression in leaf 2 of AxC line 127 which further increases with more N-demand during remobilisation/grain filling compared to high 350 kg N/ha which shows only a small increase with ongoing senescence. There is a positive correlation of TaAAT1 expression to the early N export capacity of AxC line 127 compared to the much reduced TaAAT1 gene expression in the slow N exporter line AxC line 82 especially with increasing senescence.

Grain yield



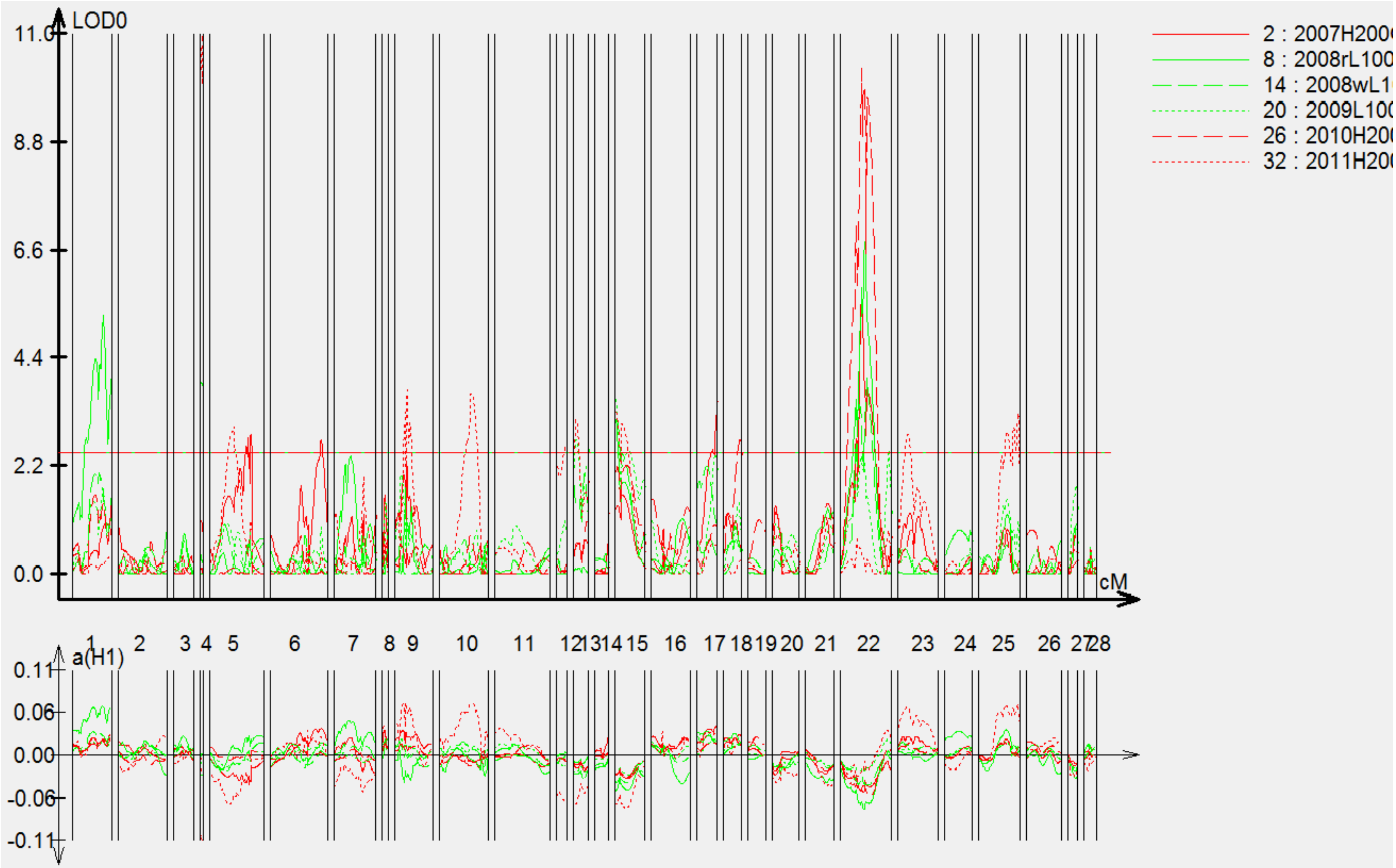
LOD0
13.0
10.4
7.8
5.2
2.6
0.0
cM
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28
a(H1)
0.58
0.29
0.00
-0.29
-0.58
1 : 2007H200
7 : 2008rL100
13 : 2008wL1
19 : 2009L100
25 : 2010H20
31 : 2011H20

Total N

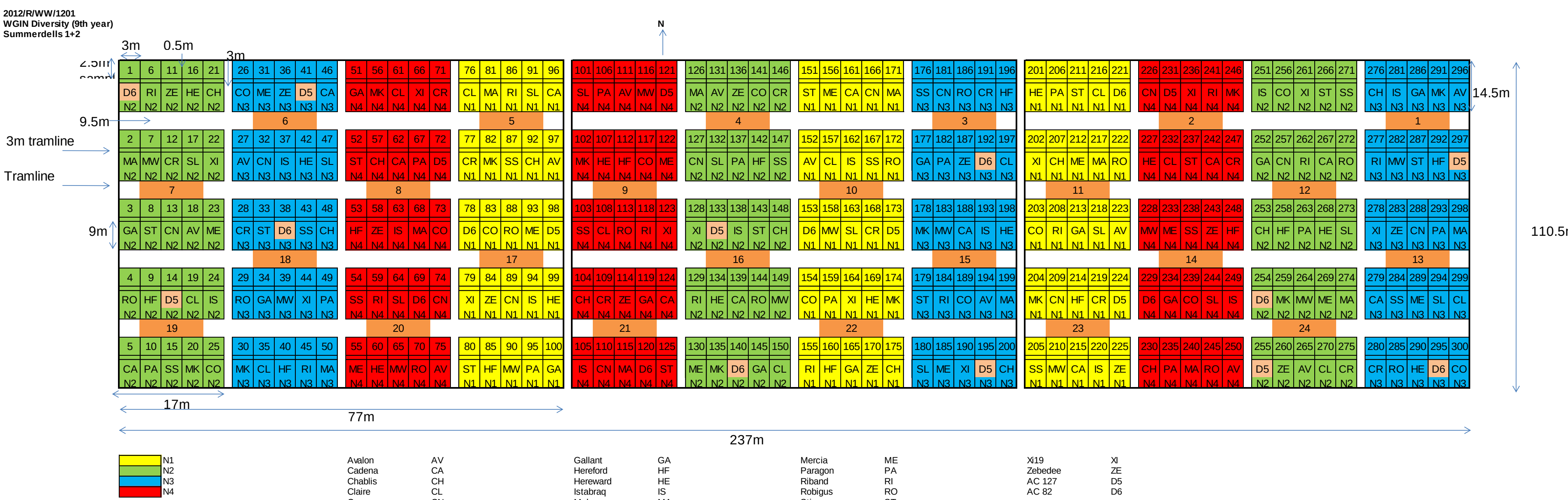


LOD0
19.0
15.2
11.4
7.6
3.8
0.0
cM
6 : 2007H200
12 : 2008rL10
18 : 2008wL1
24 : 2009L10
30 : 2010H20
36 : 2011H20
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28
a(H1)
0.01
0.01
0.00
-0.01
-0.01

Grain %N

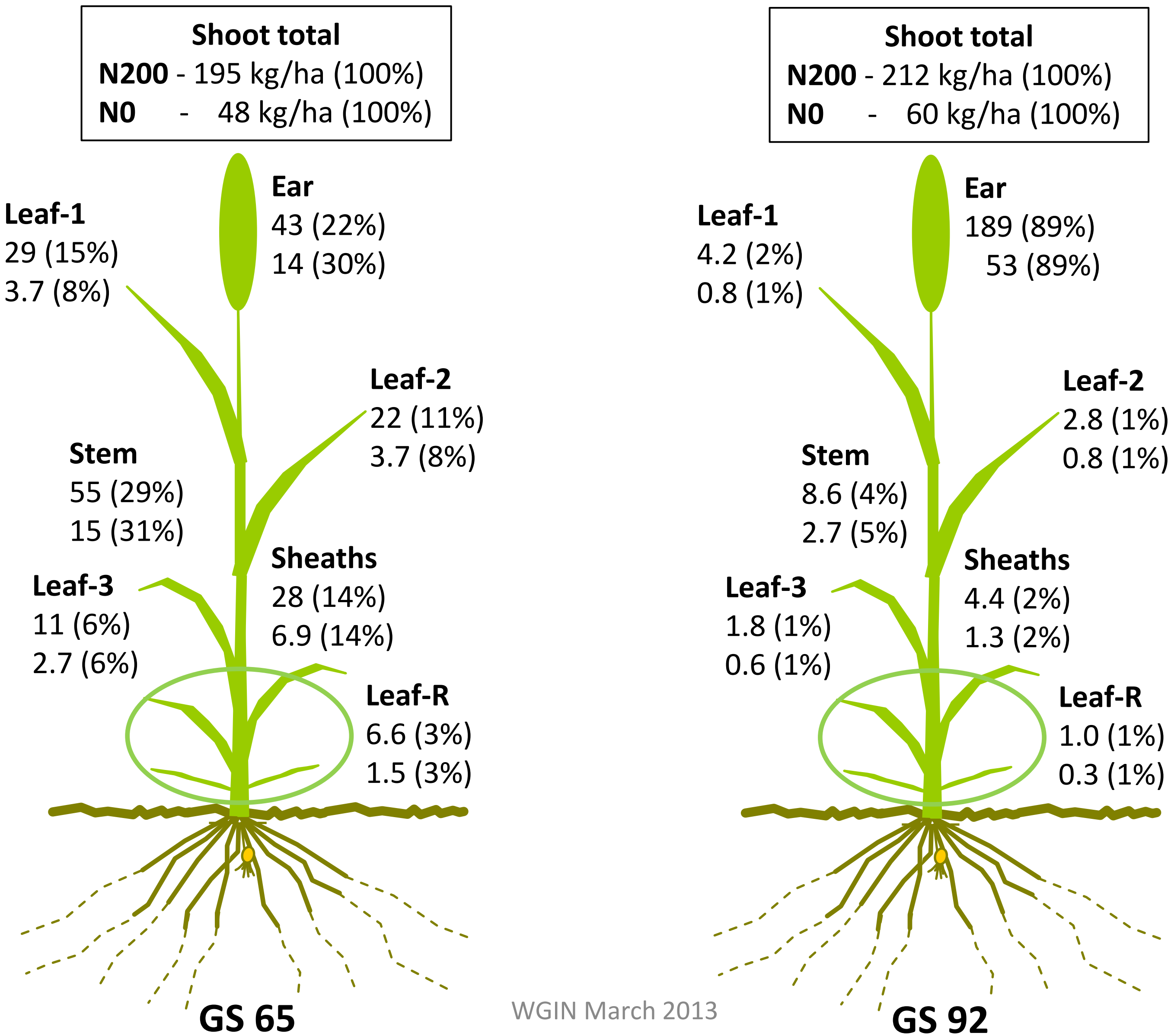

LOD0
11.0
8.8
6.6
4.4
2.2
0.0
cM
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28
a(H1)
0.11
0.06
0.00
-0.06
-0.11
2 : 2007H200
8 : 2008rL100
14 : 2008wL1
20 : 2009L100
26 : 2010H200
32 : 2011H200

WGIN Diversity harvesting DH line 127 (D5) and line 82 (D6)

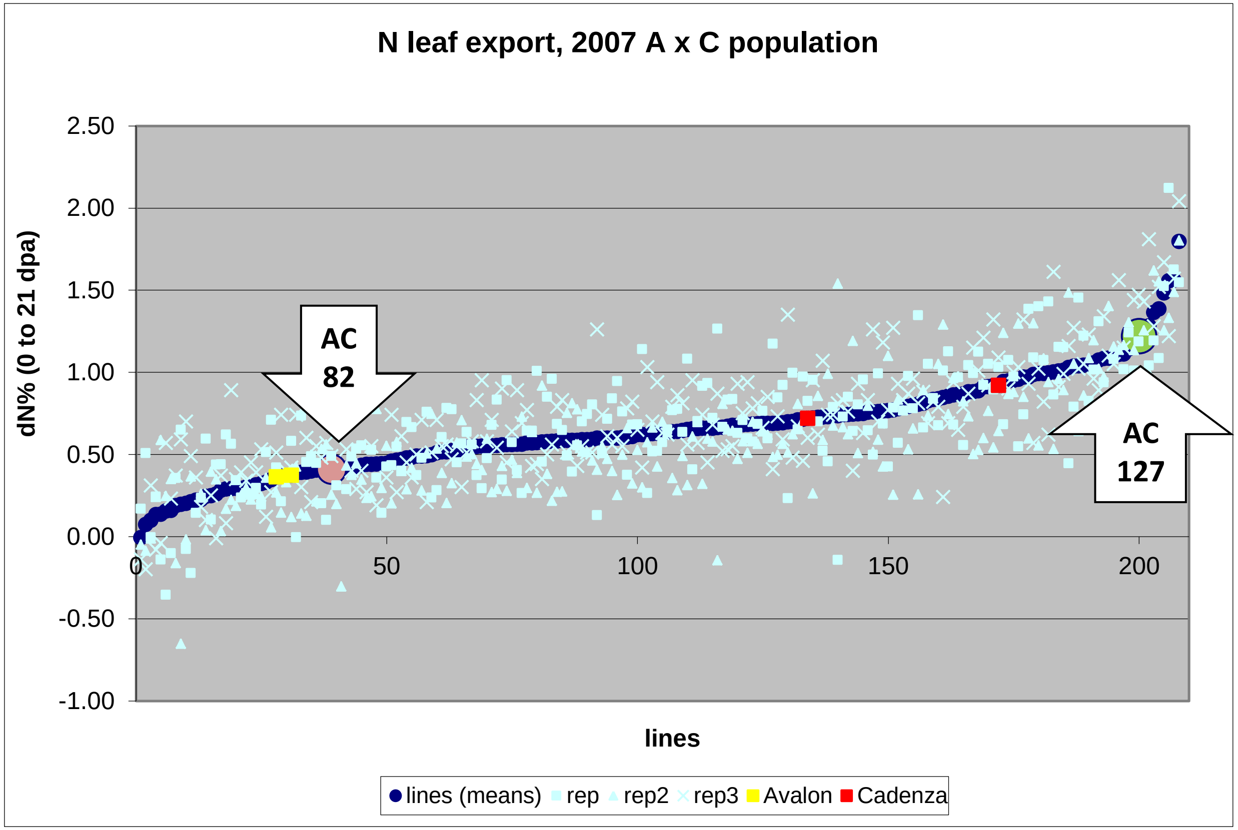


Avalon	AV	Gallant	GA	Mercia	ME	Xi19	XI
Cadena	CA	Hereford	HF	Paragon	PA	Zebedee	ZE
Chablis	CH	Hereward	HE	Riband	RI	AC 127	D5
Claire	CL	Istabraq	IS	Robigus	RO	AC 82	D6
Conqueror	CN	Malacca	MA	Stigg	ST		
Cordiale	CO	Marksman	MK	Soissons	SS		
Crusoe	CR	Maris Widgeon	MW	Solstice	SL		

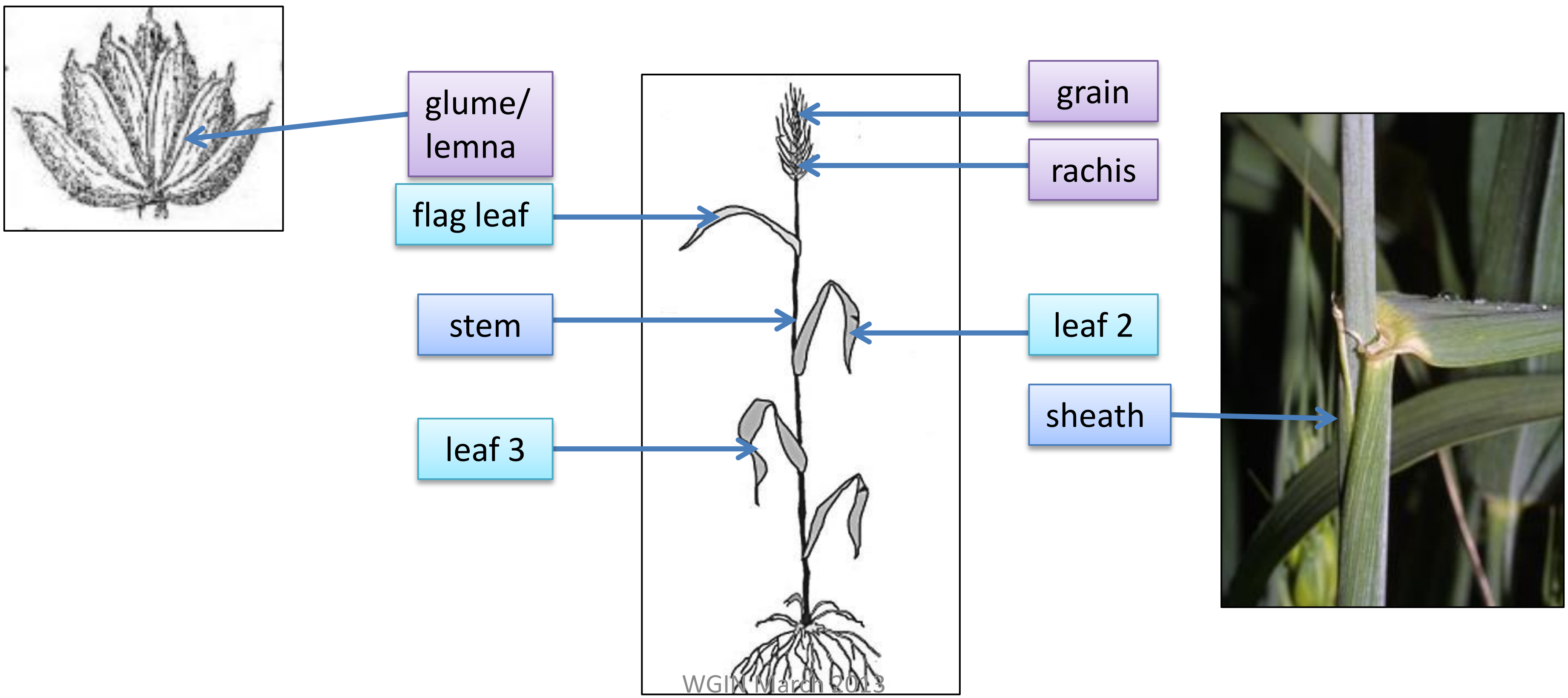
N distribution in wheat main-stems at flowering and maturity



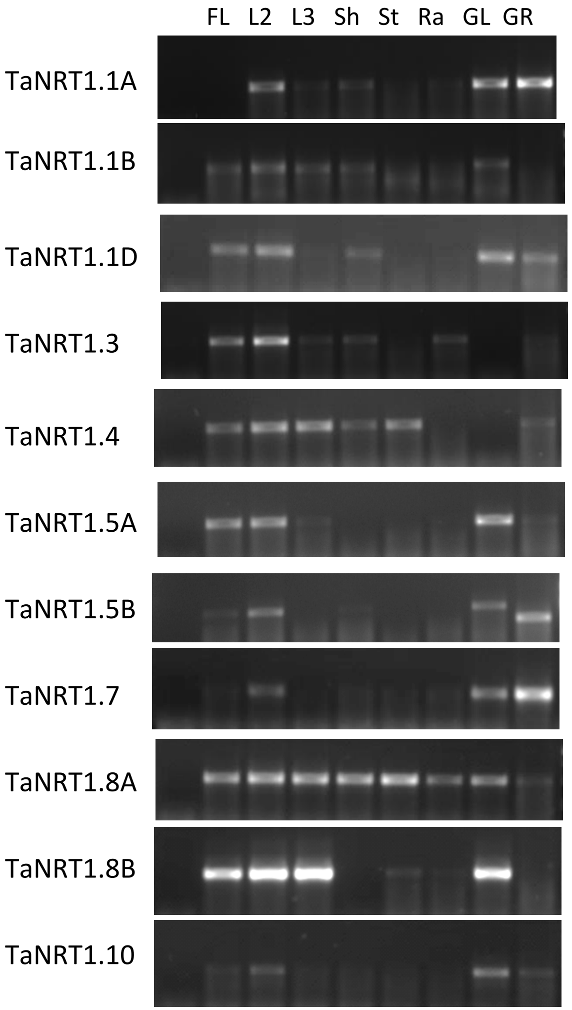
Double haploid lines 127 and line 82 were chosen from a Avalon/Cadenza double haploid mapping population because of their contrast characteristics in relation N leaf export (data 2007: early versus late leaf N-export).

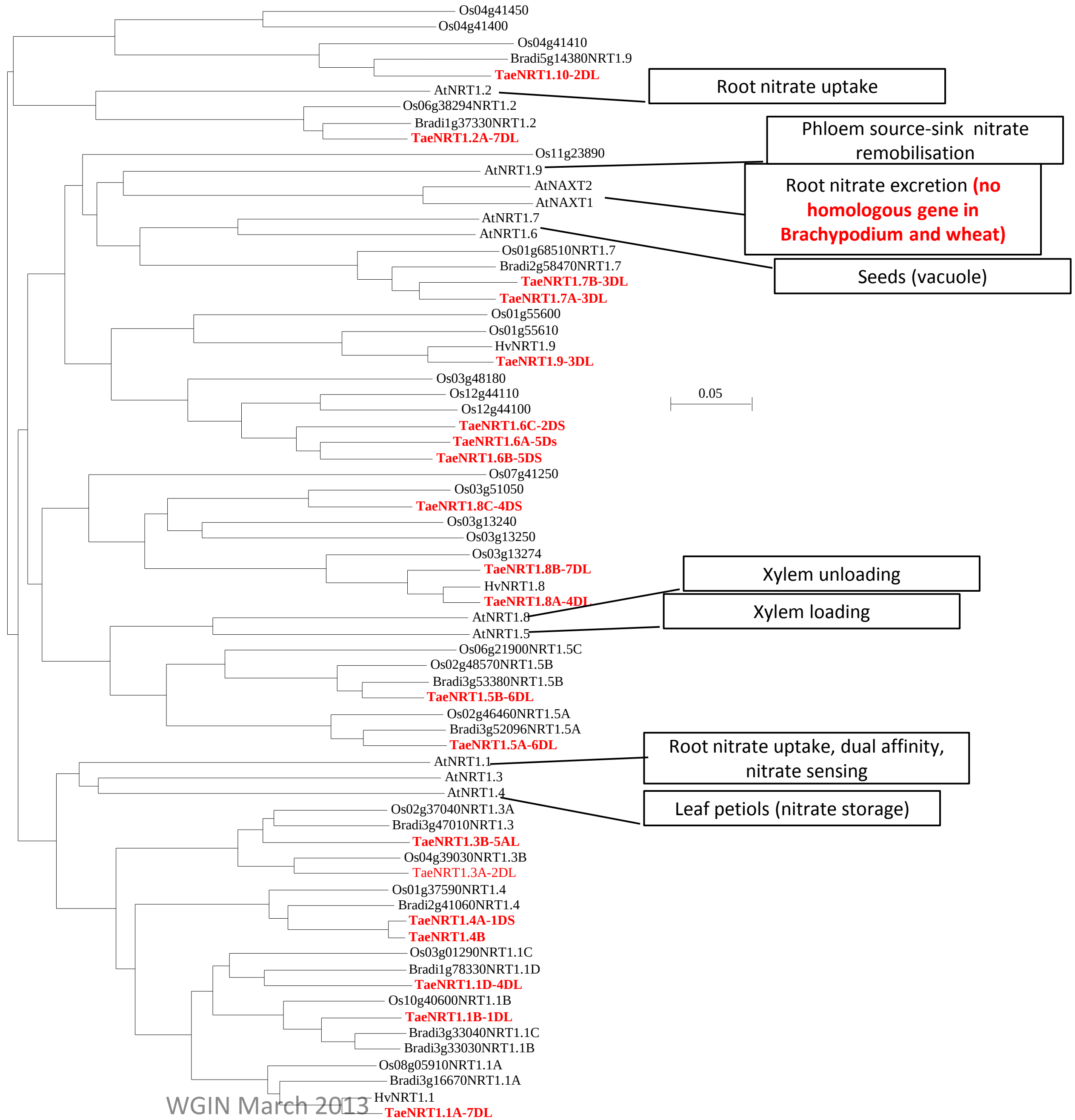


- Already observed differentially expression of specific target genes in the A xC lines 127 and 82 in leaves post anthesis
- In 2012 different tissues will be harvested at anthesis and weekly post-anthesis until complete senescence
- Extensive gene expression analysis of the different tissues will be performed to identify candidate genes involved in N-distribution and remobilisation in relation to post-anthesis grain N-filling.



Wheat low affinity Nitrate transporter in comparison to Barley, Brachypodium and Arabidopsis





Expression anthesis /
1 week post anthesis (grain/glume)

2012 varieties list (part 1)

Wheat varieties for WGIN-NUE 2010/11 W=WGIN data, D=desk study

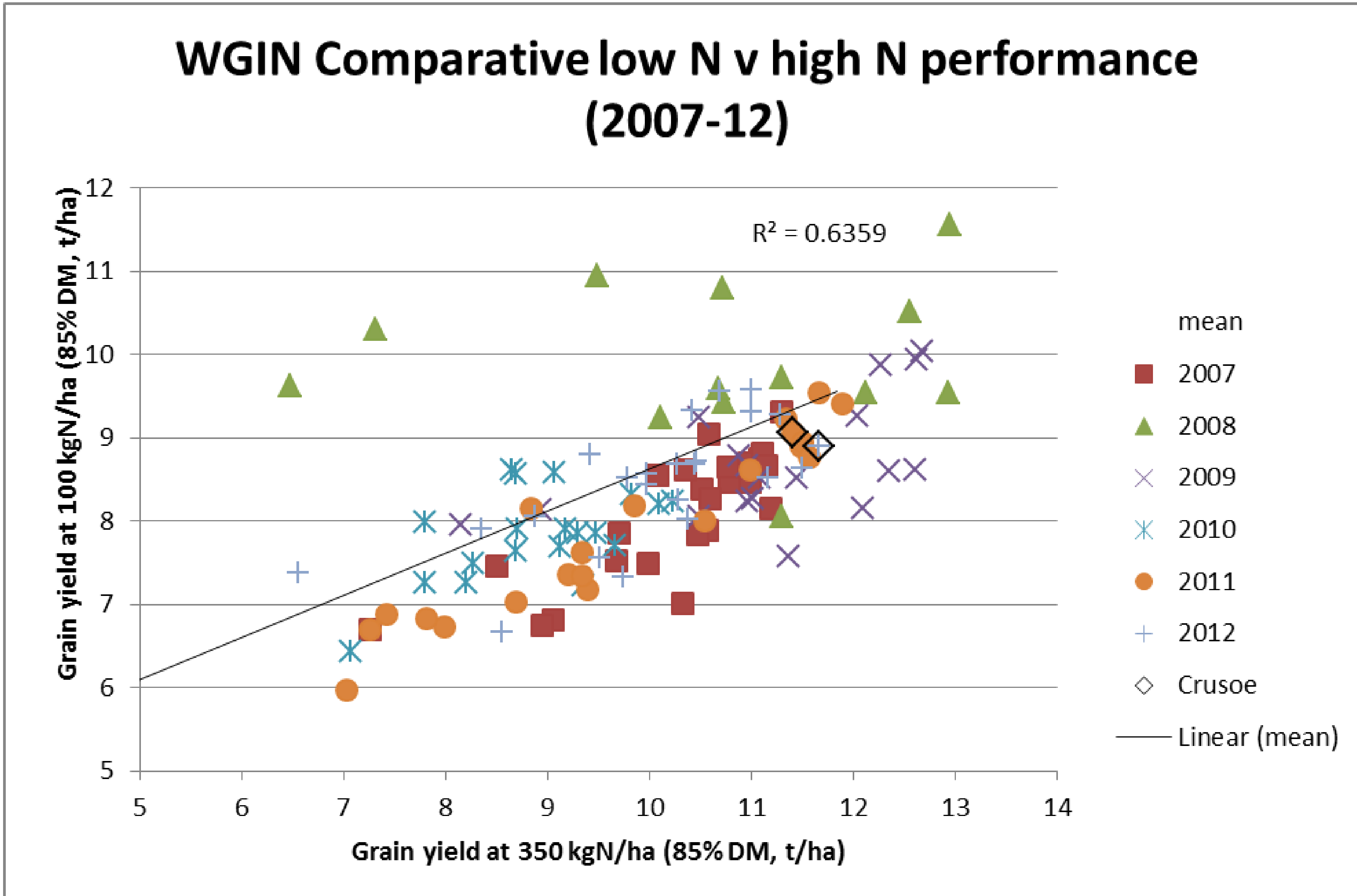
Variety	Source	Code	Nabim	Rationale	inclusion in trial requested by	Previous years of trials (harvest year)
1. Avalon	Av	AV	1	WGIN DH parent; Low NupE & NutE (D)	PB, RG, MJH	05-10
2. Cadenza	Ca	CA	2	WGIN DH parent; Best NupE (W)	PB, RG, MJH	04-10
3. Chablis NEW 09/10	KWS		2	SPRING variety (previous grown in 2004 trial) as very N-responsive variety	MH	only in 04 and 10
4. Claire NEW 2005	Nick	CL	3	Biggest area on RL; WGIN DH parent; Good second wheat	PB,PS	05-10
5. Conqueror	KWS	CN	4	New Grp 4, very high yielding	MH	new
6. Cordiale NEW 2006	KWS	CO	2	Good second wheat. BBSRC Quality project	RG	06-10
7. Crusoe NEW 10/11	Nick	CR	2	Carries dicoccoides. Shows the 'stay green' character		
8. Gallant NEW 09/10	Syn	GA	1	new claimed high yield and high protein type	MH	
9. Hereford	Syn	HF	4	Feed (not on RL), high yield, brown rust susceptible, possible low take-all build-up and good resistance.	KHK/RG	new
10. Hereward	RAGT	HE	1	Best protein on RL; benchmark bread variety. BBSRC Quality project	PB,PS	04-10
11. Istabraq NEW 2005	Nick	IS	4	Best yield on RL; Distilling cultivar; In LINK 'GREENgrain'; Good second wheat. BBSRC Quality project. WUE trial	PB,PS	05-10
12. Malacca	KWS	MA	1	Biggest Group 1 area; DH choice; Low NupE, high NutE (W). BBSRC Quality project	PS	04-10
13. Marksman	RAGT	MK	2	new for 2009, PRS request for BBSRC Quality project	PS	only 09 and 10

2012 varieties list (part 2)

W=WGIN data, D=desk study

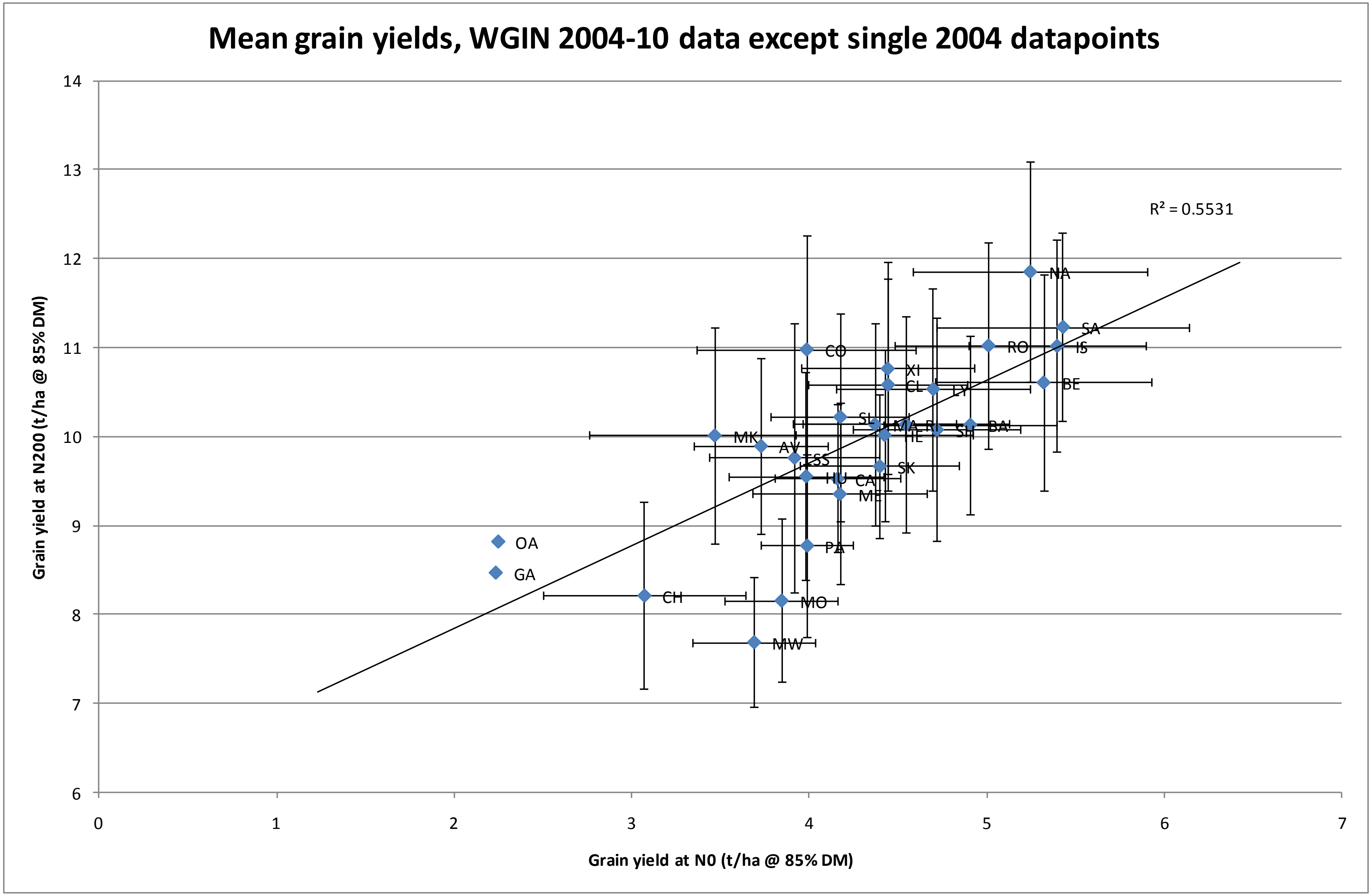
Variety	Source	Code	Nabim	Rationale	inclusion in trial requested by	Previous years of trials (harvest year)
14. Maris Widgeon		MW	1	Tall (rht), old cultivar	PB, AM	04-10
15. Mercia		ME	1	Low NupE & NutE (desk); Low Canopy N requirement; In IGF micro-array. WUE trial. RHT series	RG	04 and 06-10
16. Paragon	RAGT	PA	1	Spring variety; WGIN mutagenesis population; High NupE (W)	PB	04-10
17. Riband	RAGT	RI	3	WGIN DH parent; Distilling cultivar; In LINK 'GREENgrain'; High NutE (W)	RG	04-10
18. Robigus NEW 2005	KWS	RO	3	Best Group 3 yield; Best NUE, high NupE & NutE (D); Good second wheat. WUE trial	PB, AM	05-10
19. Stigg NEW 10/11	Nick	ST	?4	Carries dicoccoides. High disease resistance. Shows the 'stay green' character		
20 Soissons	Elsoms	SS	2	WGIN DH parent; Early maturing; High NupE, low NutE (W)	PB,RG, AM	04-10
21. Solstice	Nick	SL	2	Biggest Group 2 area; DH choice; Worst NupE (W)	RG	04-10
22. Xi19	Nick	XI	1	Best Group 1 yield; High NUE, NupE, NutE (D); Low NupE (W). BBSRC Quality project. WUE trial	PB,PS	04-10
23. Zebedee	LIM	ZE	3	High WUE, grp 3	JFoulkes	new
24. AxC line 127		D5		new in 2009 - good early export from leaves	MJH	09/10/
25. AxC line 82		D6		new in 2009 - slow early export from leaves	MJH	09/10/

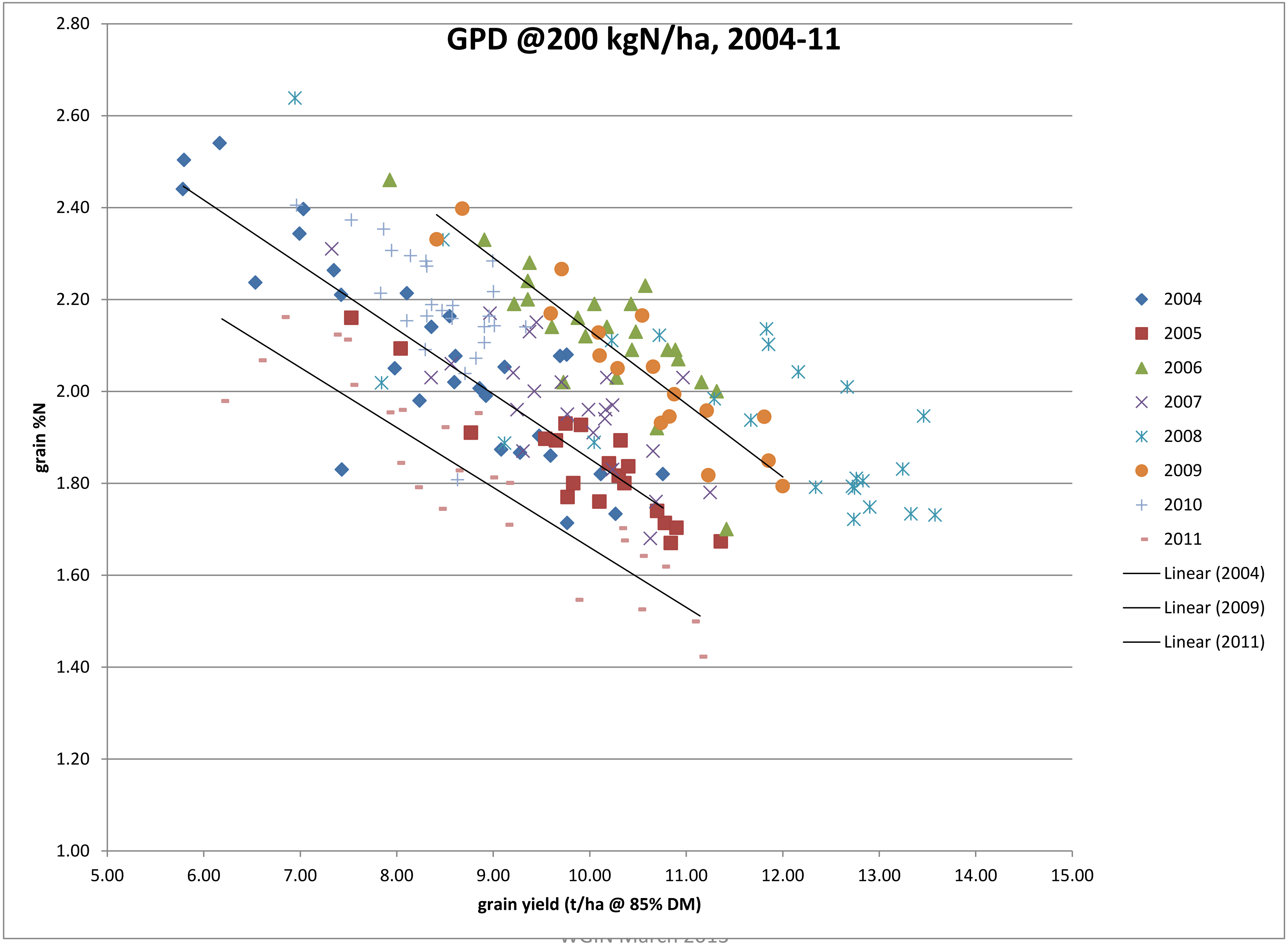
Removed from trial: 2 A x C lines and Oakley

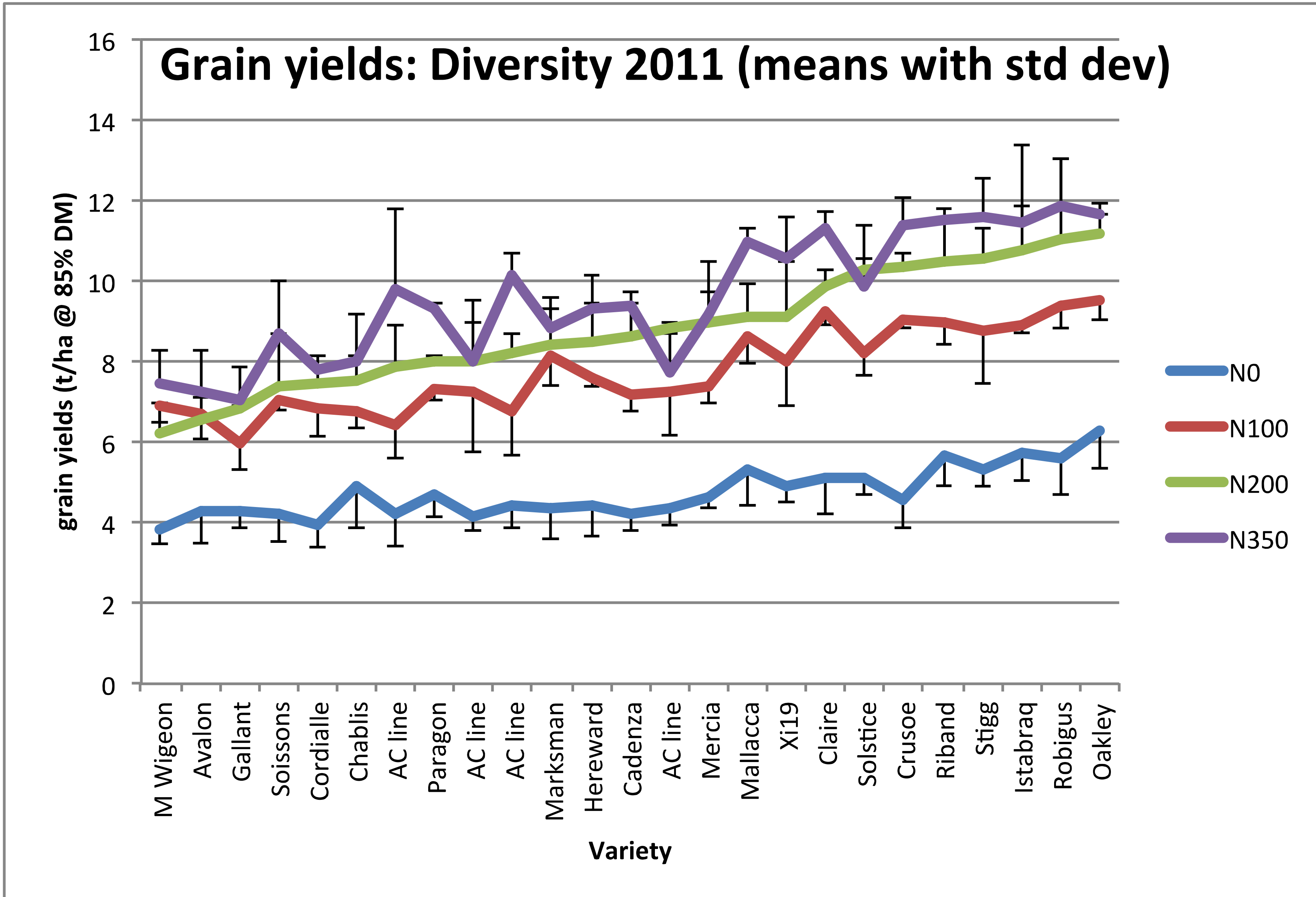


WGIN Comparative low N v high N performance (2007-12)
R² = 0.6359
Grain yield at 100 kgN/ha (85% DM, t/ha)
Grain yield at 350 kgN/ha (85% DM, t/ha)
12
11
10
9
8
7
6
5
5
6
7
8
9
10
11
12
13
14
mean
2007
2008
2009
2010
2011
2012
Crusoe
Linear (mean)

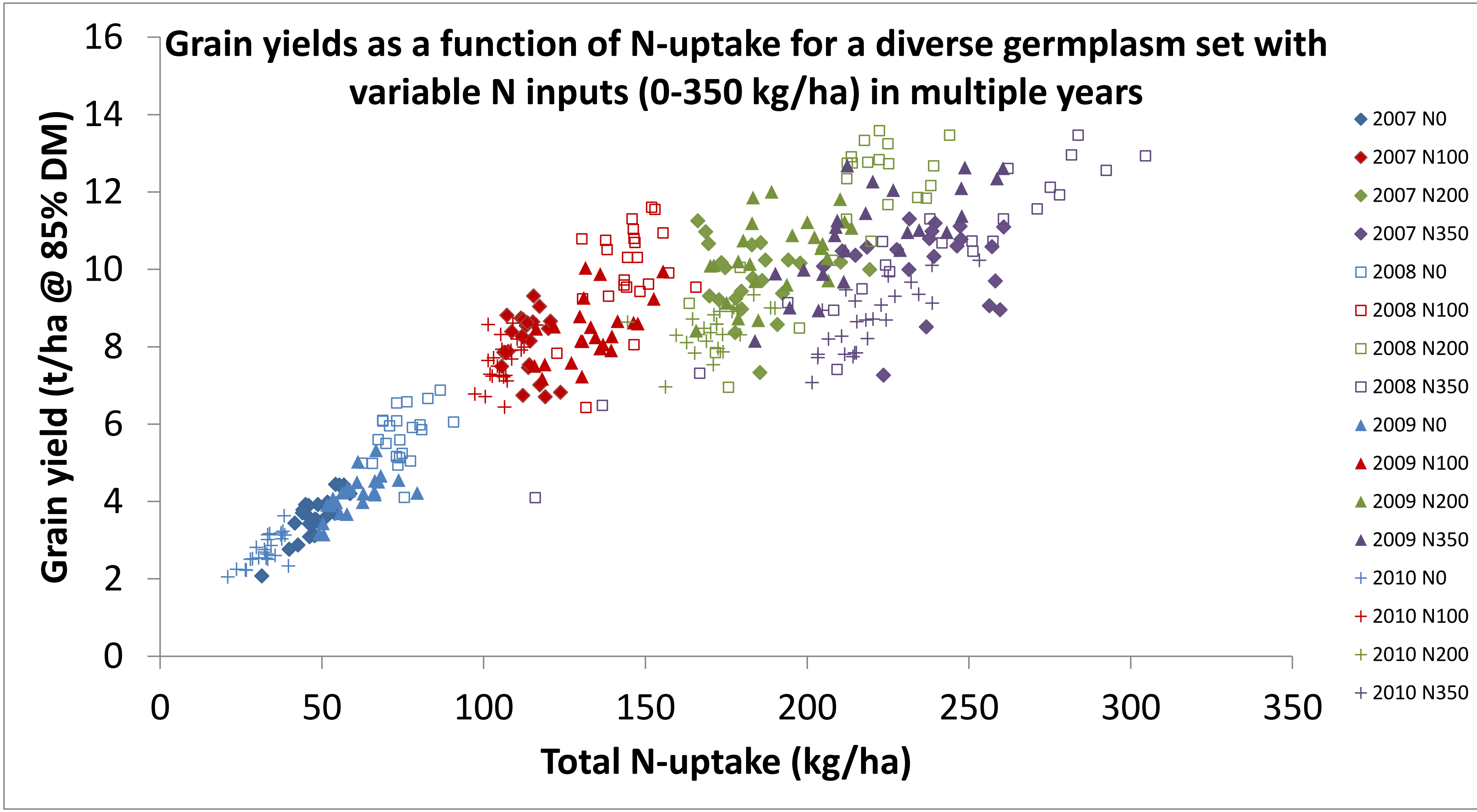
Performance at N200 compared to N0




GPD @200 kgN/ha, 2004-11
grain %N
grain yield (t/ha @ 85% DM)
2.80
2.60
2.40
2.20
2.00
1.80
1.60
1.40
1.20
1.00
5.00
6.00
7.00
8.00
9.00
10.00
11.00
12.00
13.00
14.00
15.00
2004
2005
2006
2007
2008
2009
2010
2011
Linear (2004)
Linear (2009)
Linear (2011)

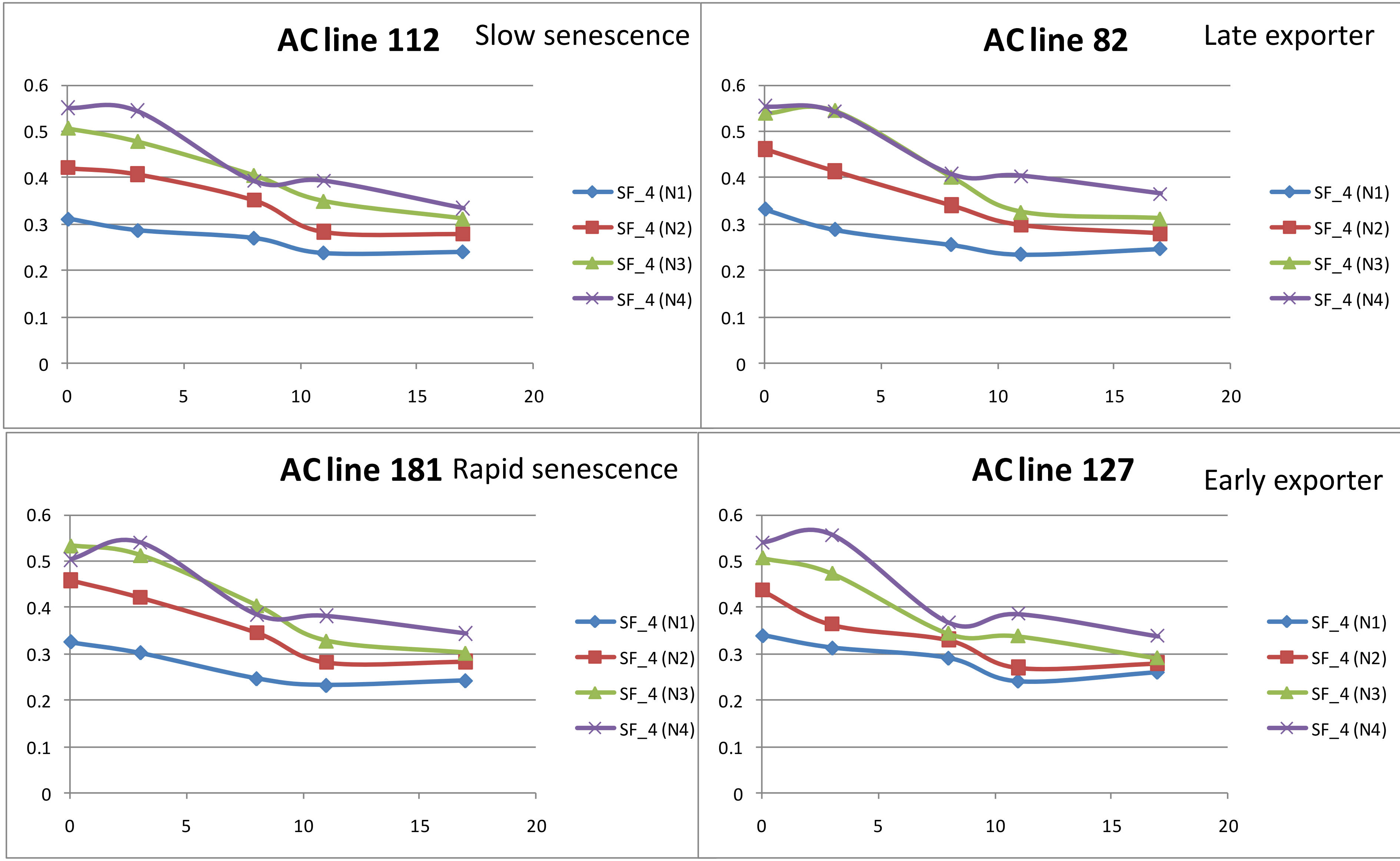

Grain yields: Diversity 2011 (means with std dev)
grain yields (t/ha @ 85% DM)
0
2
4
6
8
10
12
14
16
M Wigeon
Avalon
Gallant
Soissons
Cordialle
Chablis
AC line
Paragon
AC line
AC line
Marksman
Hereward
Cadenza
AC line
Mercia
Mallacca
Xi19
Claire
Solstice
Crusoe
Riband
Stigg
Istabraq
Robigus
Oakley
Variety
N0
N100
N200
N350

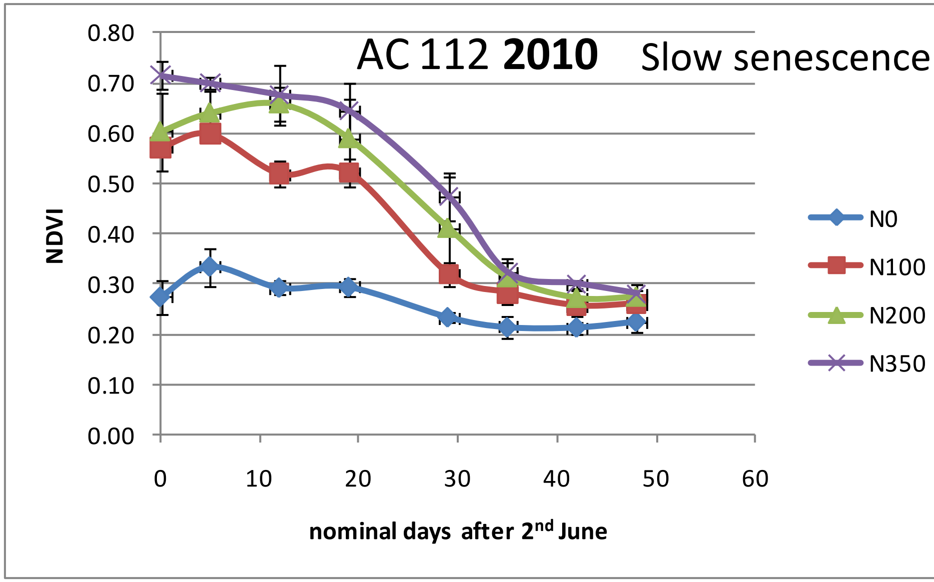
Avalon x Cadenza 2011

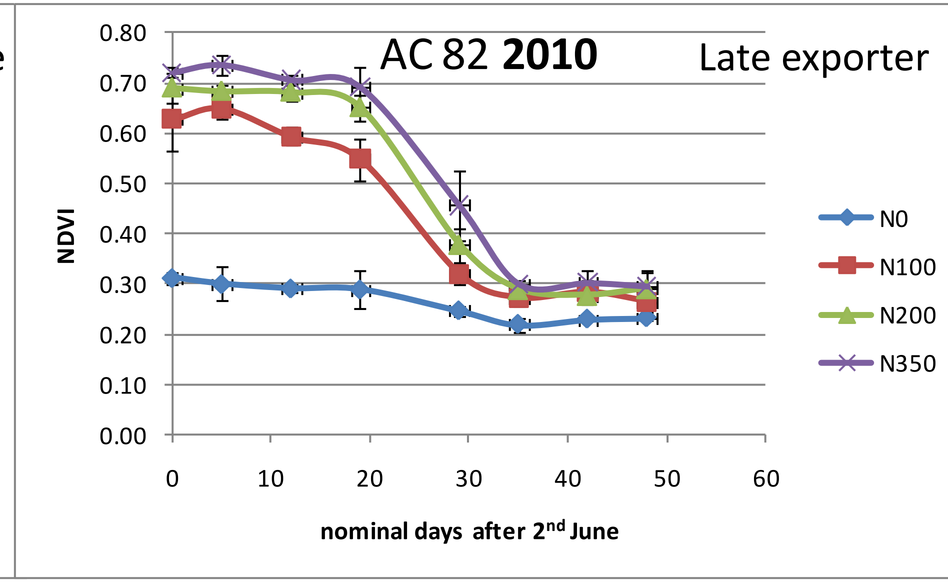

Grain yields as a function of N-uptake for a diverse germplasm set with variable N inputs (0-350 kg/ha) in multiple years
Grain yield (t/ha @ 85% DM)
16
14
12
10
8
6
4
2
0
0
50
100
150
200
250
300
350
Total N-uptake (kg/ha)
2007 N0
2007 N100
2007 N200
2007 N350
2008 N0
2008 N100
2008 N200
2008 N350
2009 N0
2009 N100
2009 N200
2009 N350
2010 N0
2010 N100
2010 N200
2010 N350

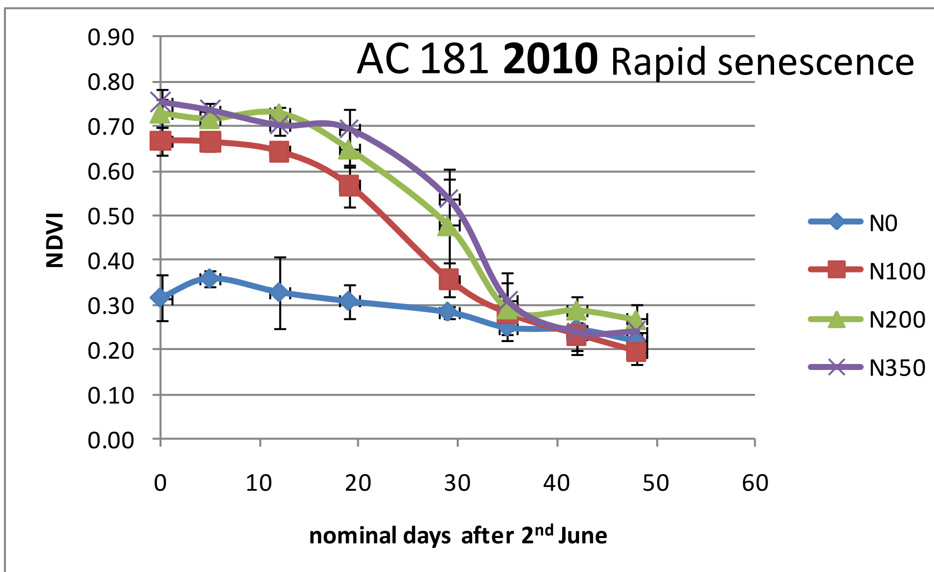
Diversity Trial 2011

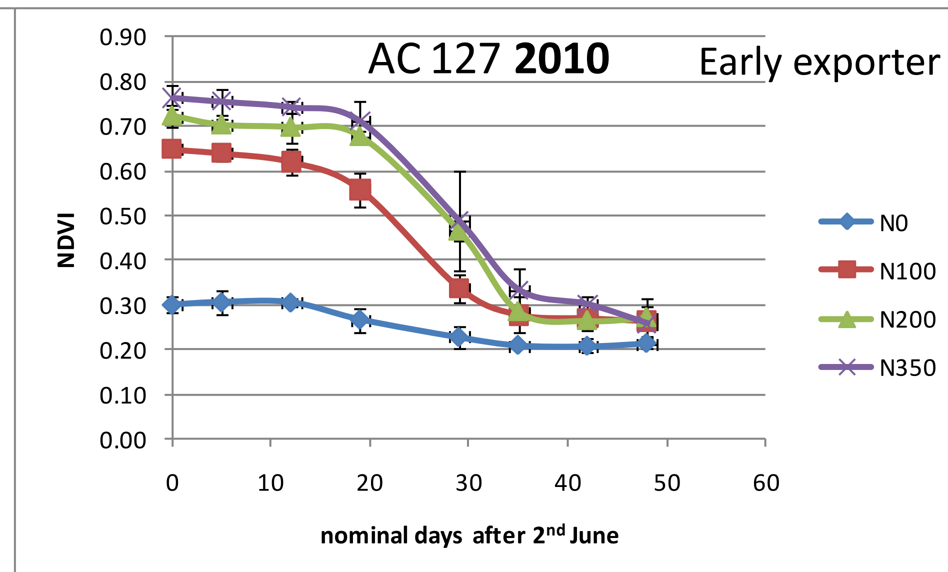
CropCircle (Holland Scientific), WGIN Diversity 2011



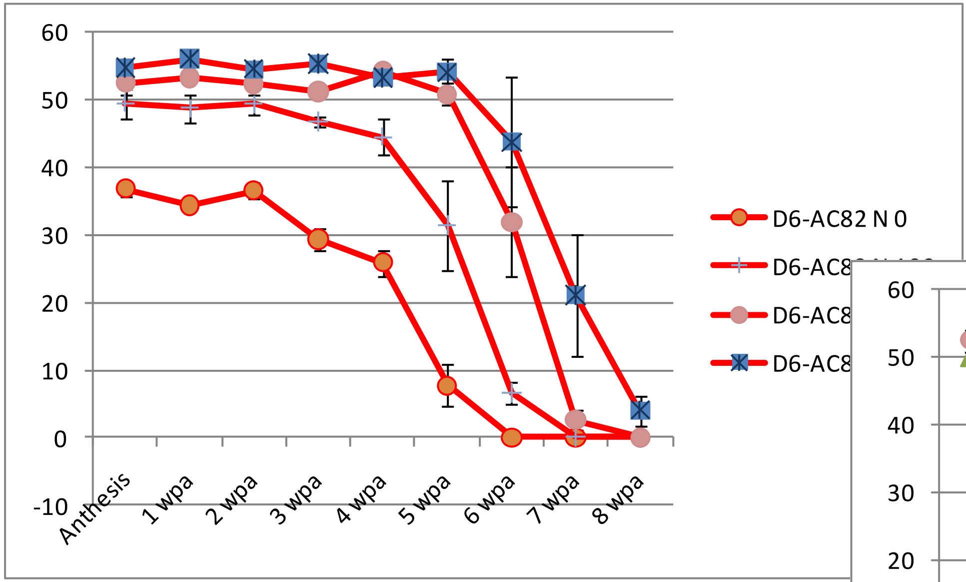

AC 112 **2010**
Slow senescence
NDVI
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
0
10
20
30
40
50
60
nominal days after 2nd June
N0
N100
N200
N350

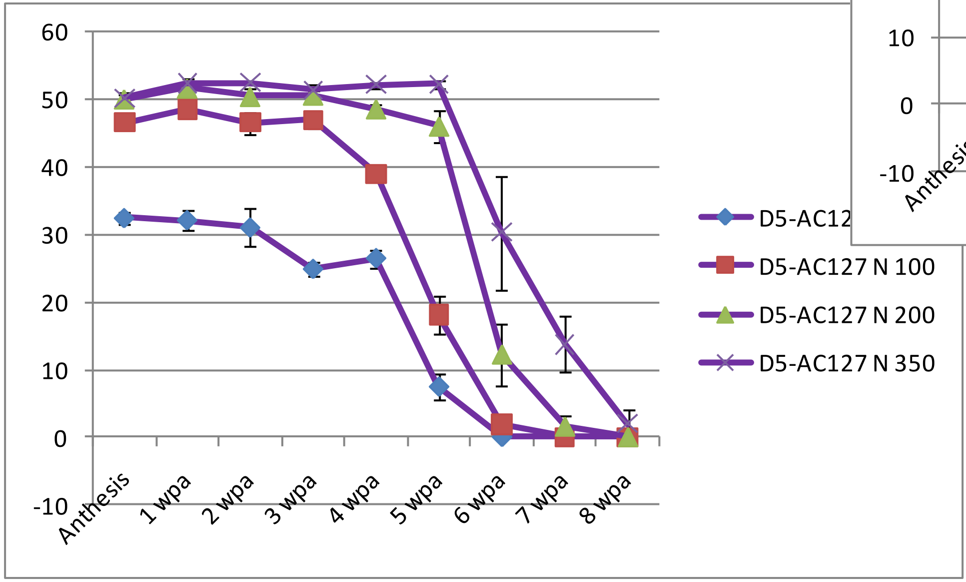

AC 82 **2010**
Late exporter
NDVI
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
0
10
20
30
40
50
60
nominal days after 2nd June
N0
N100
N200
N350

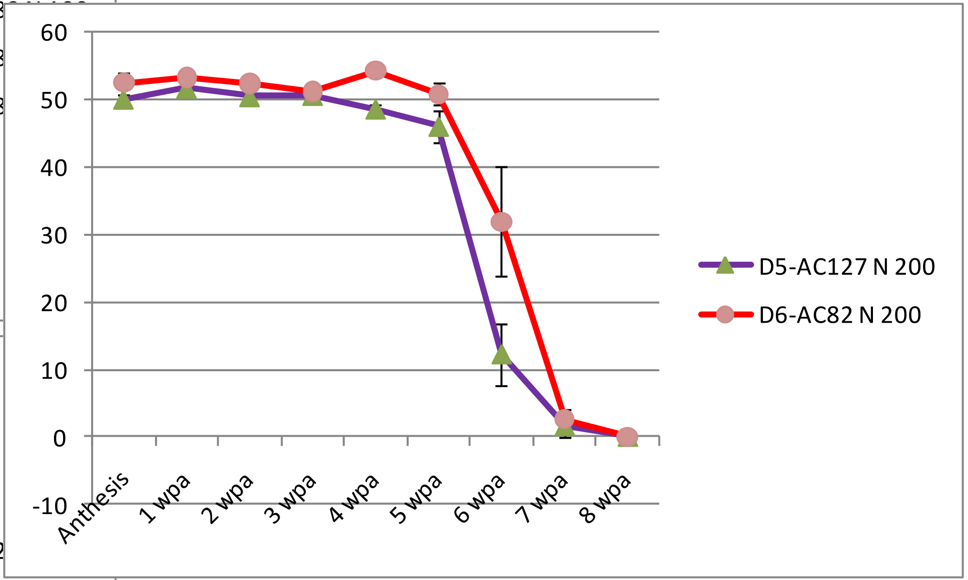

AC 181 **2010** Rapid senescence
NDVI
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
0
10
20
30
40
50
60
nominal days after 2nd June
N0
N100
N200
N350


AC 127 **2010**
Early exporter
NDVI
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
0
10
20
30
40
50
60
nominal days after 2nd June
N0
N100
N200
N350

Spad data 2011 WGIN Diversity



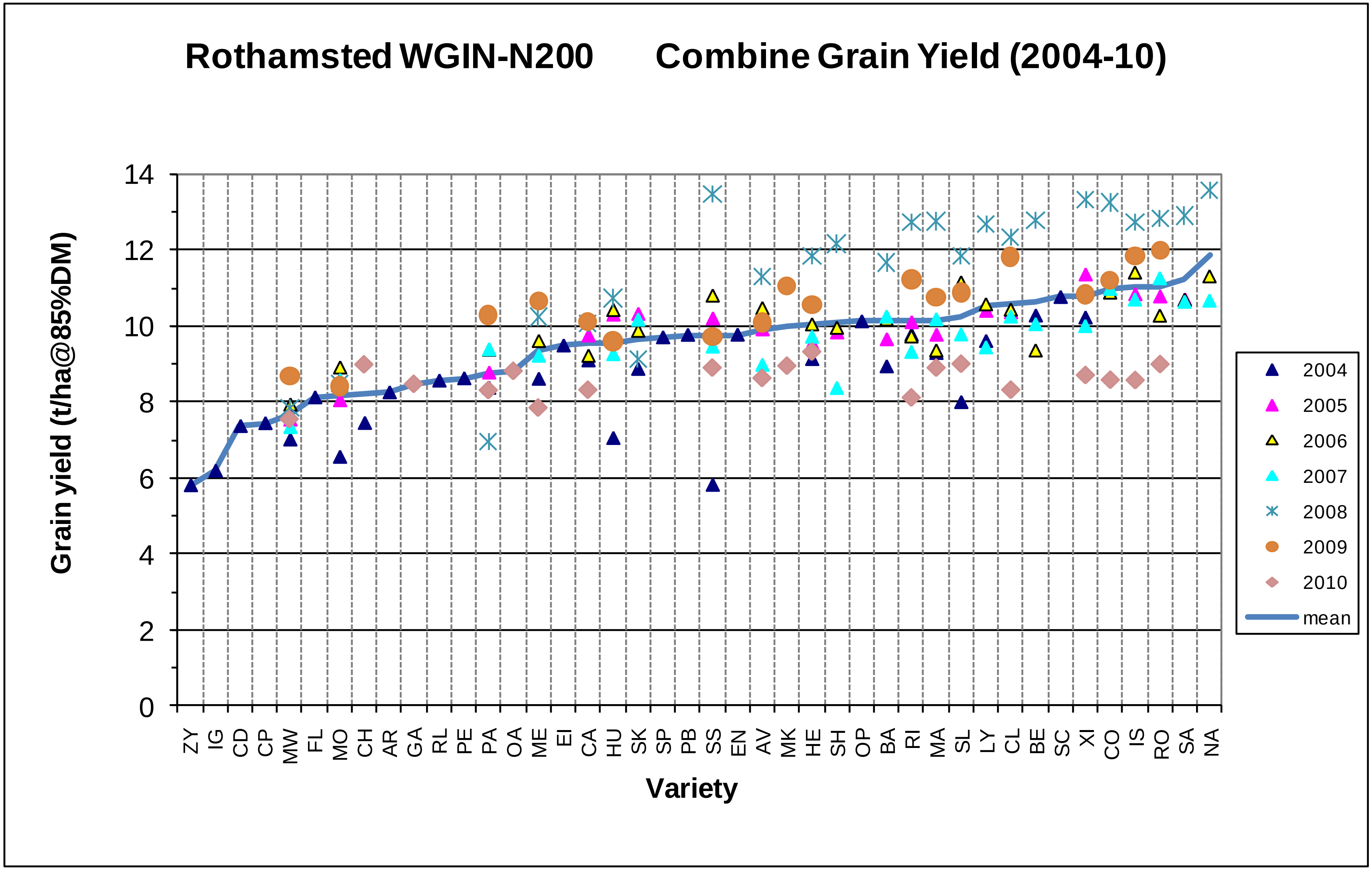




Why nitrogen?

- Required for yield
- Required for protein
- Costs – financial/environmental
- Low efficiency on worldwide scale but higher in UK
- Management and genetic components

Stability



Rothamsted WGIN-N200 Combine Grain Yield (2004-10)
Grain yield (t/ha@85%DM)
14
12
10
8
6
4
2
0
ZY IG CD CP MW FL MO CH AR GA RL PE PA OA ME EI CA HU SK SP PB SS EN AV MK HE SH OP BA RI MA SL LY CL BE SC XI CO IS RO SA NA
Variety
2004
2005
2006
2007
2008
2009
2010
mean

WGIN NUE Objectives

- Define important NUE traits
- Identify and evaluate diversity
- Determine mechanisms
- Provide leads for markers and genes
- Examine trait stability over multiple years
- Trials and basic datasets

Approaches

- Modern commercial germplasm (Diversity) and mapping population (Avalon x Cadenza) trials
- Assessment of trial diversity in the field
- Identify QTL

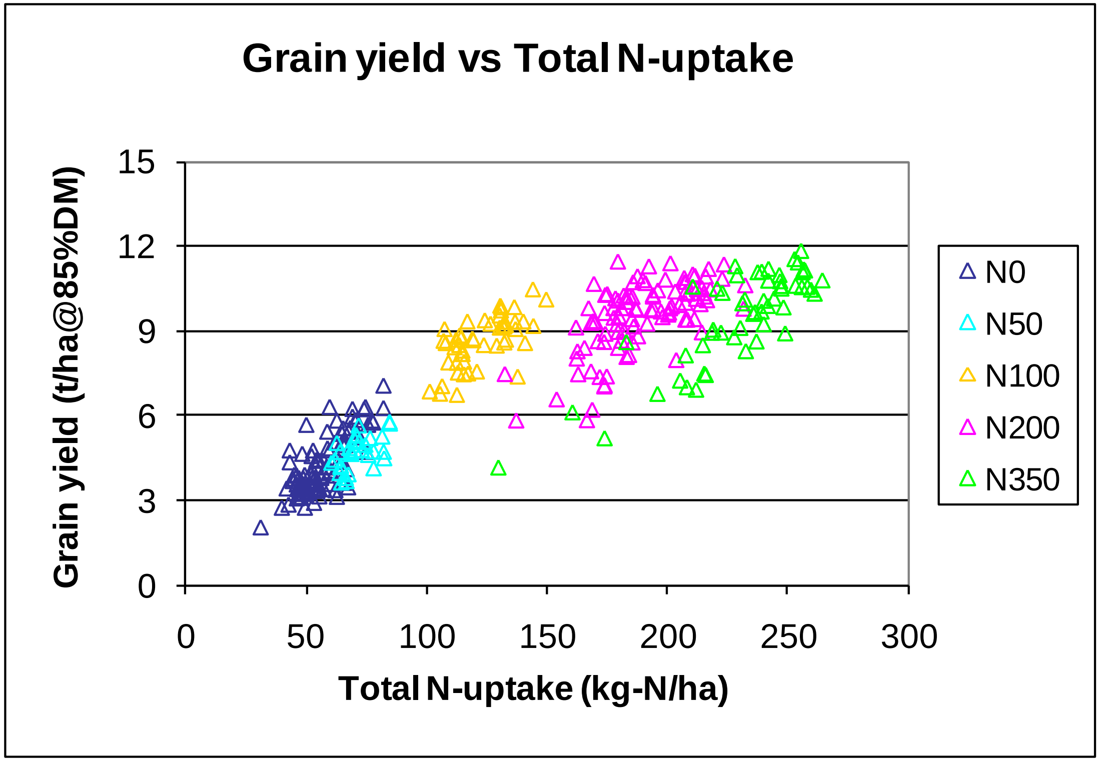
WGIN 2009-2013

- Deeper phenotyping
  - Partitioning
  - Canopy longevity
  - Roots and uptake
- Stability data
- NUE – WUE – Take-all interactions
- Encourage spin off projects

Example results

- Trait performance rankings
- Stability
- Yield plateauing
- Performance at low compared to high N input
- qtls

Grain yield plateau



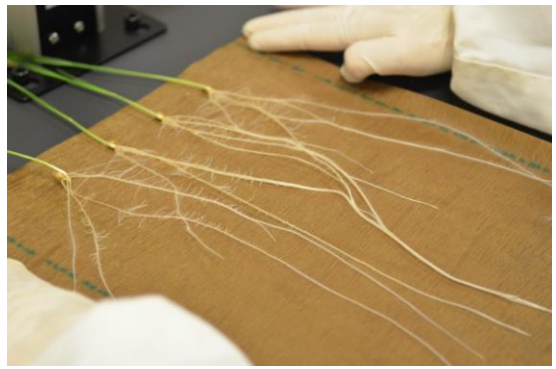
(mean data 2004-07)

- Grain yield less strongly related to N uptake
- Plateau of yield although uptake increases with increasing N supply
- Cluster (no relationship between yield and uptake) at any one N supply both between treatments and between varieties
- Factors other than uptake limiting yield

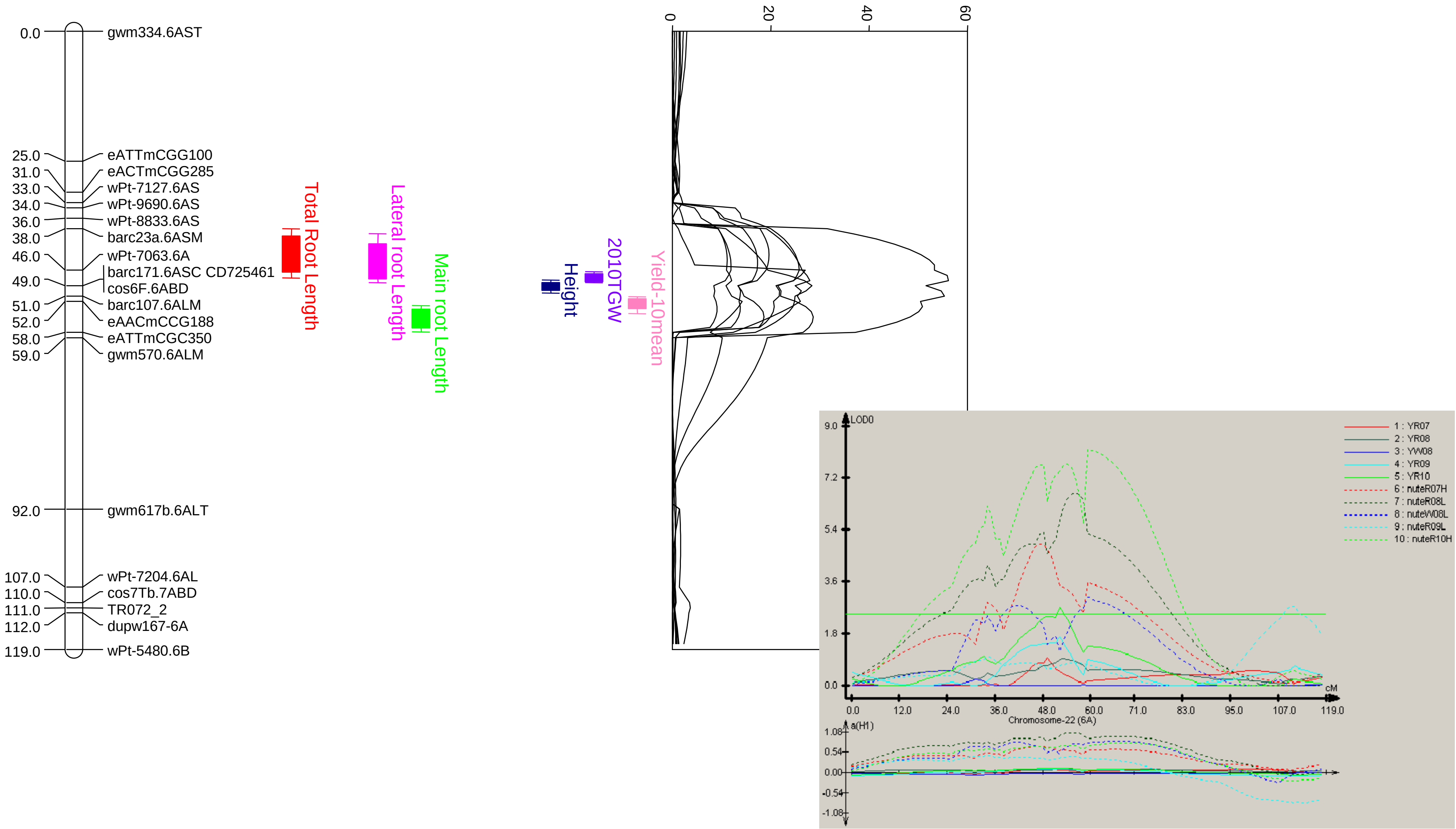
Avalon x Cadenza mapping population

- Traits for NUE – grain/straw yields/N uptake
- High and low N inputs
- Multiple years
- Analysis of post anthesis canopy dynamics and function
- Assessment of variability in uptake capabilities

Variation in root traits: mapping QTLs



6A


0.0 gwm334.6AST
25.0 eATTmCGG100
31.0 eACTmCGG285
33.0 wPt-7127.6AS
34.0 wPt-9690.6AS
36.0 wPt-8833.6AS
38.0 barc23a.6ASM
46.0 wPt-7063.6A
49.0 barc171.6ASC CD725461
cos6F.6ABD
51.0 barc107.6ALM
52.0 eAACmCCG188
58.0 eATTmCGC350
59.0 gwm570.6ALM
92.0 gwm617b.6ALT
107.0 wPt-7204.6AL
110.0 cos7Tb.7ABD
111.0 TR072_2
112.0 dupw167-6A
119.0 wPt-5480.6B
Total Root Length
Lateral root Length
Main root Length
Height
2010TGW
Yield-10mean
0
20
40
60
LOD0
1 : YR07
2 : YR08
3 : YW08
4 : YR09
5 : YR10
6 : nuteR07H
7 : nuteR08L
8 : nuteW08L
9 : nuteR09L
10 : nuteR10H
Chromosome-22 (6A)
cM
a(H1)

2011 varieties list (part 1)

Wheat varieties for WGIN-NUE 2010/11 W=WGIN data, D=desk study

Variety	Source	Code	Nabim	Rationale	inclusion in trial requested by	Previous years of trials (harvest year)
1. Avalon	Av	AV	1	WGIN DH parent; Low NupE & NutE (D)	PB, RG, MJH	05-10
2. Cadenza	Ca	CA	2	WGIN DH parent; Best NupE (W)	PB, RG, MJH	04-10
3. Chablis NEW 09/10	KWS		2	SPRING variety (previous grown in 2004 trial) as very N-responsive variety	MH	only in 04 and 10
4. Claire NEW 2005	Nick	CL	3	Biggest area on RL; WGIN DH parent; Good second wheat	PB,PS	05-10
5. Cordiale NEW 2006	KWS	CO	2	Good second wheat. BBSRC Quality project	RG	06-10
6. Crusoe NEW 10/11	Nick	CR	2	Carries dicoccoides. Shows the 'stay green' character		
7. Gallant NEW 09/10	Syn	GA	1	new claimed high yield and high protein type	MH	
8. Hereward	RAGT	HE	1	Best protein on RL; benchmark bread variety. BBSRC Quality project	PB,PS	04-10
9. Istabraq NEW 2005	Nick	IS	4	Best yield on RL; Distilling cultivar; In LINK 'GREENgrain'; Good second wheat. BBSRC Quality project. WUE trial	PB,PS	05-10
10. Malacca	KWS	MA	1	Biggest Group 1 area; DH choice; Low NupE, high NutE (W). BBSRC Quality project	PS	04-10
11. Marksman	RAGT	MK	2	new for 2009, PRS request for BBSRC Quality project	PS	only 09 and 10
12. Maris Widgeon		MW	1	Tall (rht), old cultivar	PB, AM	04-10
13. Mercia		ME	1	Low NupE & NutE (desk); Low Canopy N requirement; In IGF micro-array. WUE trial. RHT series	RG	04 and 06-10

2011 varieties list (part 2)

W=WGIN data, D=desk study

Variety	Source	Code	Nabim	Rationale	inclusion in trial requested by	Previous years of trials (harvest year)
14. Oakley NEW 09/10	KWS		4 (hard)	Hard milling type. Highest yielding wheat on RL.	MH	
15. Paragon	RAGT	PA	1	Spring variety; WGIN mutagenesis population; High NupE (W)	PB	04-10
16. Riband	RAGT	RI	3	WGIN DH parent; Distilling cultivar; In LINK 'GREENgrain'; High NutE (W)	RG	04-10
17. Robigus NEW 2005	KWS	RO	3	Best Group 3 yield; Best NUE, high NupE & NutE (D); Good second wheat. WUE trial	PB, AM	05-10
18. Stigg NEW 10/11	Nick	ST	?4	Carries dicoccoides. High disease resistance. Shows the 'stay green' character		
19 Soissons	Elsoms	SS	2	WGIN DH parent; Early maturing; High NupE, low NutE (W)	PB,RG, AM	04-10
20. Solstice	Nick	SL	2	Biggest Group 2 area; DH choice; Worst NupE (W)	RG	04-10
21. Xi19	Nick	XI	1	Best Group 1 yield; High NUE, NupE, NutE (D); Low NupE (W). BBSRC Quality project. WUE trial	PB,PS	04-10
22. AxC line 181		D3		new in 2010 - rapid canopy senescence	MJH	10/
23. AxC line 112		D4		new in 2010 - slow canopy senescence	MJH	10/
24. AxC line 127		D5		new in 2009 - good early export from leaves	MJH	09/10/
25. AxC line 82		D6		new in 2009 - slow early export from leaves	MJH	09/10/

Resistance to the take-all fungus in the diploid wheat, *Triticum monococcum*

Vanessa McMillan
Richard Gutteridge
Kim Hammond-Kosack

Wheat Genetic Improvement Network

defra
Department for Environment Food and Rural Affairs

ROTHAMSTED RESEARCH

Take-all disease of wheat

• *Gaeumannomyces graminis* var. *tritici* (*Ggt*)

- ascomycete soil borne fungus

- *Ggt* infects the roots

- No genetic solution to the control of take-all disease available

Severely take-all infected plant


A *Ggt* infected wheat root
Take-all lesion
Runner hypha

Typical take-all patch showing stunting and premature ripening of the crop

Disease development

- **1st wheat crop-** very little disease provided break crop is free from take-all carriers

- **2nd – 4th wheat crop-** severe disease can occur during this period

- **5th wheat crop onwards-** take-all severity decreases compared to a crop at its peak. This is known as Take-all Decline (TAD)

Triticum monococcum

T. monococcum wheat ear

- The diploid wheat, *T. monococcum* ($A^m A^m$), was widely cultivated during early cereal farming

- After the Bronze Age the cultivation of higher yielding polyploid wheat species dominated

- Genetic research has shown that the *T. monococcum* A^m genome was not directly involved in the generation of modern durum (tetraploid) and common wheat (hexaploid) species

Diploid wheat field trials - 5 years

Take-all Index-assessment of field experiments

- Whole plant root systems are assessed in a white dish under water and the proportion of roots affected by the disease are graded as follows:

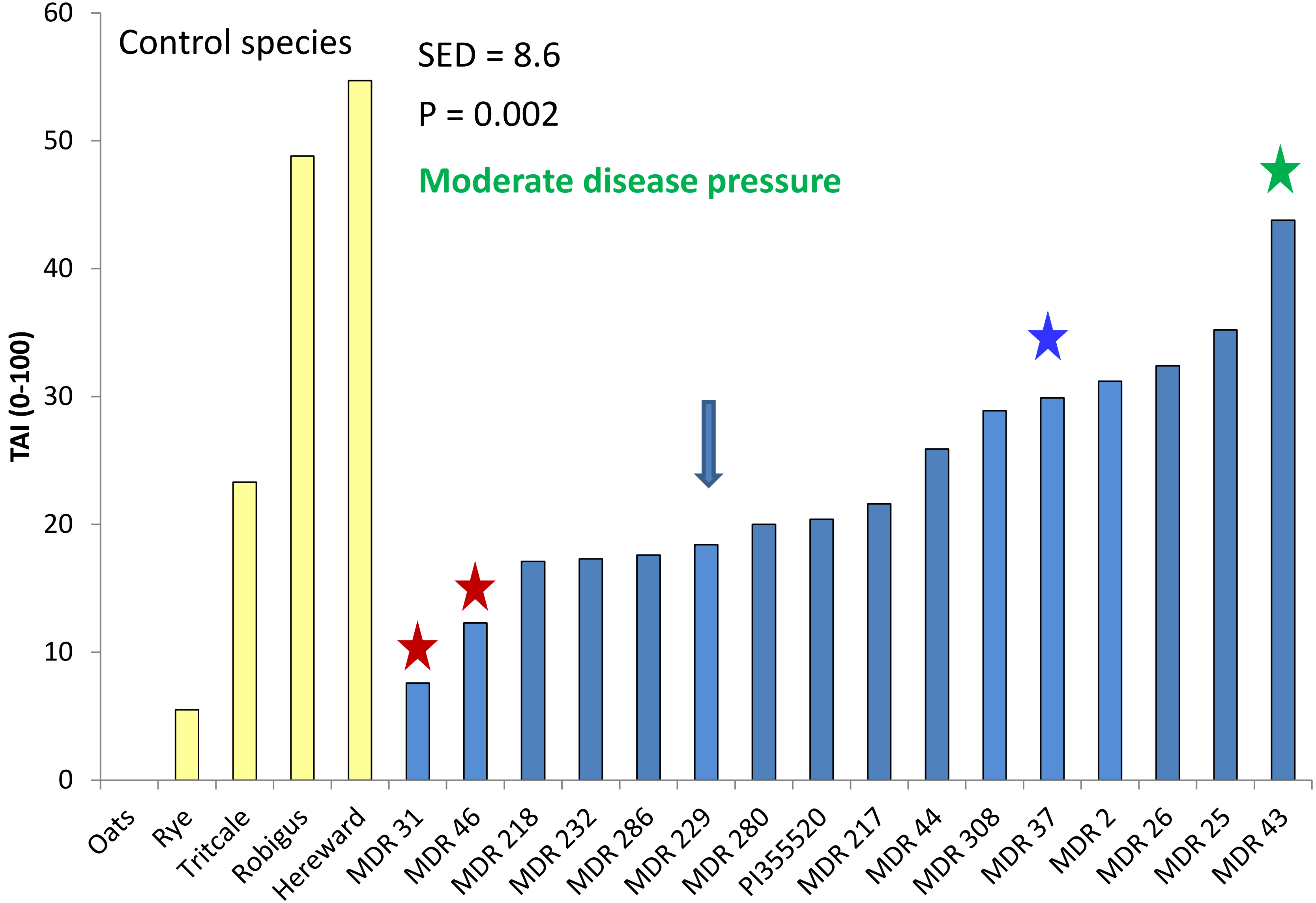
  Slight 1: 1 – 12%; **Slight 2**: 13 – 25%; **Moderate 1**: 26 – 50% **Moderate 2**: 51 – 75%; **Severe** >75%

- **Take-all Index (TAI)** calculated by:

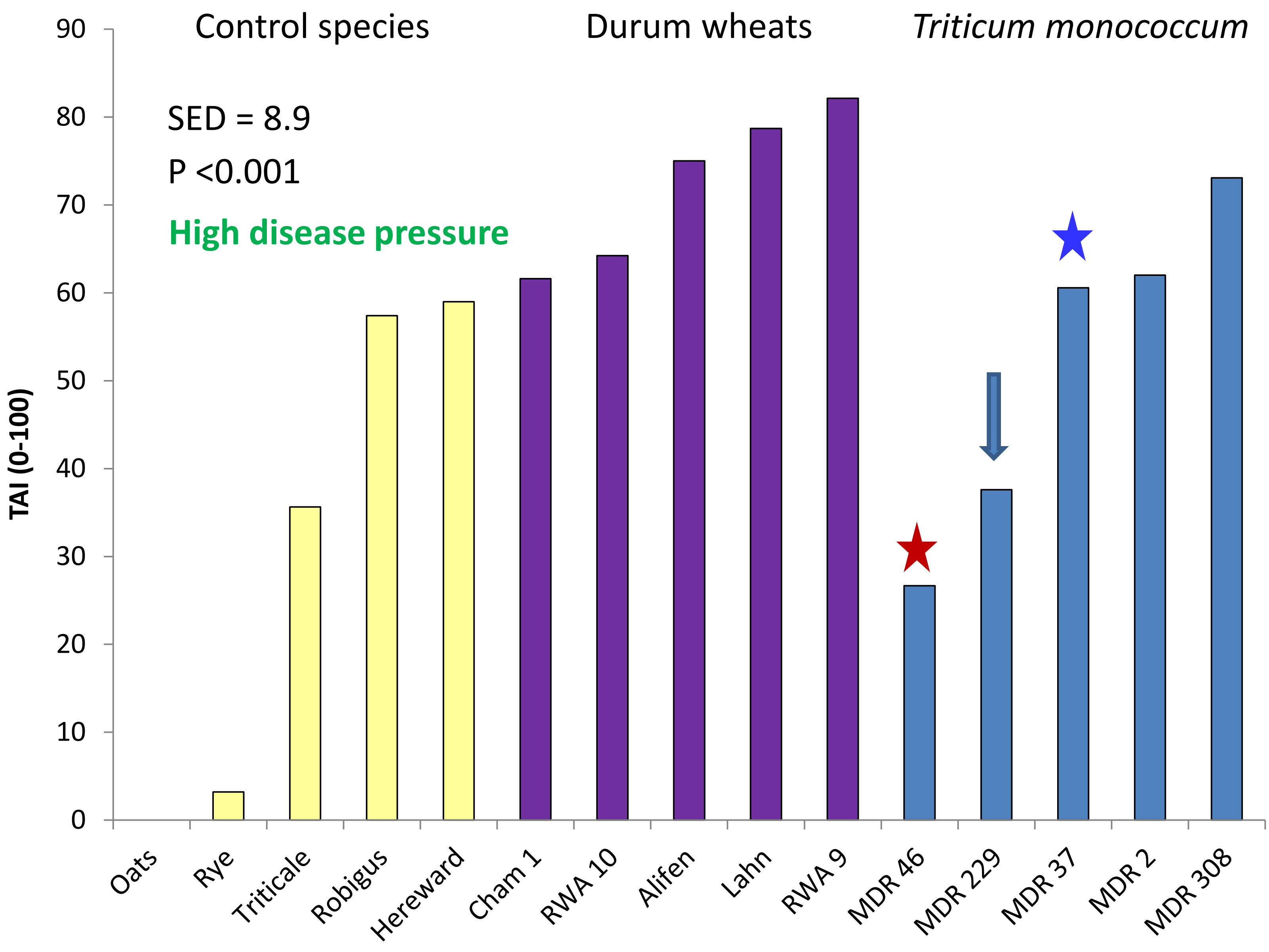
  1 x %plants with slight 1; + 2 x %plants slight 2; + 3 x %plants moderate 1; + 4 x %plants moderate 2; + 5 x % plants severe

  Divide by the number of categories (5) ; **Maximum index = 100**

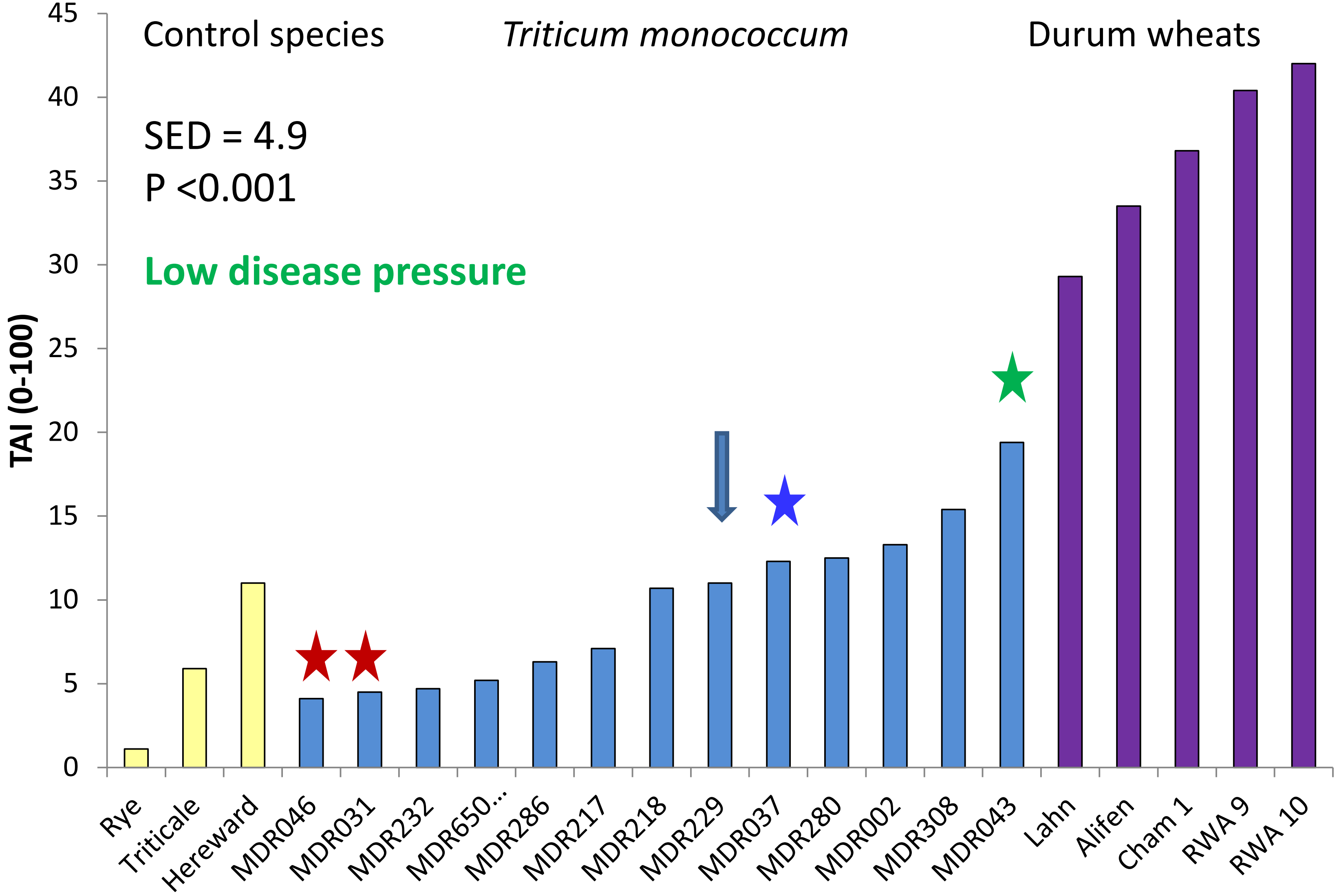
Diploid wheat field experiment 2008



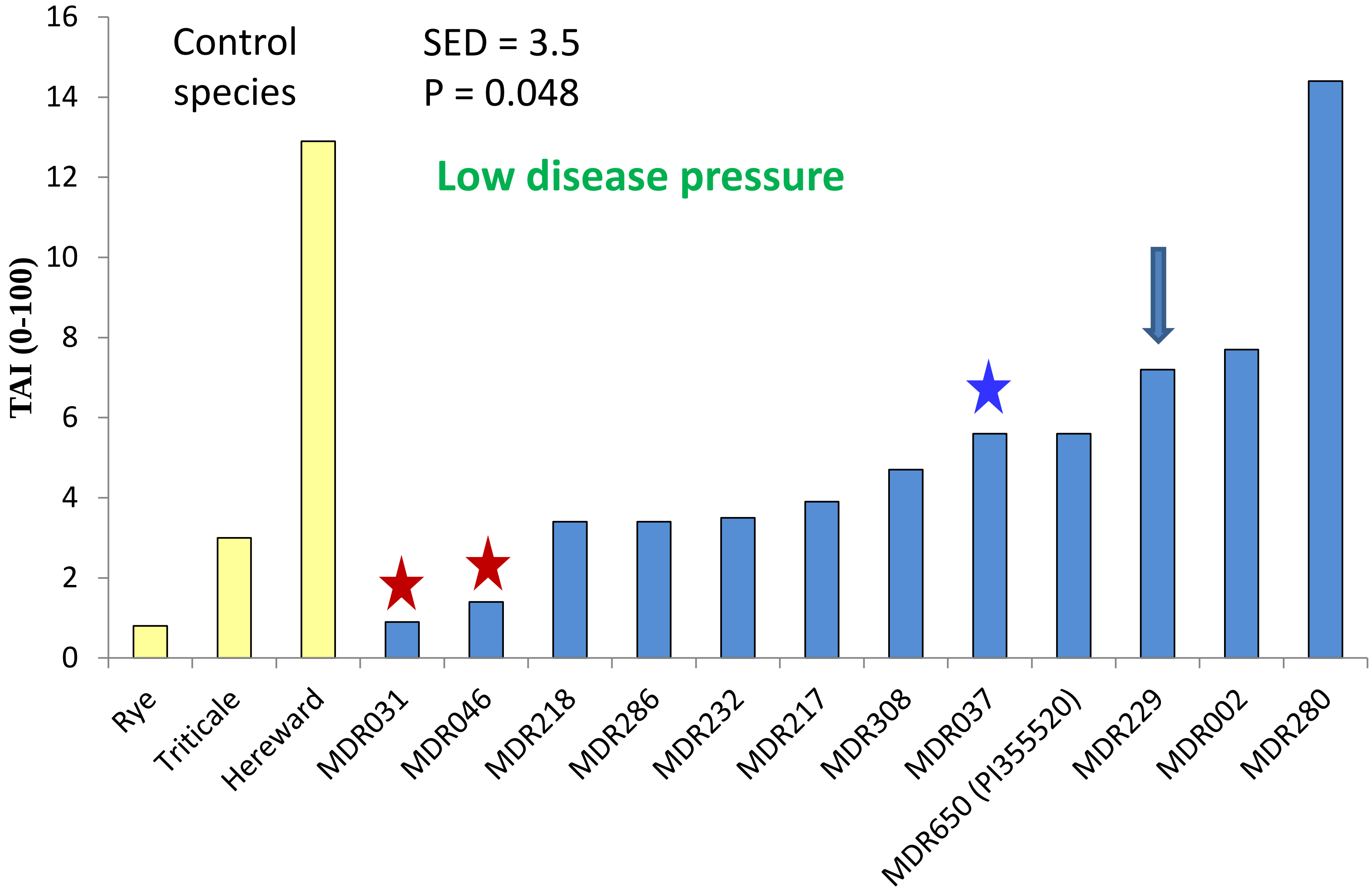
Diploid wheat field experiment 2009



Diploid wheat field experiment 2010



Diploid wheat field experiment 2011



Summary - *T. monococcum* lines of particular interest

Highly resistant under a range disease pressures
MDR 31 and MDR 46

Highly resistant under high disease but only moderate resistance under low disease / different RRes fields
MDR 229

Susceptible under a range disease pressures
MDR 37

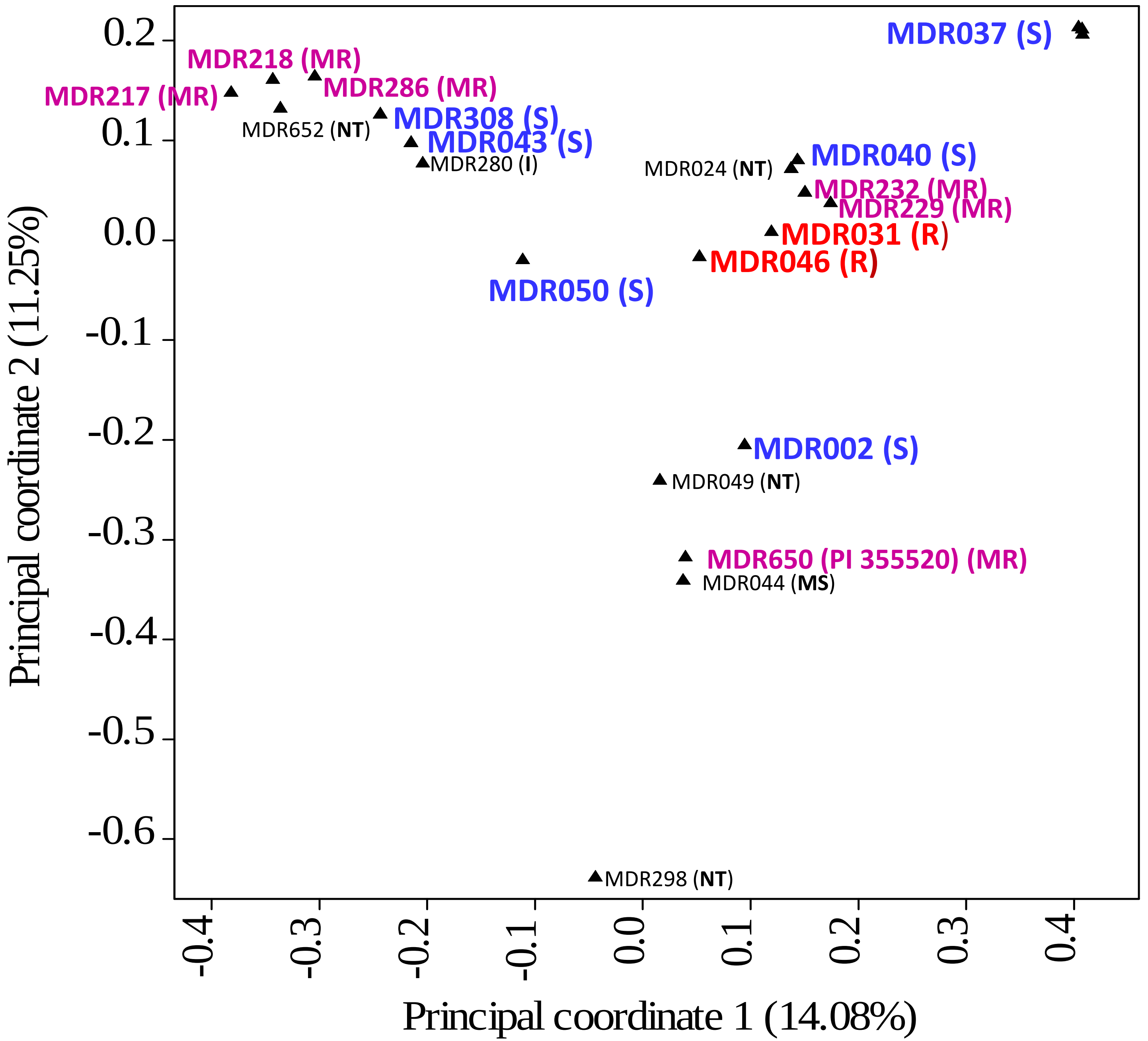
Highly susceptible under a range disease pressures
MDR 43

MDR308

Assessing the genetic diversity of the *Triticum monococcum* accessions

- Pedigrees of accessions are unknown
- Country of origin: MDR046 = Romania, MDR031 = Turkey
- Jing et al. (2009) first reported on the development of DArT markers for *T. monococcum*. This was used to fingerprint 16 *T. monococcum* accessions from diverse geographic origins.
- In 2012 twenty of the *T. monococcum* accessions in our take-all field trials were genotyped in an array using 1041 markers. DArT marker assay was carried out by Triticarte, Australia (www.triticarte.com.au)
- Principal coordinate analysis carried out to look at the grouping of accessions based on their genotype

DArT marker and PCA analysis of *T. monococcum* accessions



- susceptible (S)
- moderately susceptible (MS)
- moderately resistant (MR)
- resistant (R)
- inconsistent performance (I)
- not tested in the field (NT)

Resistance to the take-all fungus in *Triticum monococcum*

Key results:

- Consistent contrasting susceptibilities to take-all root infection demonstrated over multiple field trial years
- 1st time strong resistance to the take-all fungus has been reported in a *Triticum* species
- Susceptibility to take-all was not closely associated with whole genome diversity

→ Future studies will focus on defining the genetic basis of this trait and the introgression of resistance into modern hexaploid wheat

Triticum monococcum mapping populations

F6 populations:

MDR037 (S) x **MDR046 (R)** – 79 F6 lines (started with ~180 F3 plants)

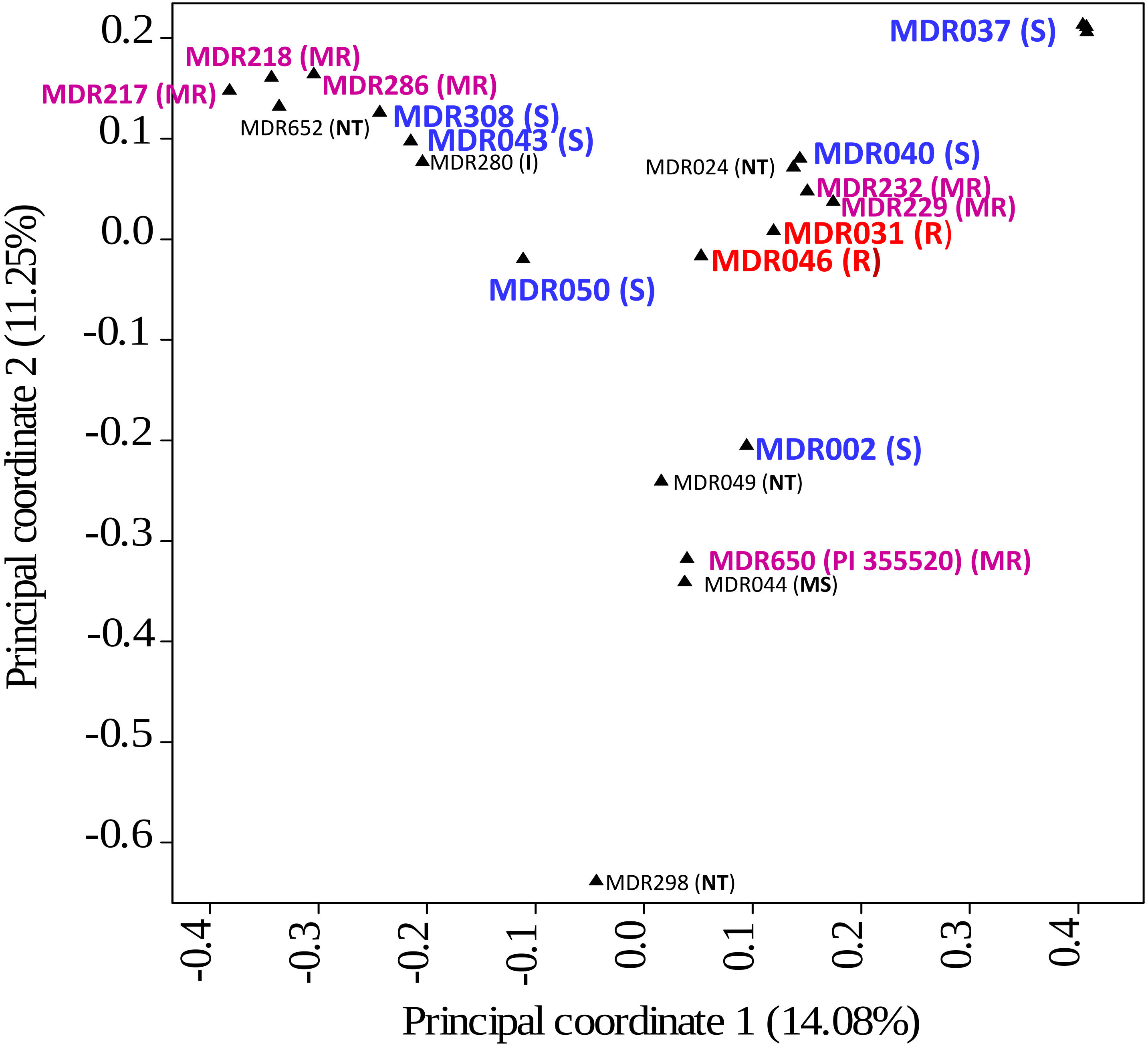
MDR037 x MDR229 – 85 F6 lines

F2 *Tm* cross progeny numbers:

Parentage		Estimated F3 progeny number
MDR031 (R) x MDR043 (vS)	31 ears from 3 plants	450 ⬅
MDR031 x MDR229	16 ears from 1 plant	320
MDR031 x MDR650	48 ears from 3 plants	900
MDR043 (vS) x MDR031 (R)	48 ears from 3 plants	960
MDR043 (vS) x MDR046 (R)	36 ears from 3 plants	750 ⬅
MDR229 x MDR031	94 ears from 6 plants	2000

Taking forward to F6 ⬅

DArT marker and PCA analysis of *T. monococcum* accessions



- susceptible (S)
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Disease development

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Take-all inoculum build-up : 1st wheats

- Take-all inoculum in the soil at harvest is correlated with disease severity in the following crop

- A soil core bioassay, taken after harvest, is used to measure the take-all infectivity of the soil

- Commercial hexaploid wheat varieties differ in their ability to build-up inoculum of the take-all fungus during a first wheat crop (McMillan et al. 2011).

1. Soil core taken angled underneath row

2. Core inverted into plastic cup

THE SOIL CORE BIOASSAY

3. Ten bait wheat (cv Hereward) seeds sown

4. Growth room for 5 weeks

Soil core bioassay plants

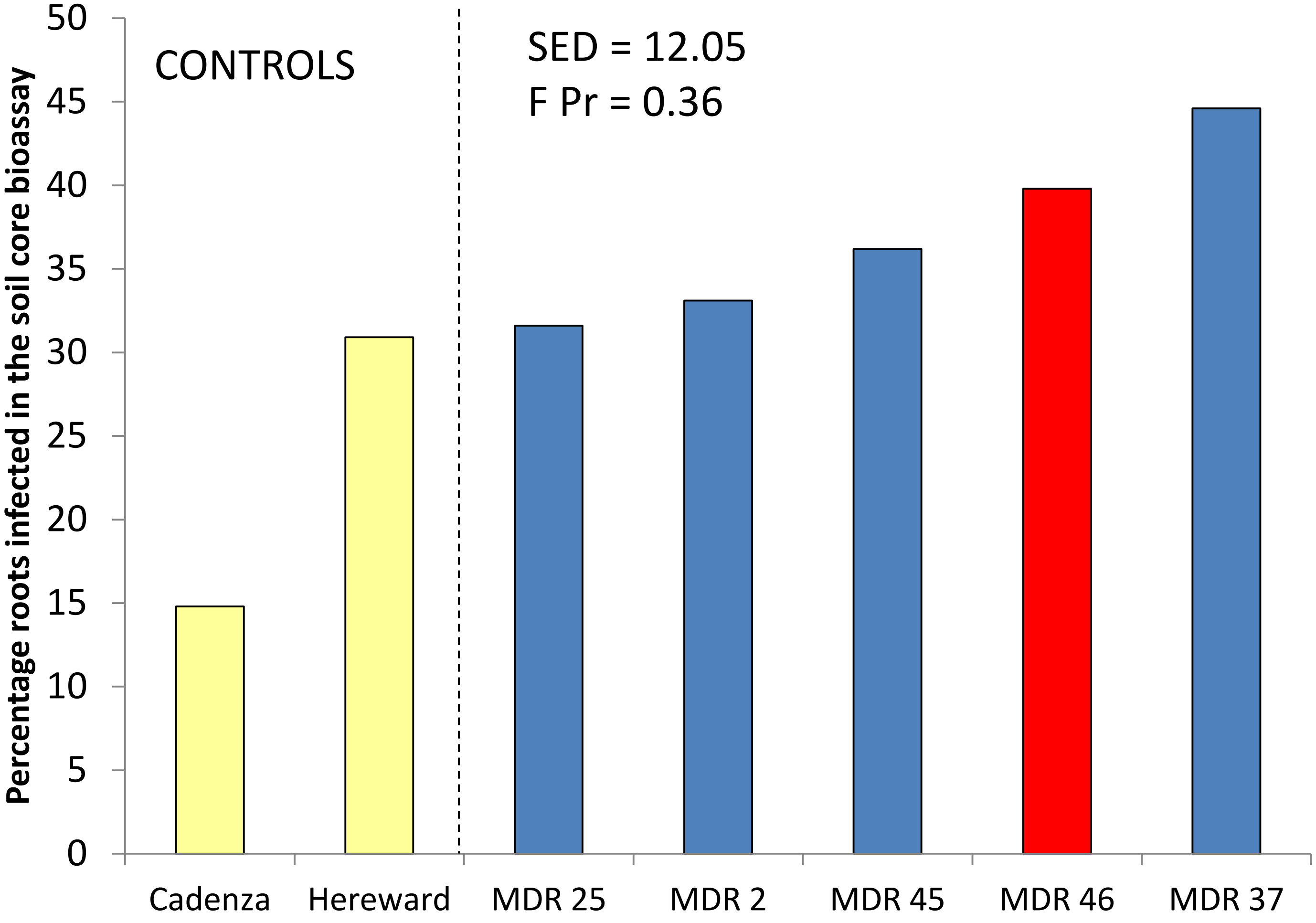
Severe take-all infection

Slight take-all infection

Is take-all inoculum build-up an ancient trait?

Diploid wheat 1st wheat field trial
2011/R/WW/1110 Field: Long Hoos 6&7

3 reps
Plot size: 10 x 1.8m



Introgression of *Tm* resistance into hexaploid wheat

First cross to Paragon ph-1 mutant (Paragon as female parent)

Backcross the F1 plants displaying resistance to take-all into Paragon ph-1

Use the closest SSR markers to track the presence of the *Tm* resistance loci (from BC1 generation onwards)

Many thanks to

BBSRC bioscience for the future

defra Department for Environment Food and Rural Affairs

Wheat Genetic Improvement Network

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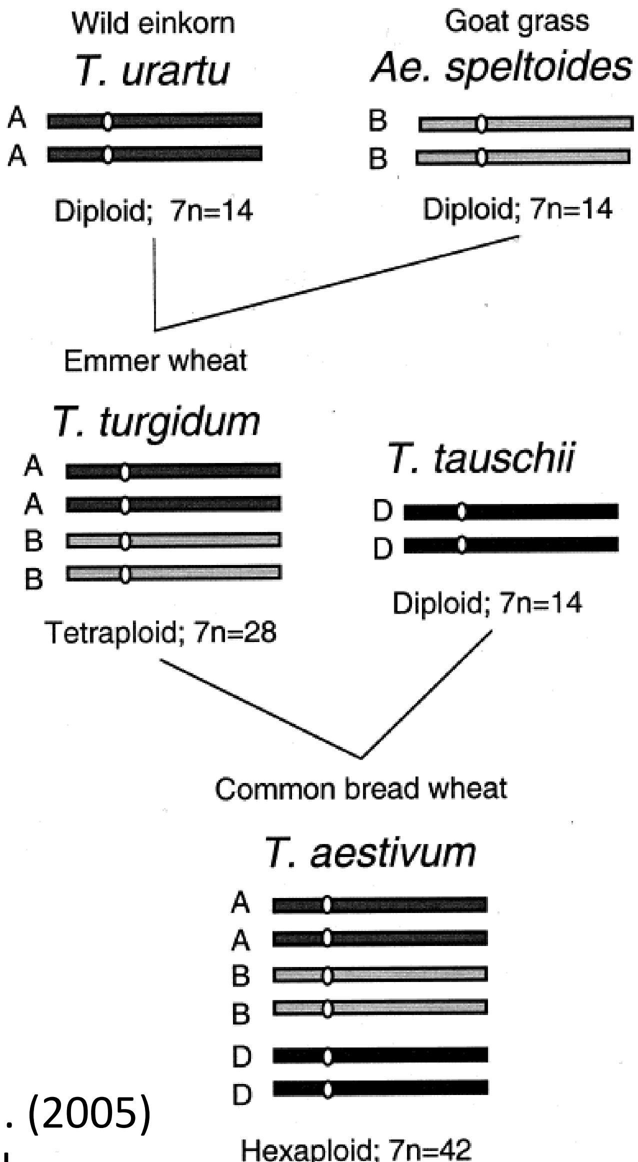
Marcin Czaban (WGIN)
James Bruce (HGCA-BBSRC)
Steve Freeman (WGIN)
Carl Halford (WGIN)
Daniela Izera (WGIN)
Mike Hammond-Kosack (TSB)
Mike Hall (TSB-WGIN)

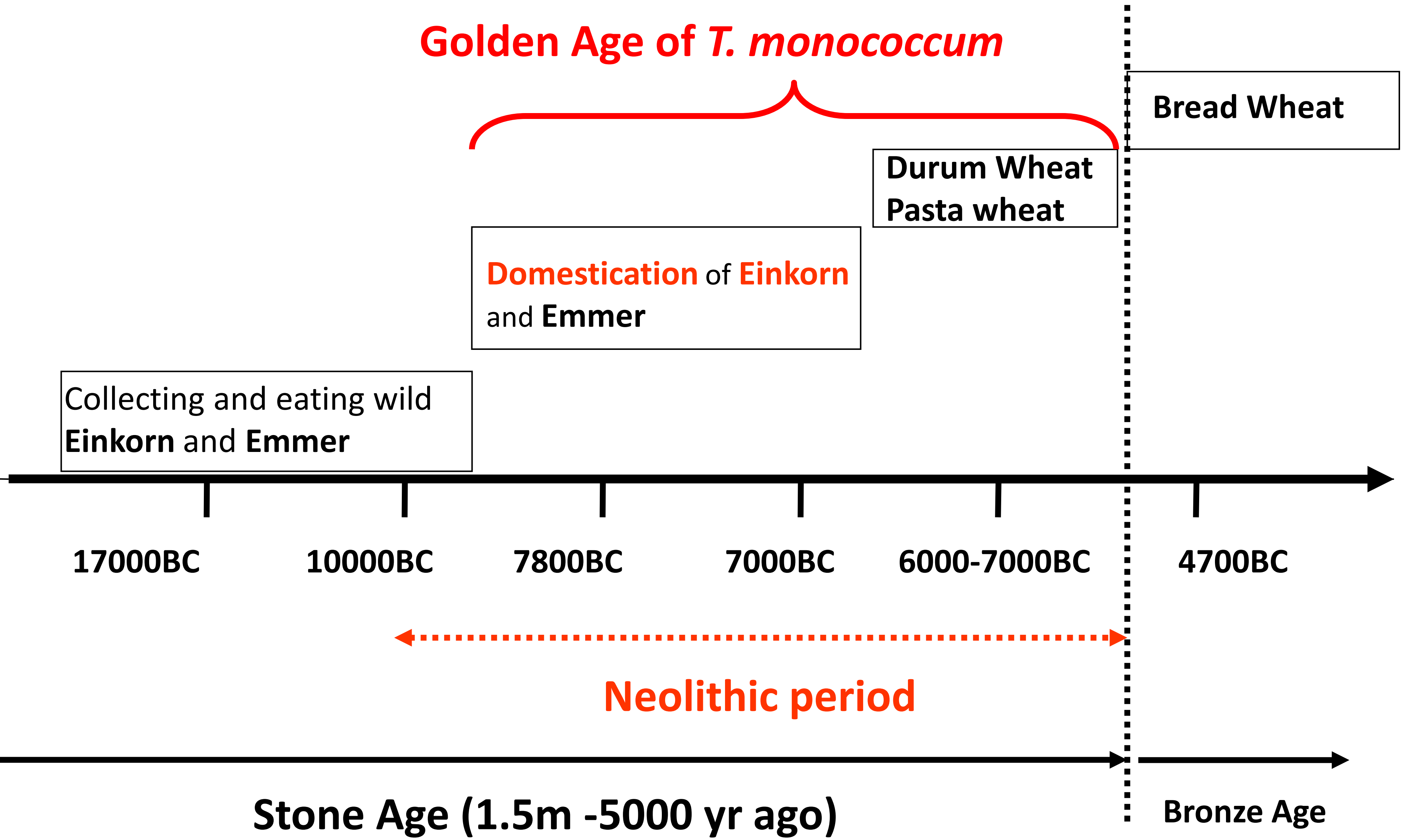
Origin of bread wheat



Molberg et al. (2005) Gastroenterology

- Two diploid wheat species in *Triticum* genus, diverged less than 1 million years ago
- *Triticum urartu* - A genome progenitor species of bread wheat
- *Triticum monococcum* is believed to have been domesticated from the wild einkorn species *T. boeoticum*
- *T. boeoticum* reproductively isolated from *T. urartu*

T. monococcum, an ancient grain



Experimental design

Field trial code: 2009/R/WW/911 Field: Stackyard Treatments: 22 x 5 reps

B1	1 T13	2 T4	3 T3	4 T19	5 T17	6 T8	7 T14	8 T11	9 T18	10 T1	11 T5
	12 T7	13 T2	14 T12	15 T22	16 T20	17 T9	18 T21	19 T10	20 T15	21 T6	22 T16
B2	23 T22	24 T10	25 T14	26 T16	27 T8	28 T7	29 T12	30 T4	31 T6	32 T18	33 T20
	34 T19	35 T11	36 T21	37 T5	38 T9	39 T13	40 T3	41 T2	42 T1	43 T15	44 T17
B3	45 T22	46 T3	47 T21	48 T6	49 T11	50 T7	51 T17	52 T16	53 T2	54 T18	55 T9
	56 T8	57 T15	58 T4	59 T5	60 T20	61 T13	62 T10	63 T1	64 T14	65 T12	66 T19
B4	67 T10	68 T2	69 T5	70 T6	71 T19	72 T7	73 T15	74 T14	75 T3	76 T20	77 T9
	78 T8	79 T17	80 T12	81 T21	82 T18	83 T13	84 T22	85 T1	86 T16	87 T4	88 T11
B5	89 T3	90 T12	91 T15	92 T11	93 T16	94 T19	95 T2	96 T8	97 T20	98 T1	99 T21
	100 T13	101 T7	102 T22	103 T10	104 T5	105 T18	106 T4	107 T9	108 T17	109 T6	110 T14

0.5 m path

9.5 m

0.5 m

10.5 m

0.5 m

Increasing the efficiency of water use of wheat by isotope screens indicative of water use, transpiration efficiency and drought tolerance

John Foulkes[1] , Simon Griffiths[2], Simon Orford[2], Pedro Carvalho[1] & Jayalath DeSilva[1]

AAB "Crop Resource Use Efficiency and Field Phenotyping"

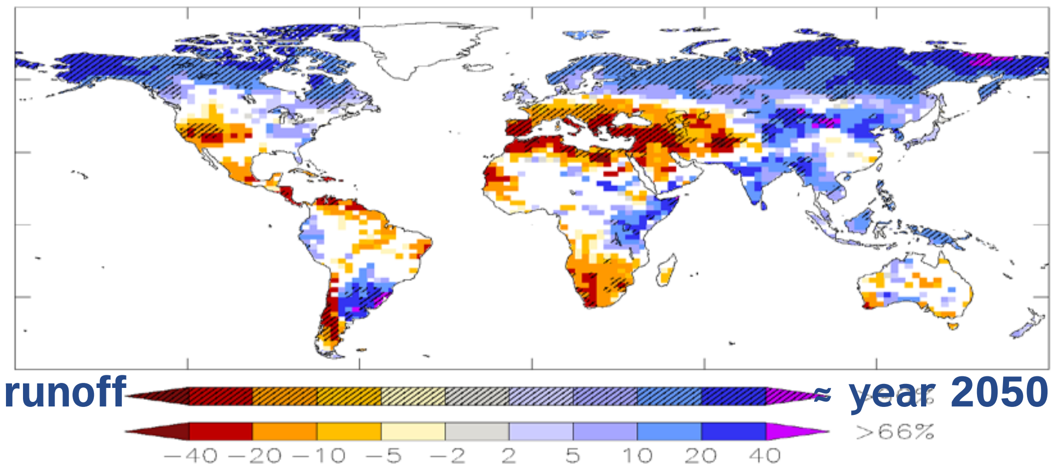
Belton Woods Hotel, Grantham 25-26 March 2013

1 The University of Nottingham

2 John Innes Centre

Background: Water supply and Productivity

Climate change & water supply:



The Wet gets wetter! - The Dry gets drier!

By 2025, two-thirds of the world population could be under "*stress conditions*" (500-1000 m^3 per year per capita), and 1800 million people are expected to be living in countries or regions with "*absolute water scarcity*" (<500 m^3 per year per capita)

The good news is that 1% of water productivity gain in agriculture means 10% increase of availability for other uses

Litres per day per person	
Drinking	2-4
Domestic	40-400
Food	1000-5000 (and more)

Drivers for increasing WUE and drought tolerance in UK

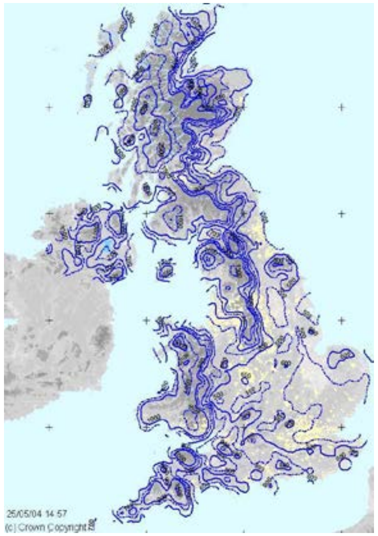
- 30% of UK wheat on drought-prone land, losses are 1-2 t ha^{-1} = >£50M per year.
- With climate change summer rainfall will decrease, potentially increasing these losses.
- Improving WUE will decrease crop water use in non-drought years, increasing water for:
  - use in irrigating other crops
  - increasing water flows in rivers and aquifer recharge.

Impact of drought on UK wheat yields

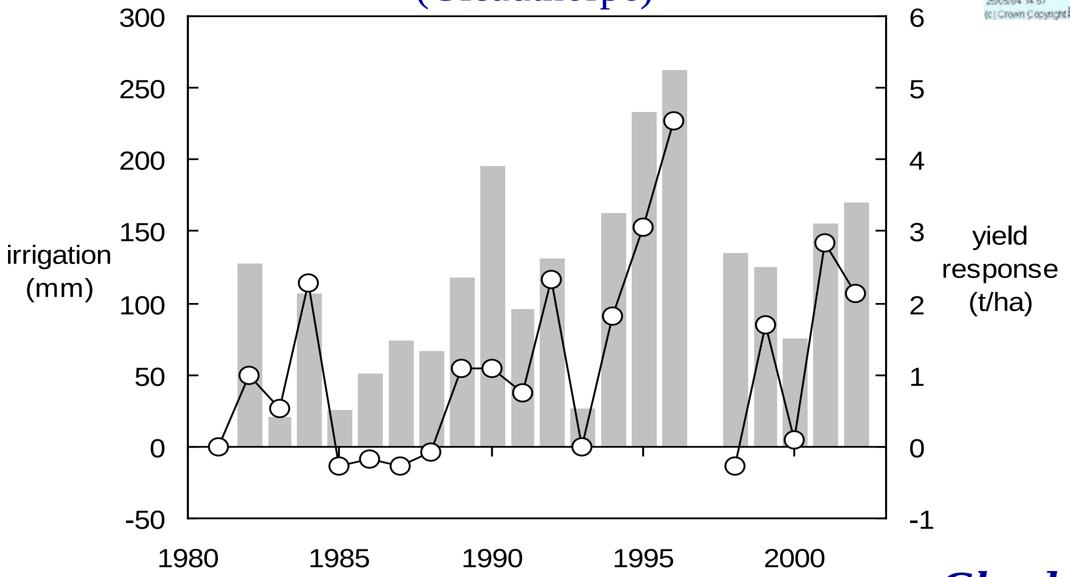
Distribution of available water to 1.2 m in UK wheat

Soil AWC mm	%
126-150	12
151-175	26
176-200	13
201-225	39
226-250	9

Rainfall contour map



Yield response to irrigation on light soil (Gleadthorpe)



Gleadthorpre Notts
AWC = 140 mm

Foulkes et al. 2001, 2002, JAg Sci; FCR 2007

How will UK weather change?

- **Summer rainfall to decrease by 11- 27% by 2080s; decrease 40% in S. England, less change in N. Scotland.**
- **Average summer temp. to rise by 3-4° C by 2080s; changes greatest in S. England (2.2-6.8°C) and least in N. Scotland (1.2-4.1°C).**
- **Sea levels are expected to rise by 36 cm by the 2080s.**
- **Extreme weather events are likely to become more common.**

Predictions based UK Climate Projections (UKCP09)

Traits associated with main drivers of yield under drought

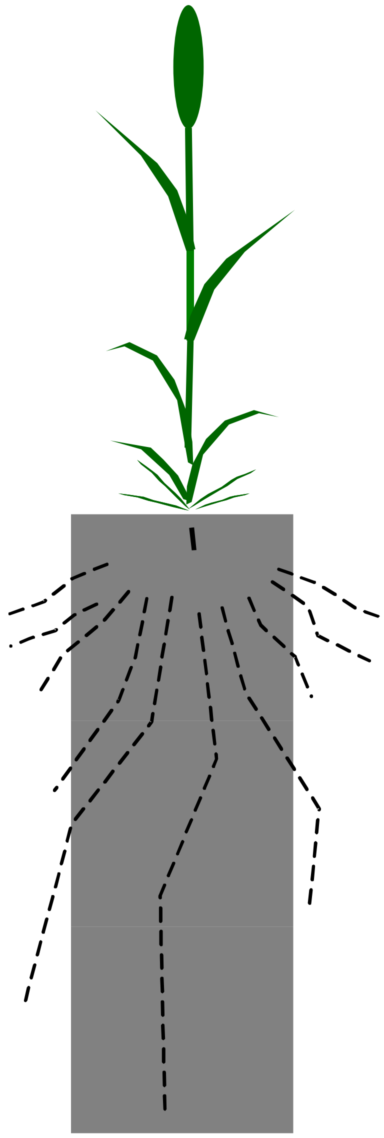
Yield = WU x WUE x HI

OPTIMIZE WUE

- WUE of leaf photosynthesis
- Low $^{13/12}C$ discrimination

MAXIMIZE HARVEST INDEX

- Pre-antheis partitioning to stem CHO reserves
- Functional stay green



MAXIMIZE WATER CAPTURE

- Increase root density at depth
- Distribute roots deeper
- Access to water by roots indicated by cooler canopy

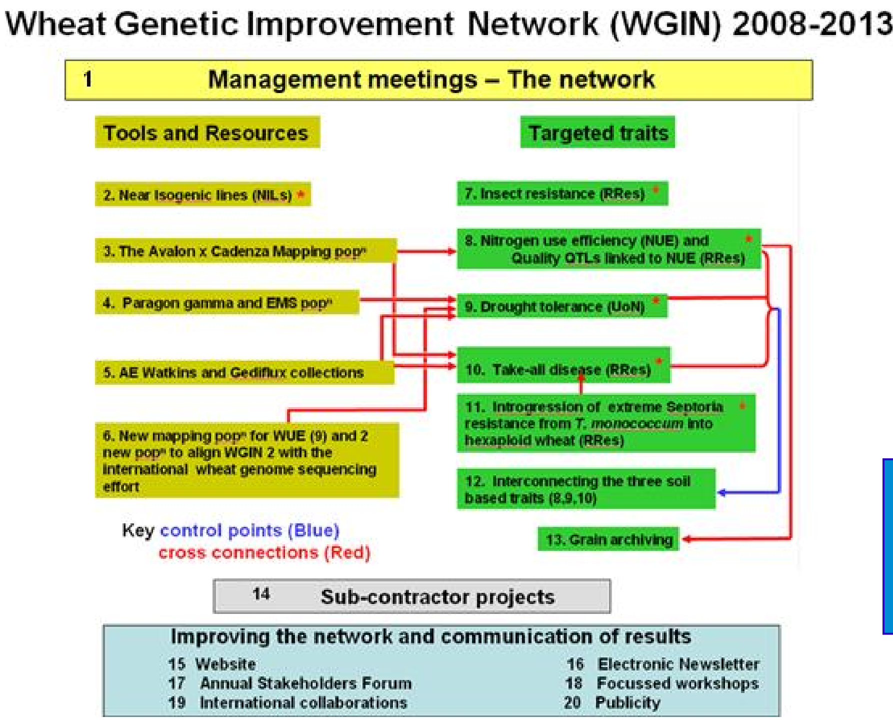
EARLINESS

- Extend stem elongation phase
- Early onset GS31

Drought tolerance

WGIN-2 SG meeting

KWS, Thriplow 25 March 2013



Wheat Genetic Improvement Network

Genetic Improvement of Drought Tolerance

Target physiological traits:

- Grain Δ 13 C (WUE)
- Flag Δ 18 O (Water Use)
- Stem WSC Reserves (HI)
- Canopy water status (NIR - WI)

GY = Water Use x WUE x HI

Passioura 1977

18 Cultivar wheat panel selection informed by LINK 0986 Wheat WUE project, Eric Ober

Wheat Genetic Improvement Network

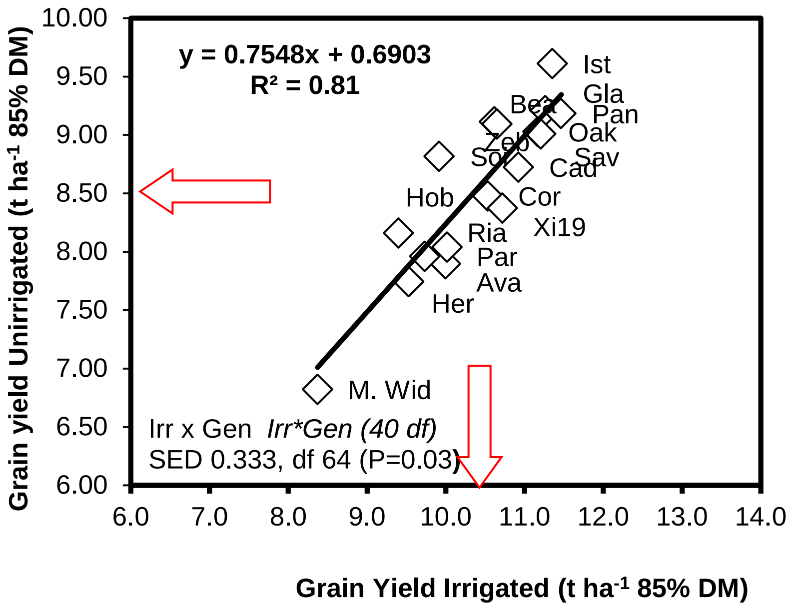
Years: 2009-10 & 2010-11
Split plot design (3 reps): plot size 1.6 x 12 m
Main plot: Fully irrigated (trickle irrigation)
Unirrigated

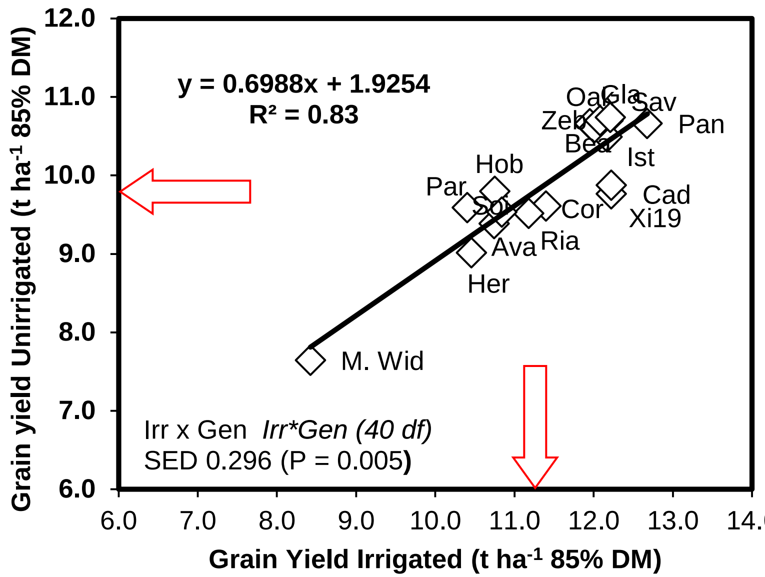
Split plot (variety):

1. Avalon
2. Beaver
3. Cadenza
4. Cappelle Desprez/Sterling
5. Cordiale
6. Glasgow
7. Hereward
8. Hobbit
9. Istabraq
10. M. Widgeon
11. Oakley
12. Panorama
13. Paragon
14. Rialto
15. Savannah
16. Soissons
17. Xi 19
18. Zebedee

Wheat Genetic Improvement Network

Grain yield responses to Drought

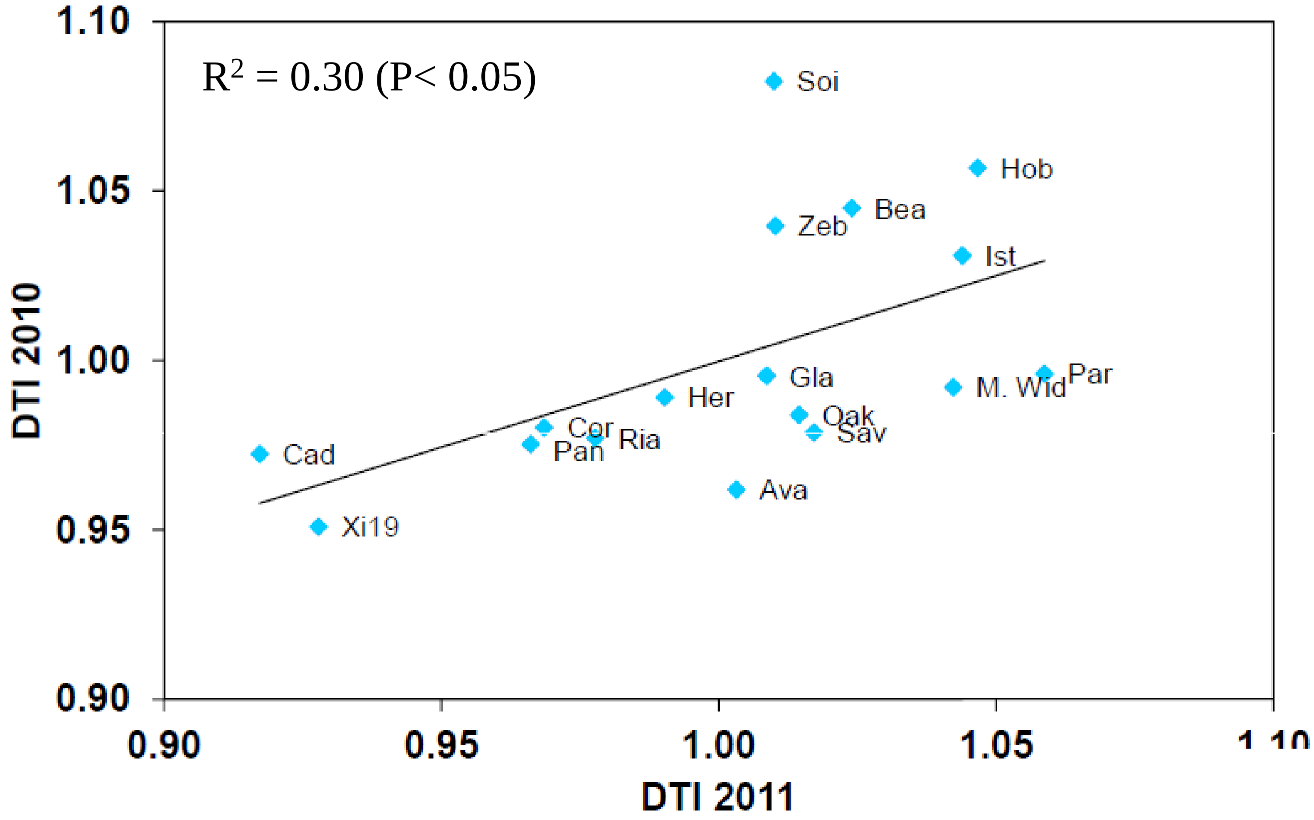




	Rainfall mm (% LTM)	
	2010	2011
January	33.0 (62)	33.2 (62)
February	41.6 (95)	44.6 (101)
March	36 (67)	1.2 (2)
April	24 (55)	23 (53)
May	16.2 (35)	27.8 (61)
June	69.2 (152)	45.4 (100)
July	42.6 (86)	17.8 (36)

Irrigated vs Unirrigated 19 July

Drought tolerance index: (Y_{Dr}/Y_{Irr}) / (mean Y_{Dr} / mean Y_{Irr})



Wheat Genetic Improvement Network

Water use efficiency: definition and estimation

- **Water-use efficiency (WUE) is the ratio of above-ground dry matter production to evapotranspiration.**
- **$^{13}C/^{12}C$ isotope ratio of fixed CO_2 can be used to estimate WUE**
- **Low discrimination against $^{13}CO_2$ → high WUE**

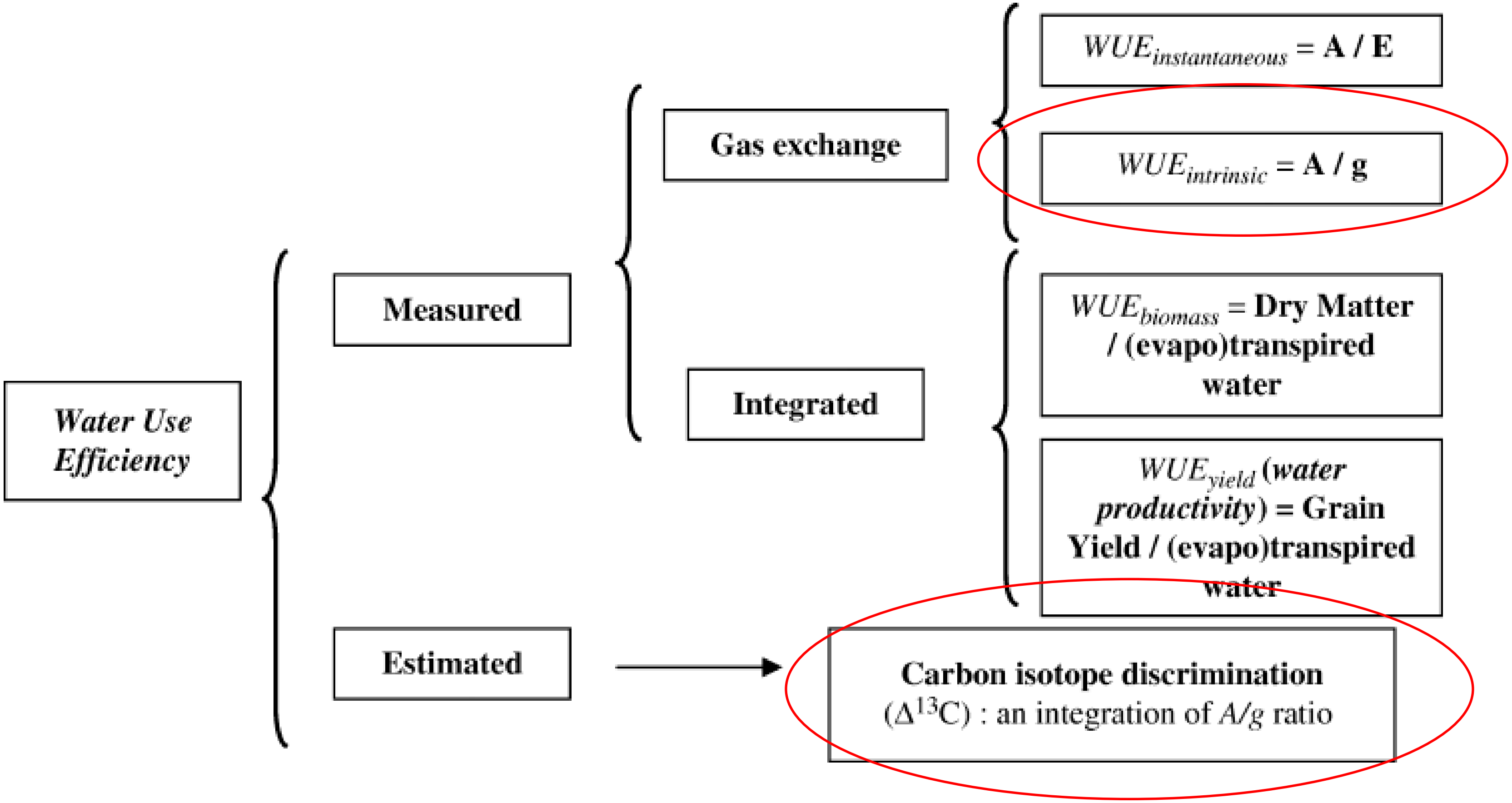


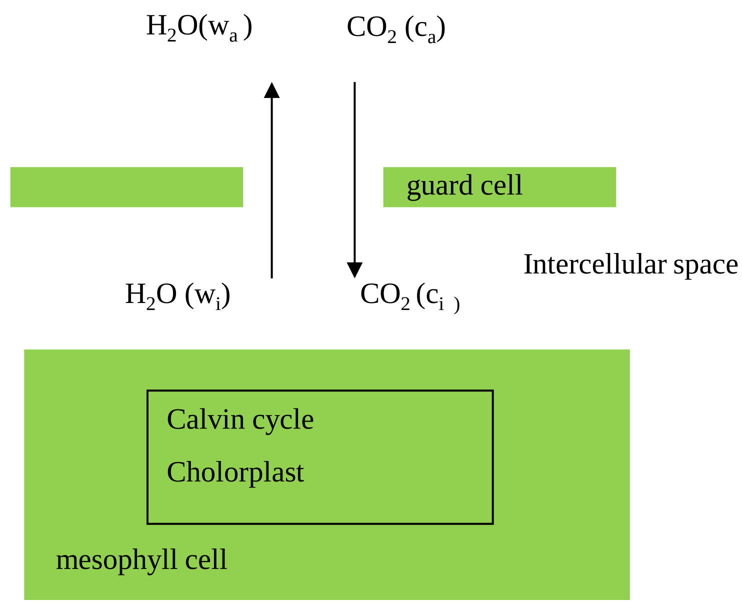
Figure 1. Definitions of 'water use efficiency'. The scheme represents the several definitions of water use efficiency (WUE) used in the text. *A*, net photosynthetic rate expressed as μmol CO_2 m^{-1} s^{-1}; E, transpiration rate expressed as mmol H_2O m^{-2} s^{-1}; $\Delta^{13}C$, carbon isotope discrimination.

Tambussi et al. 2007 Field Crops Res

Relationship between c_i and leaf transpiration efficiency

- ***Stomatal conductance:***. Lower conductance ↓ ci hence ↑ TE.
- ***N or Rubisco content per unit leaf area:*** Greater photosynthetic activity ↓ c_i , hence ↑ TE.

Condon et al. (2002). Crop Science



Irrigated conditions

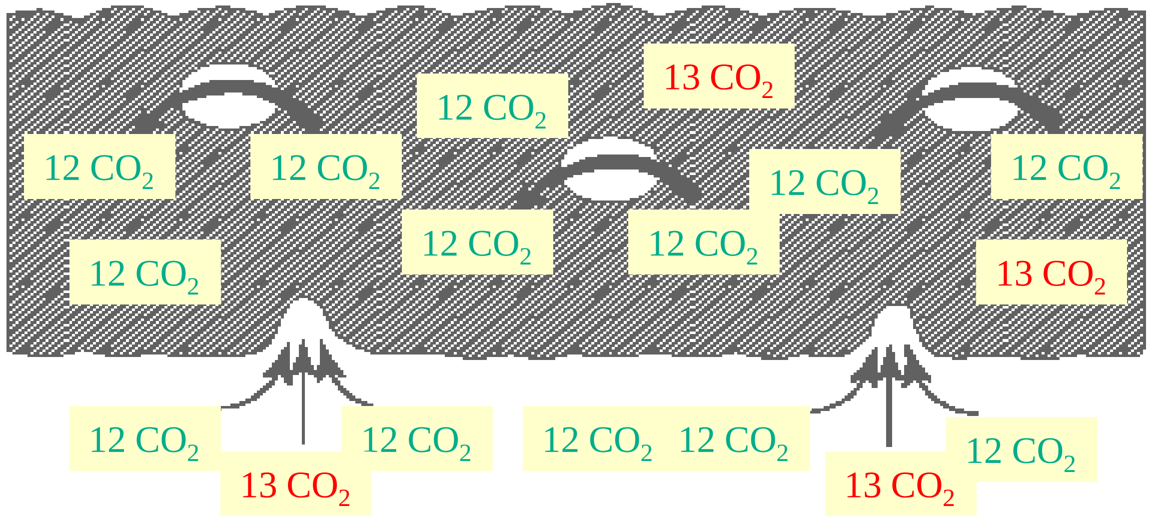
Stomata open (high stomatal conductance)

↓

High Ci

High Discrimination against $^{13}CO_2$ - - - → **Low WUE**

Stomata open (irrigated conditions): Discrimination in favour of $12C0_2$ isotope form at high internal $C0_2$ concentration.



Drought conditions

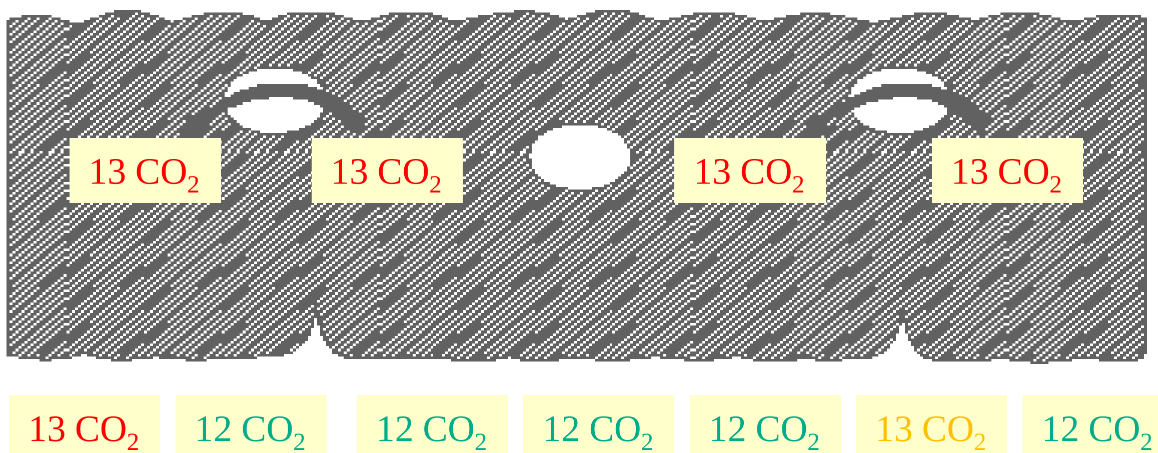
Stomata close (low stomatal conductance)

↓

Low Ci

Low Discrimination against $^{13}CO_2$ - - - → **High WUE**

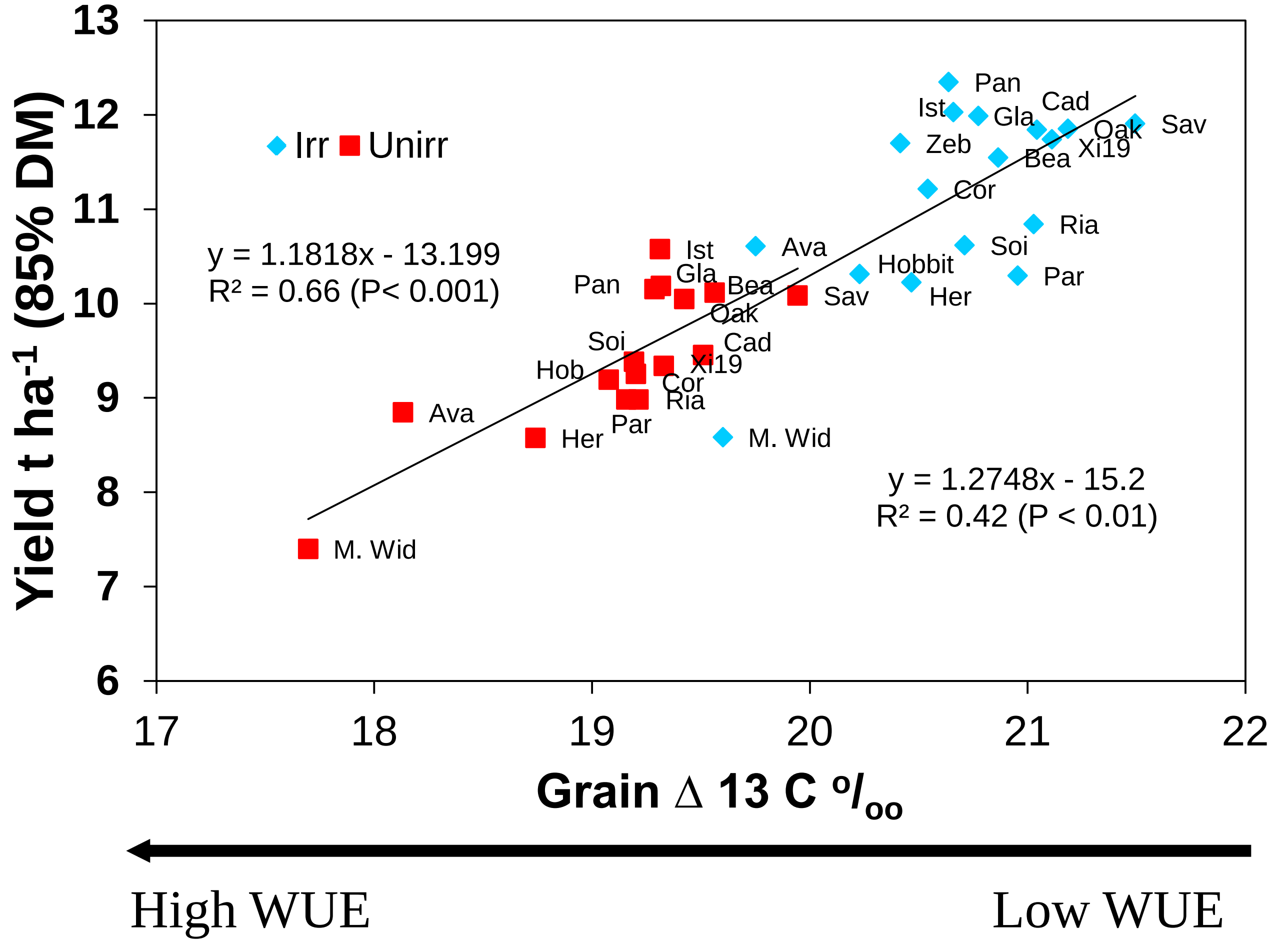
Stomata closed (moisture stress): Discrimination less favourably to $12C0_2$ as internal $C0_2$ concentration falling.



Araus 2005

Diagram 1. Carbon isotope discrimination under irrigated and dry conditions.

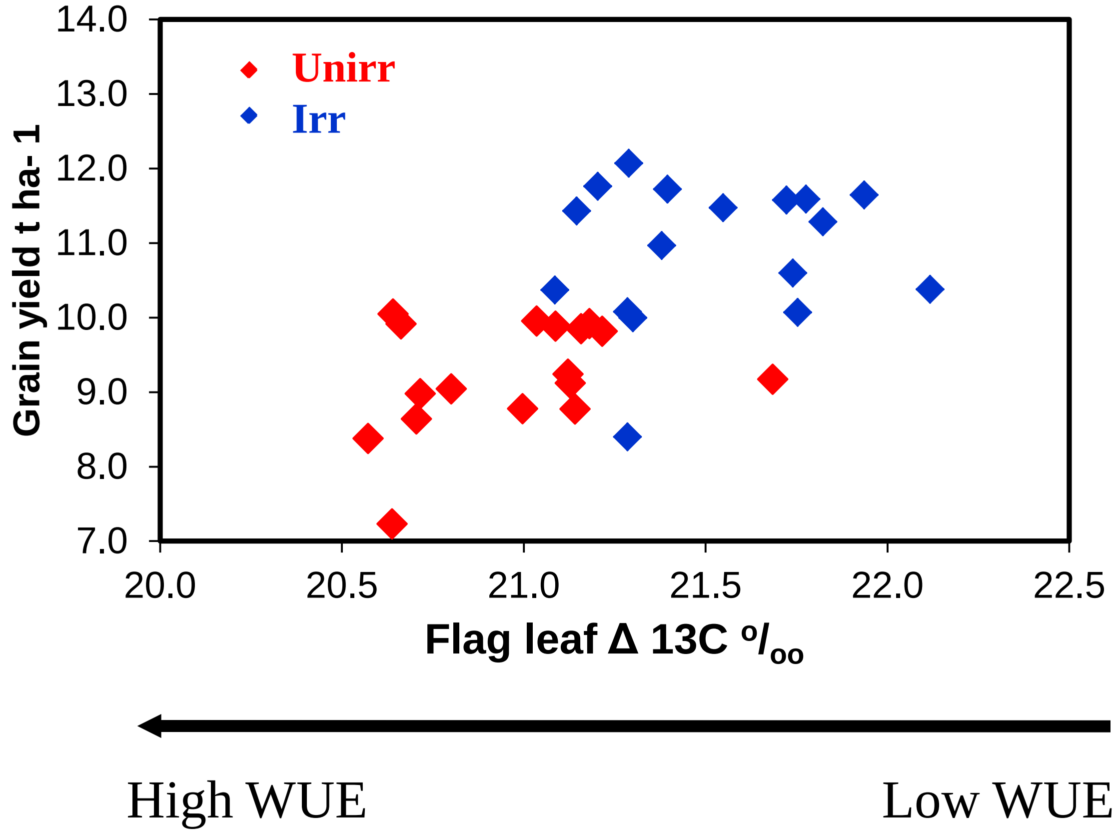
Δ ^{13}C vs grain yield in 18 wheat cultivars



- ***Grain $^{13C}\Delta$ positively associated with yield under drought – indicator of ability to access water***
- ***Trade-off between WUE and season-long water use***

Sutton Bonington Mean 2009-10 & 2010-11

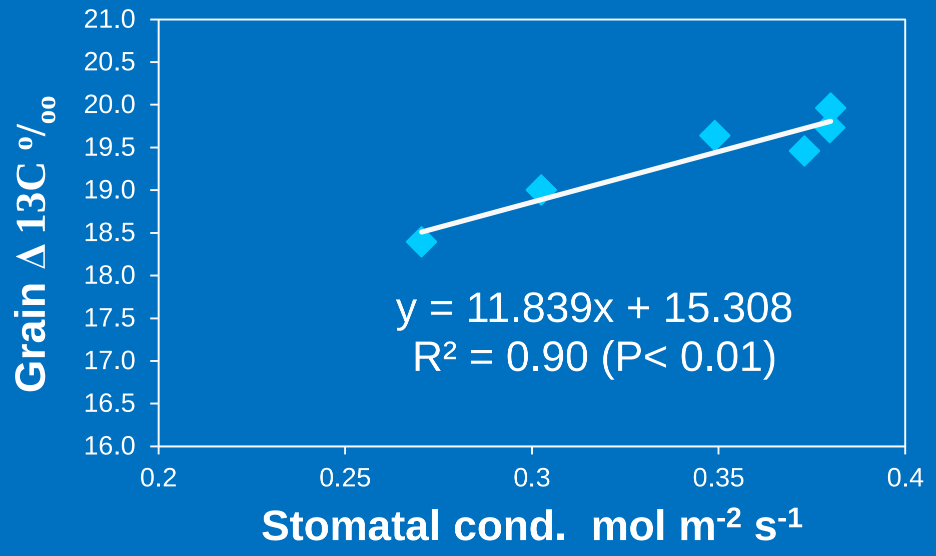
Δ ^{13}C flag leaf vs grain yield



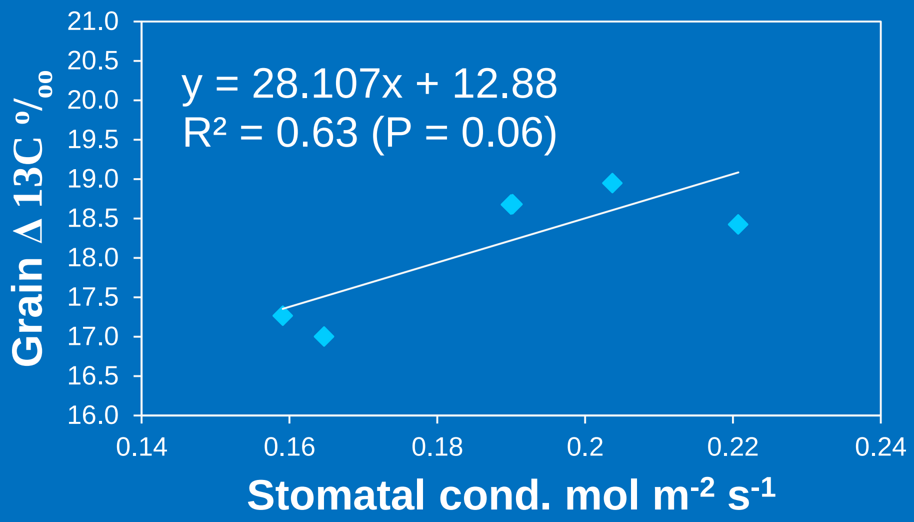
Sutton Bonington Mean 2009-10 & 2010-11

Grain Δ13C versus stomatal conductance (Unirrigated)

2009-10

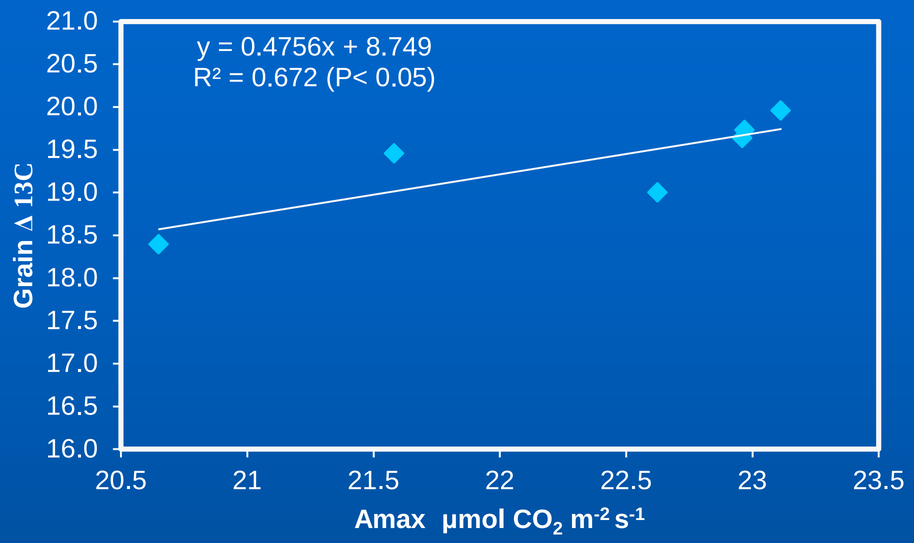


2010-11

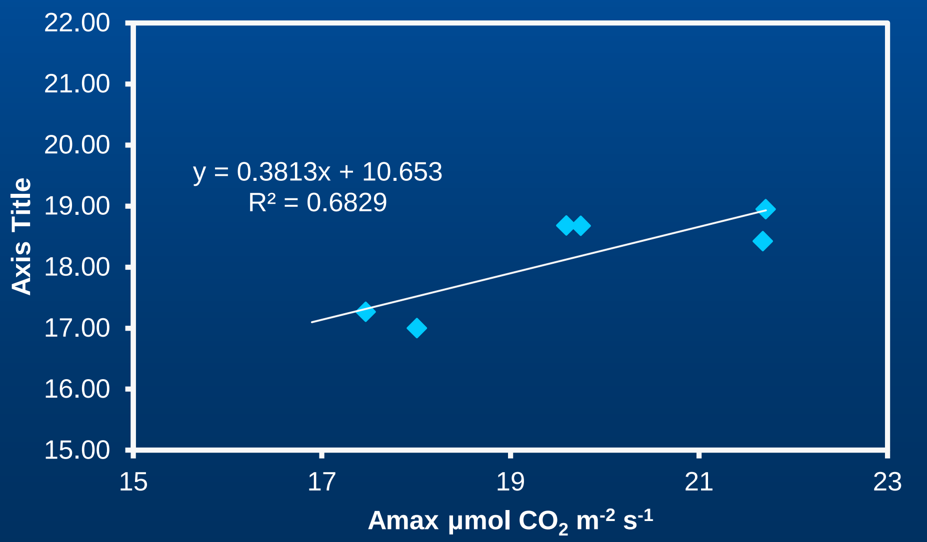


Grain Δ13C versus Pn rate (Amax) (Unirrigated)

2009-10



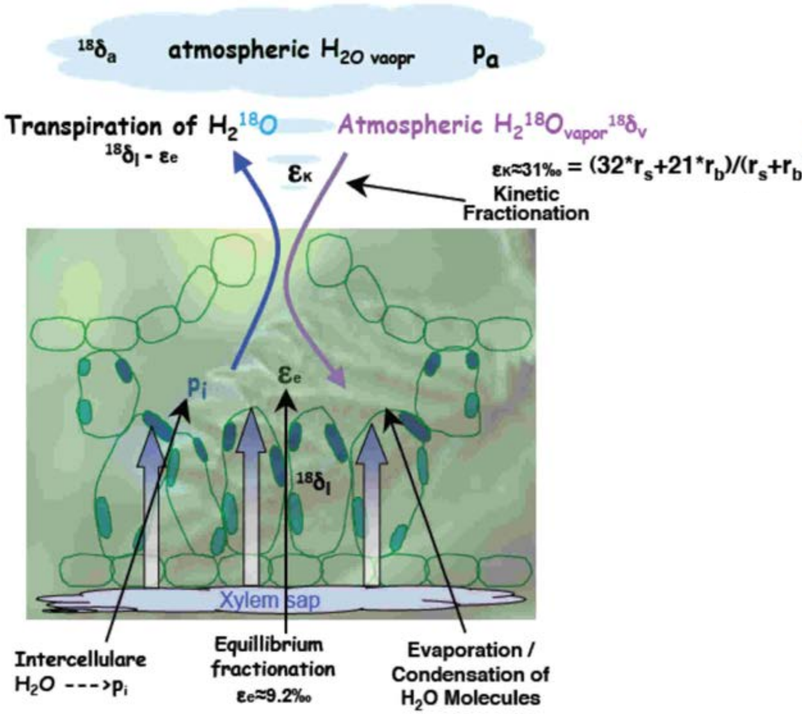
2010-11



Trade off between water-use efficiency and water use

Use Δ18O as an indicator of transpiration to allow stomatal and Ps effects on Δ13C to be teased apart

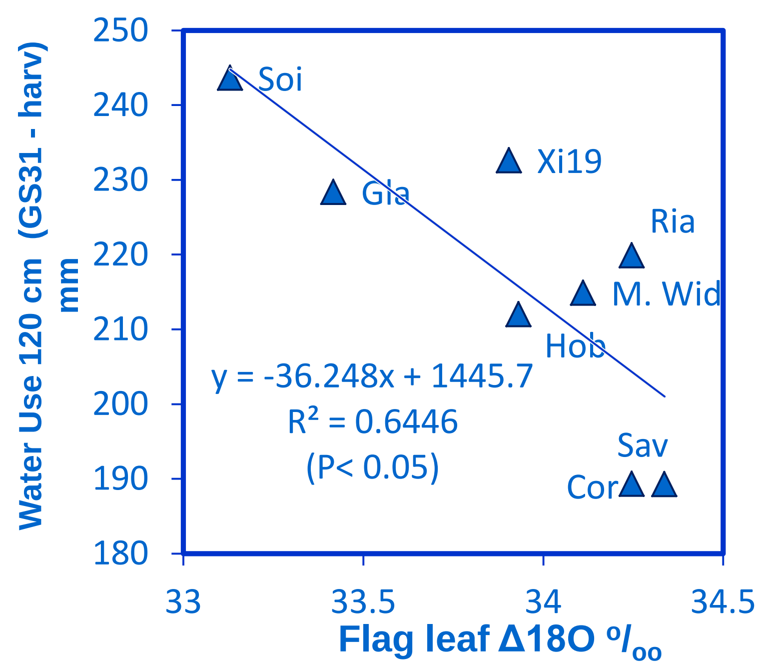
Oxygen isotope ratio technique ~ leaf transpiration



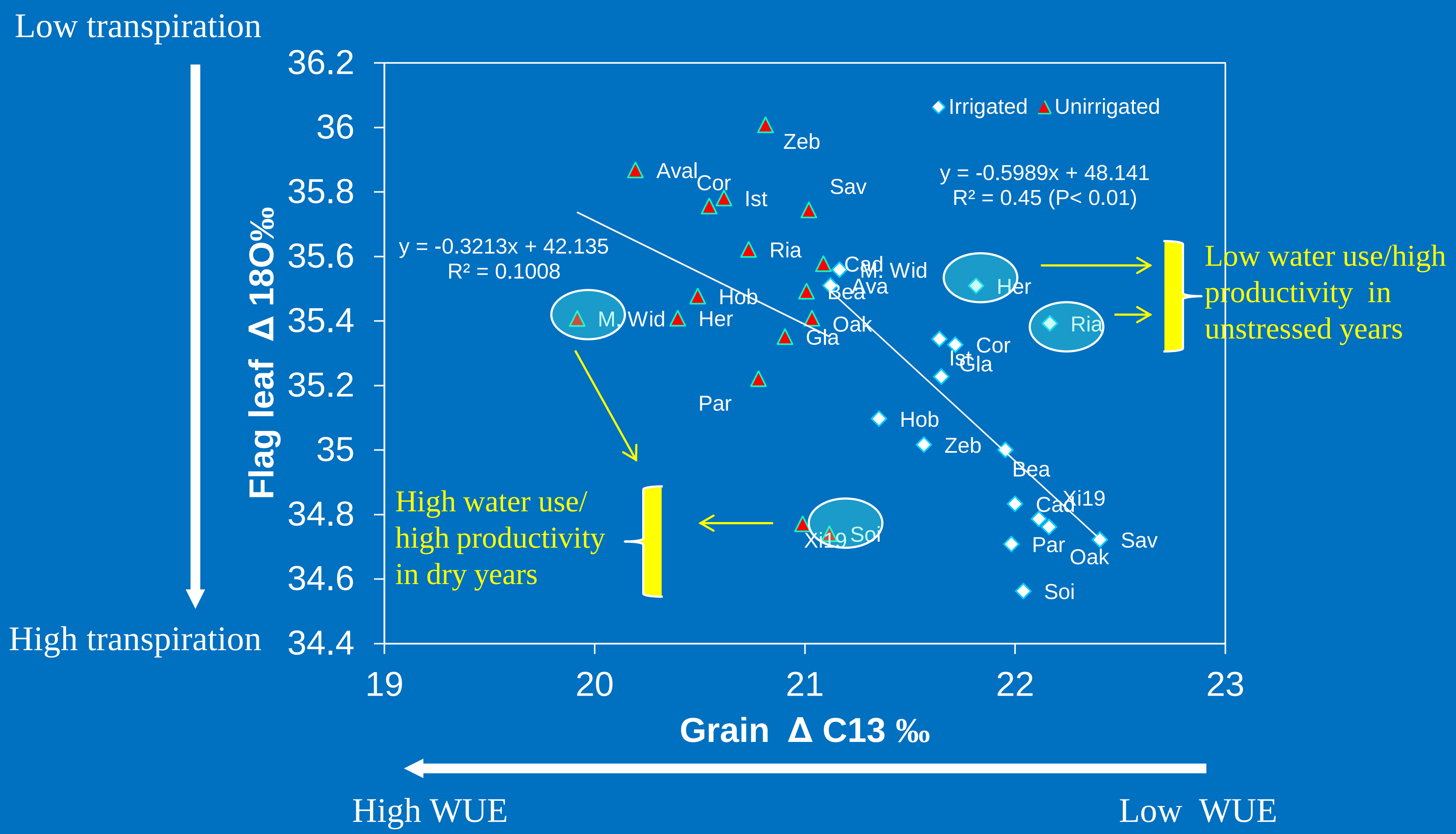
- $^{18}O/^{16}O$ ratio determined by enrichment in the leaf water due to transpiration.

- Leaf water enriched due to preferential loss of the lighter $H_2{}^{16}O$ during evaporation.

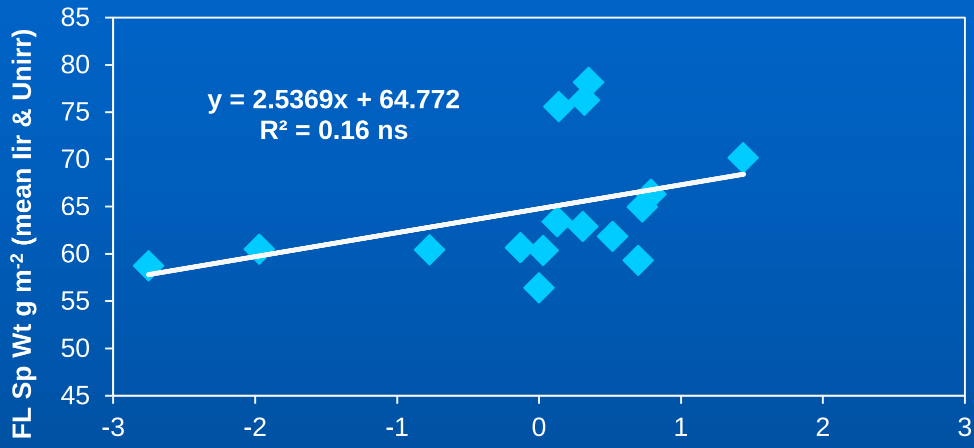
- An increase in leaf transpiration decreases leaf T°C (hence intercellular vapour pressure) resulting in less $H_2{}^{18}O$ enrichment at the evaporating site.



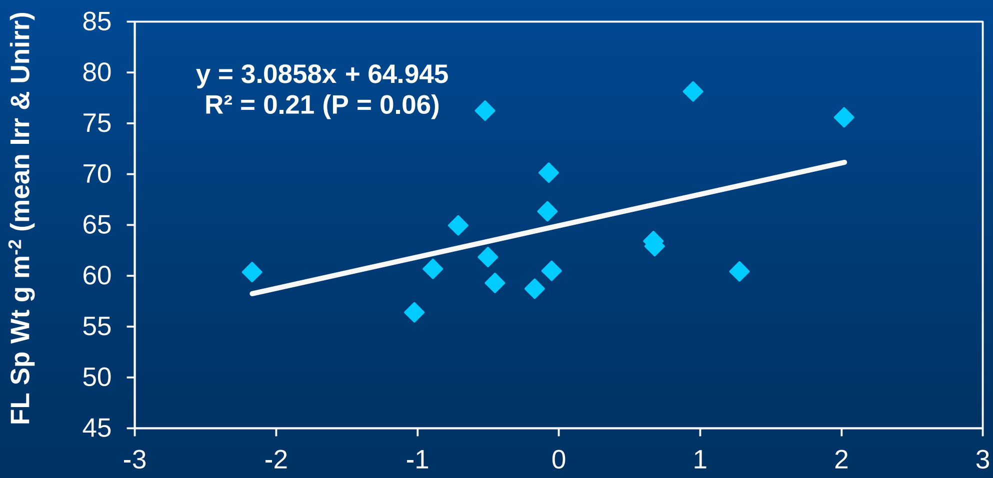
Relationship between $\Delta^{13}C$ and $\Delta^{18}O$ in 18 wheat cultivars (mean 2010 and 2011)



Residual flag leaf $\Delta^{18}O$ vs grain $\Delta^{13}C$ relationship versus flag leaf specific weight at GS61



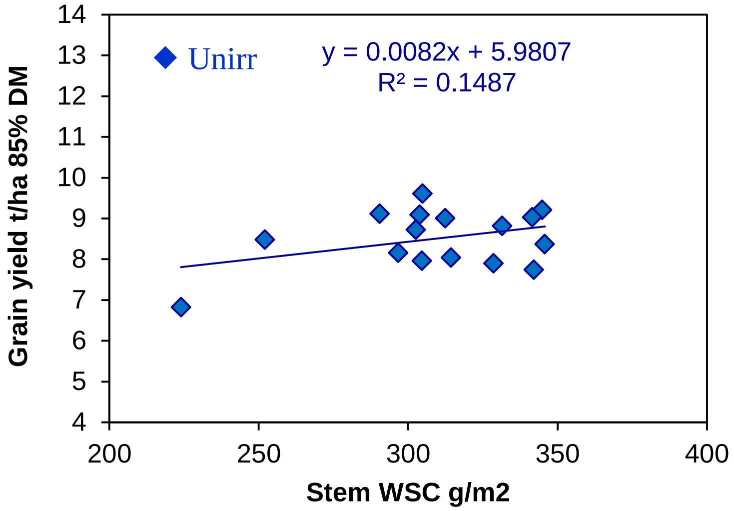
Residual FL Δ 18O versus grain Δ 13 C Unirrigated



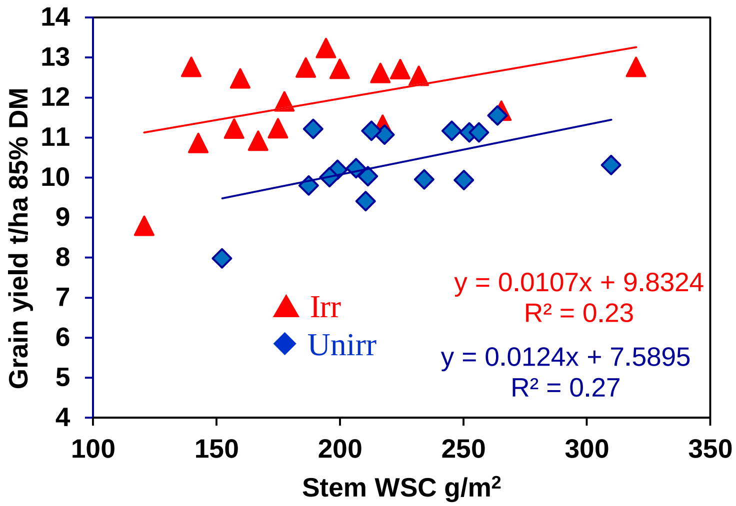
Residual FL 18O versus grain 13C Irrigated

Other traits correlations: Stem WSC @ GS61+9d

Grain yield versus stem WSC reserves

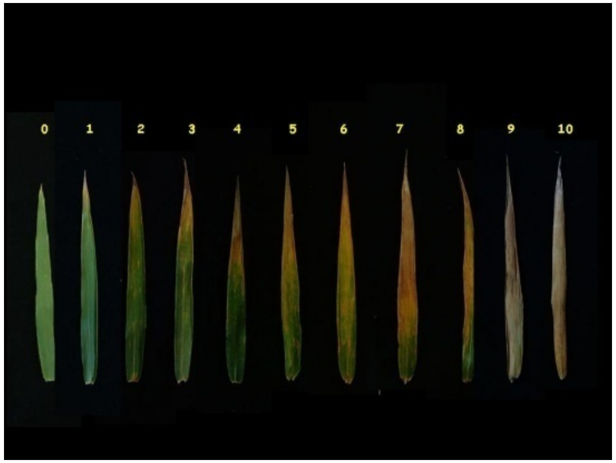


Sutton Bonington 2009-10



Sutton Bonington 2010-11

Flag leaf senescence score



Fitting the senescence data

$$score = p0 + p1 * (1 - \exp((-p2 * STA / p1)) + (10 - p1 - p0 / (1 + \exp(-4 * p4(STA - p5) / (10 - p1 - p0)))$$

score : visual senescence score

STA : thermal time after anthesis (°C.days)

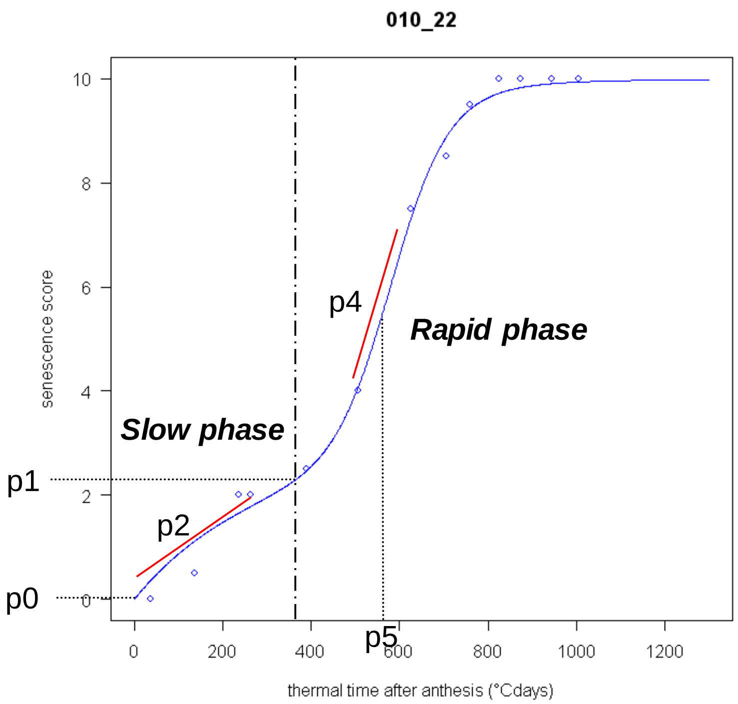
p0 : score at anthesis

p1 : score at the end of the slow phase

p2 : max rate of the slow phase

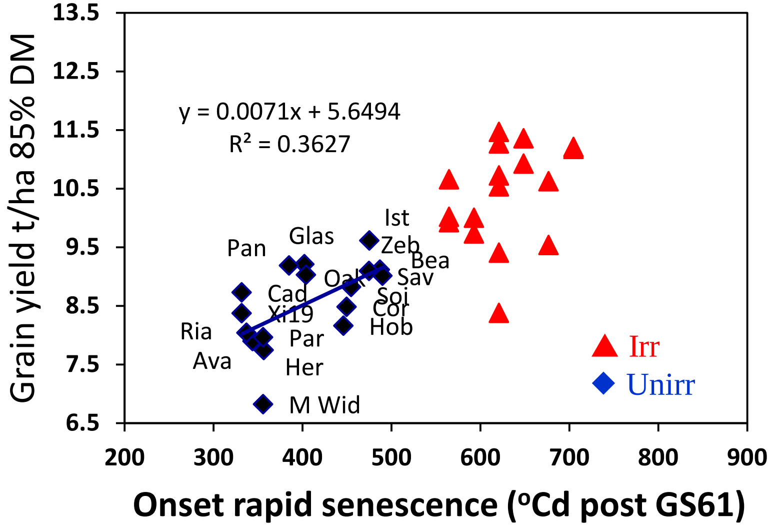
p4 : max rate of the rapid phase

p5 : date at which p4 is reached

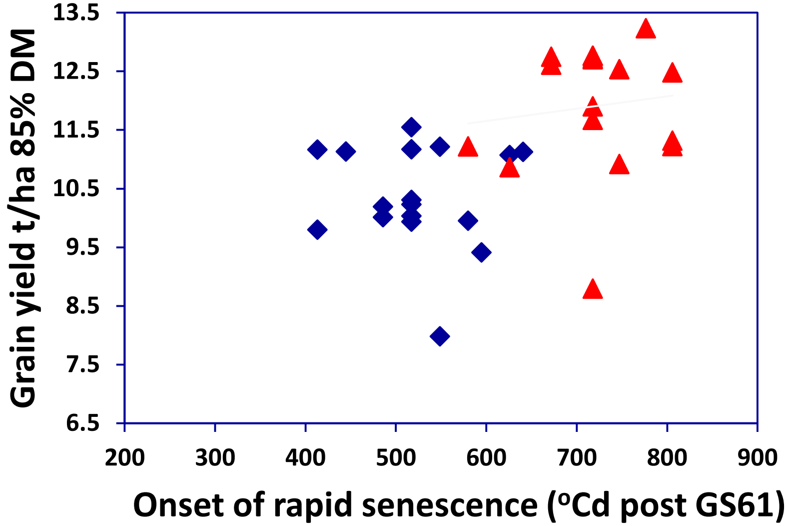


Other traits correlations: Flag leaf senescence

Grain yield versus Onset of Senescence

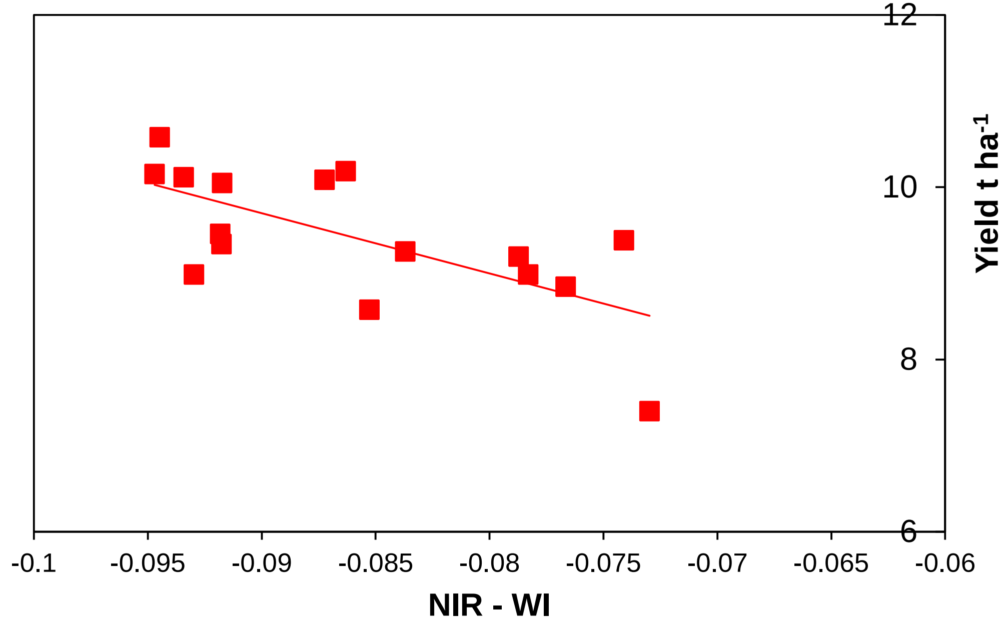


Sutton Bonington 2009-10



Sutton Bonington 2010-11

Spectral reflectance: Water index at GS61+14 d



WI = (R970-R900/)/(R970+R900)

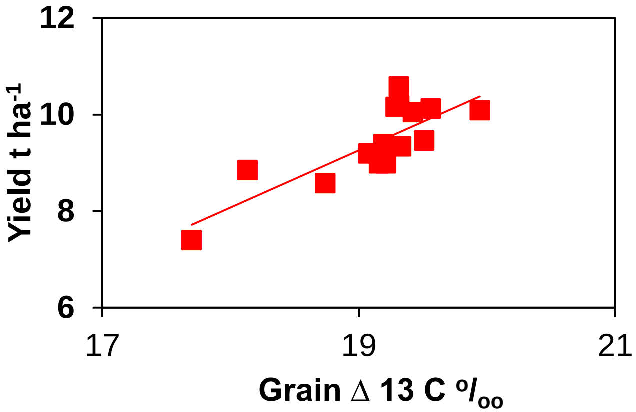
Sutton Bonington Mean 2009-10 & 2010-11

Drought tolerant plant ideotype

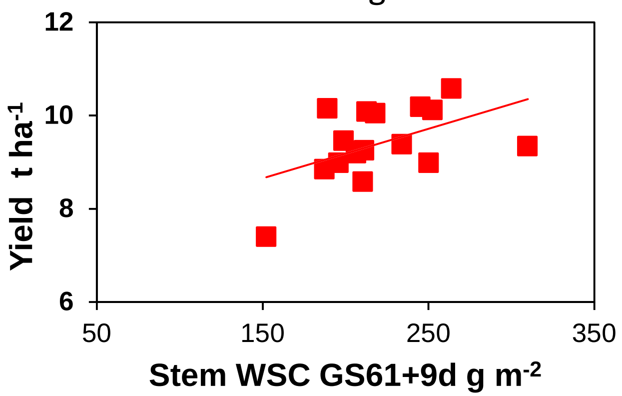
- **Multiple linear regression (P<0.001) accounted for 71% of the yield under drought and showed that:**

$$GY = -41.9\ x_1 + 0.08\ x_2 + 12.3\ x_3$$

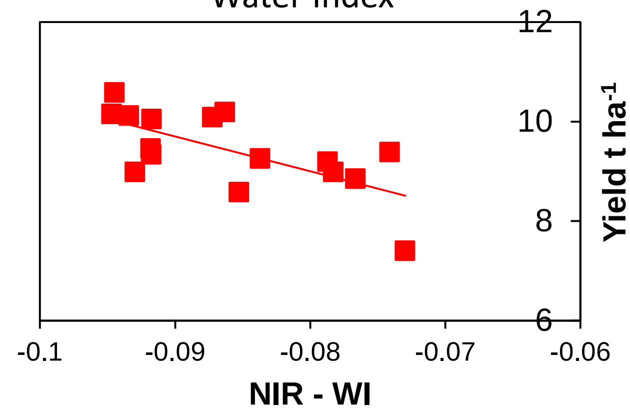
GY increases with increasing Δ 13 C (↓WUE) :



Grain yield increases with increasing stem WSC



GY increases with decreasing Water Index



WI = (R970-R900/)/(R970+R900)

Traits summary

Estimated value of traits to avoid or minimise effects of drought in UK

Variety character	How it might work	Value
High $^{13}C\ \Delta$ grain	Captures extra water	High
Flag leaf 'stay-green'	Extends grain filling during late drought	High
Low canopy T°C/ deep roots	Captures extra water	High
High stem sugars	Buffers effects of post-flowering drought on grain filling.	Moderate
Early flowering	Advances grain filling before the drought risk period.	Neutral
Awns	Use less water per unit growth.	Slight

WGIN Objective 9.2 QTL Detection

2010-11 and 2011-12 expts

• Rialto x Savannah DH population for phenotying for yield physiological traits (94 lines and 2 parents)

• 2 sites: Nottingham - irrigated & unirrigated; JIC - unirrigated

• Target traits

- $^{13}C\ \Delta$ grain
- senescence kinetic
- stem WSC

Measurements on DH pop

- **Combine grain yield, yield components**
- **% stem WSC at GS61+10d (unirrigated)**
- **Leaf senescence kinetics for flag-leaf, L2 and L3.**
- **Canopy temperature**
- **grain Δ 13C (unirrigated)**
- **NDVI**

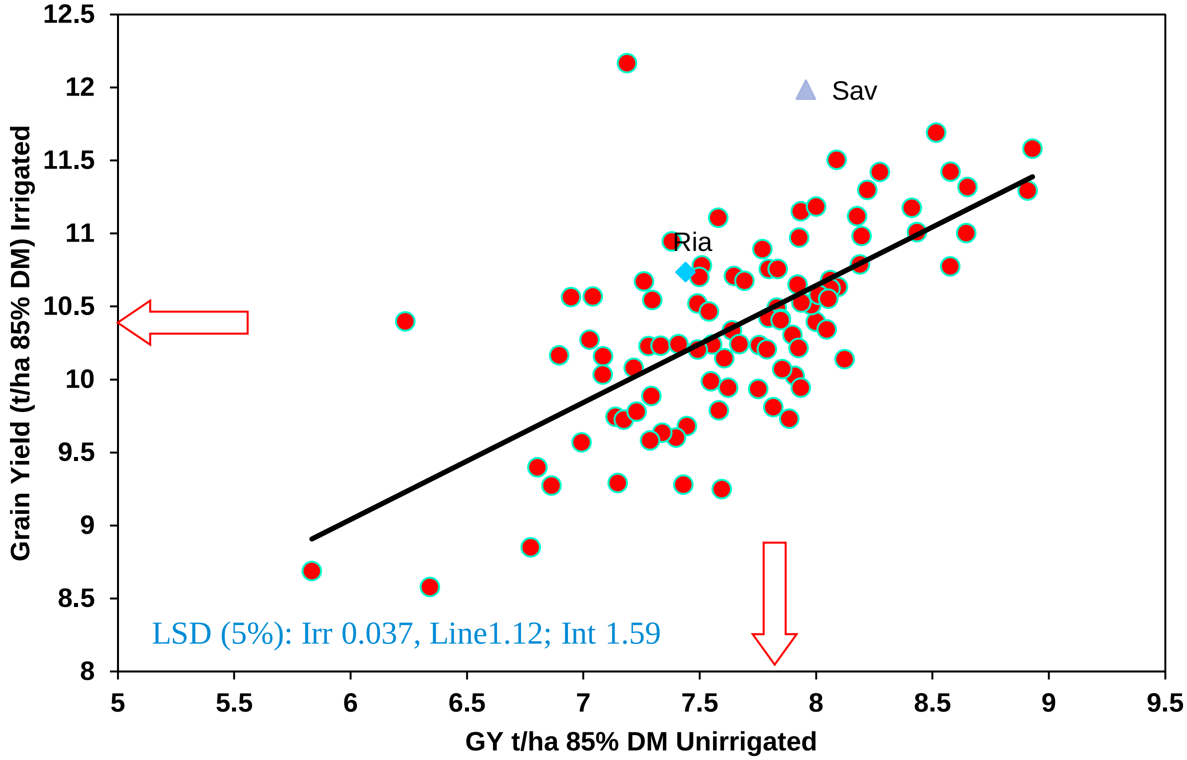
Drought effects 11 July 2011

L2

L39

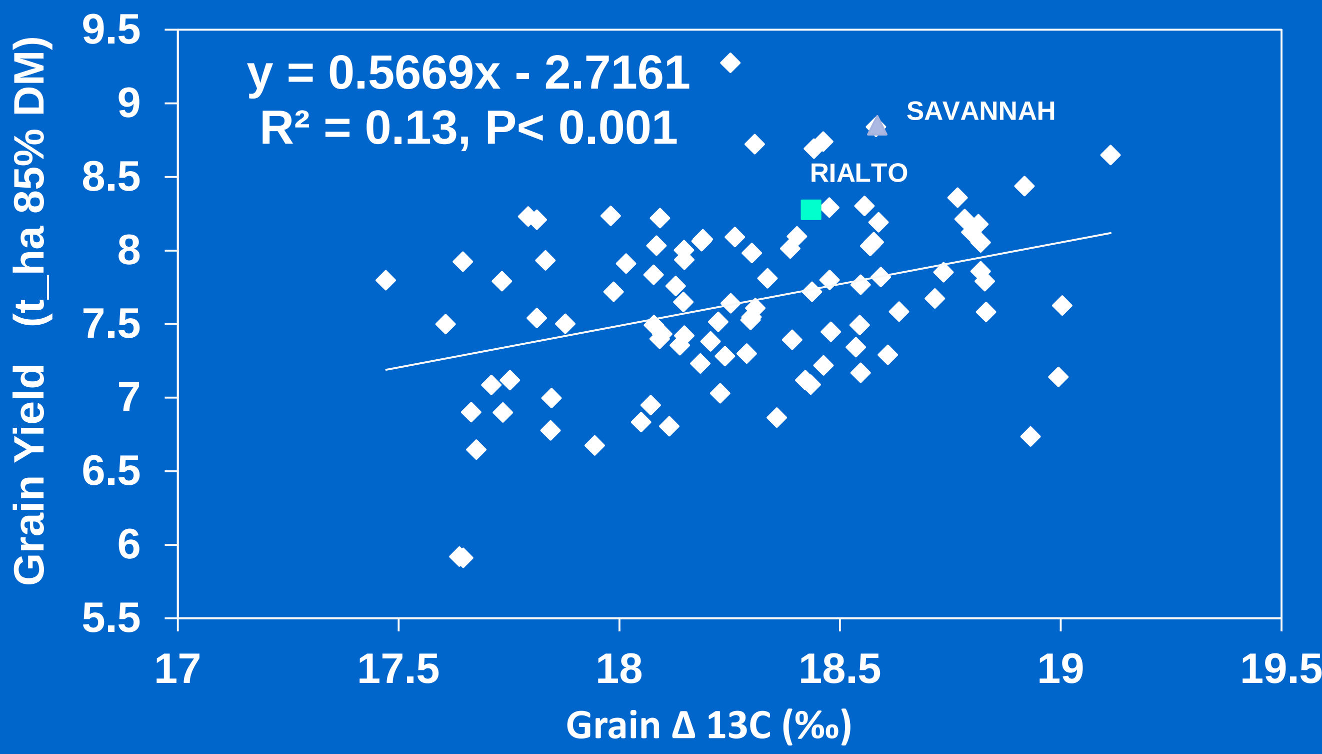
L47

Grain yield responses to irrigation



Sutton Bonington 2010-11

Δ ^{13}C vs grain yield: Savannah x Rialto DH 2010-11



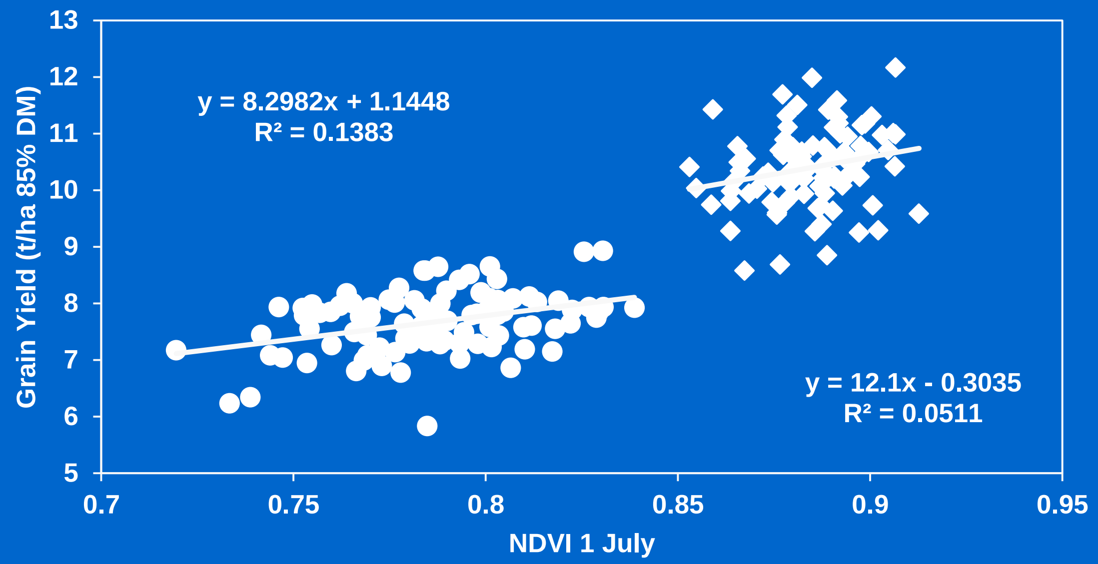
High WUE ← Low WUE

L2 L39 L47

Spectral Reflectance Indices vs Grain Yield

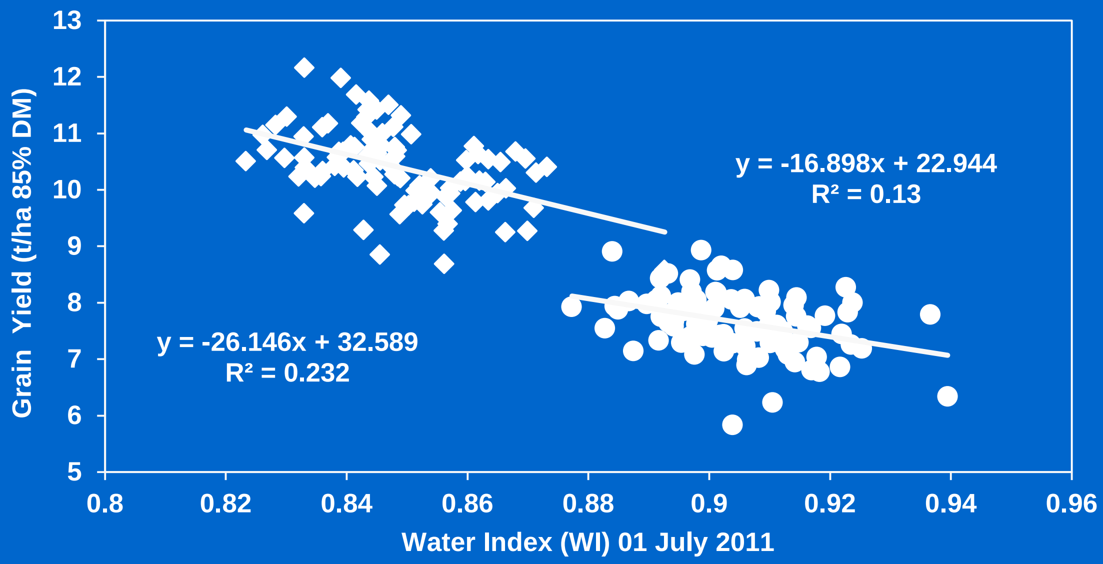
NDVI

LSD:
Irr 0.074 ***;
Line 0.061 ns
Int 0.042 ns

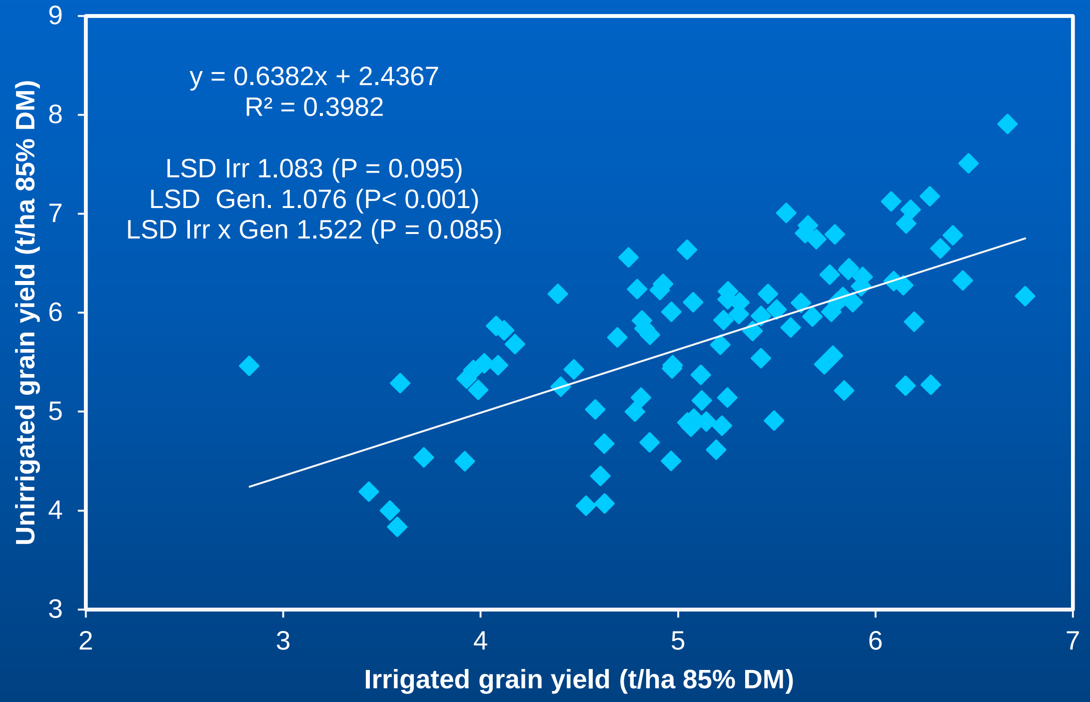


Water Index

LSD:
Irr 0.003 ***
Line 0.002 **
Int 0.004 ns

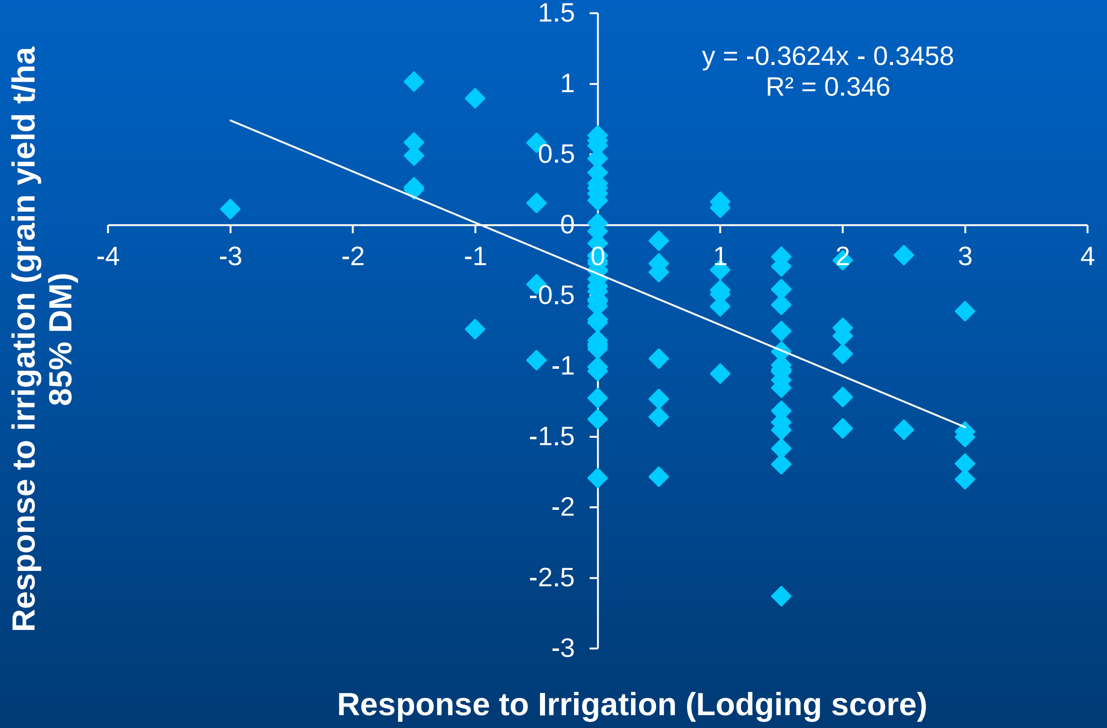


Rialto x Savannah DH exp 2011-12



	Rainfall (mm)	
	2012	**LTM 75-09**
January	**54.2**	**54.3**
February	**13.2**	**44**
March	**24.4**	**46.2**
April	**111.4**	**46.8**
May	**26.2**	**44.3**
June	**110.6**	**58.7**
July	**107.1**	**49.8**

Rialto x Savannah DH exp 2011-12



9.2 QTL Detection

2011-13 expt (Sown 16 October 2012)

• Rialto x Savannah DH population for phenotying for yield physiological traits (94 lines and 2 parents)

• Nottingham - irrigated & unirrigated;

• Target traits

- ^{13}C Δ grain
- senescence kinetic
- stem WSC

WGIN Objective 9.3 Develop SSD Pop

- Paragon x Garcia (contrasting for drought tolerance traits)
- Population segregating for *Ppd1a*:
  - use WGIN resource to select against *PpdD1a* - ie make the pop photoperiod sensitive.
  - keep the pop large, so we can have flowering time strata and perform analysis within them
- F3 sown in October 2012, population is in excess of 350 lines
  -

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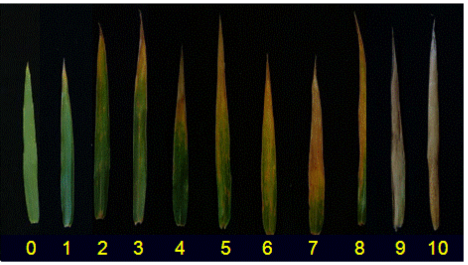
WGIN 2 (9.4 Association Genetics)

	Project Month	Milestone
31/03/2012	40	Act 9 Obj3. Complete development of one new DH population in an elite modern background segregating for drought-tolerance traits.

120Watkins lines assessed for leaf Ps rate (quantum yield, fluorpen) and visual senescence scores (weekly post anthesis) in 2010-11 and 2011-12



Preliminary Conclusions

- **Consistent differences in Drought Tolerance Index identified amongst panel of 18 cultivars**

- **Ability to access water appears to be a key driver for productivity under UK drought.**

- **High 13C Δ correlated with grain yield under drought. Physiological basis ~ increased stomatal conductance, deeper roots?**

- **Measurement of stable isotopes in plant dry matter may a useful phenotypic tool for speeding up breeding**
  - **Grain ^{13}C Δ**
  - **Flag leaf Δ ^{18}O**

- **Work is ongoing to:**
  - **identify opportunities to break linkage between WU and WUE**
  - **develop high-throughput screens for breeding**
  - **Understand the genetic basis of drought tolerance and WUE traits (QTL detection)**

The University of Nottingham

Jayalath DeSilva
Pedro Carvalho

PhD student: Y.adgar Mahmood

JOHN INNES CENTRE

Simon Griffiths
Simon Orford
Luzie Wingen

BRITISH WHEAT BREEDERS

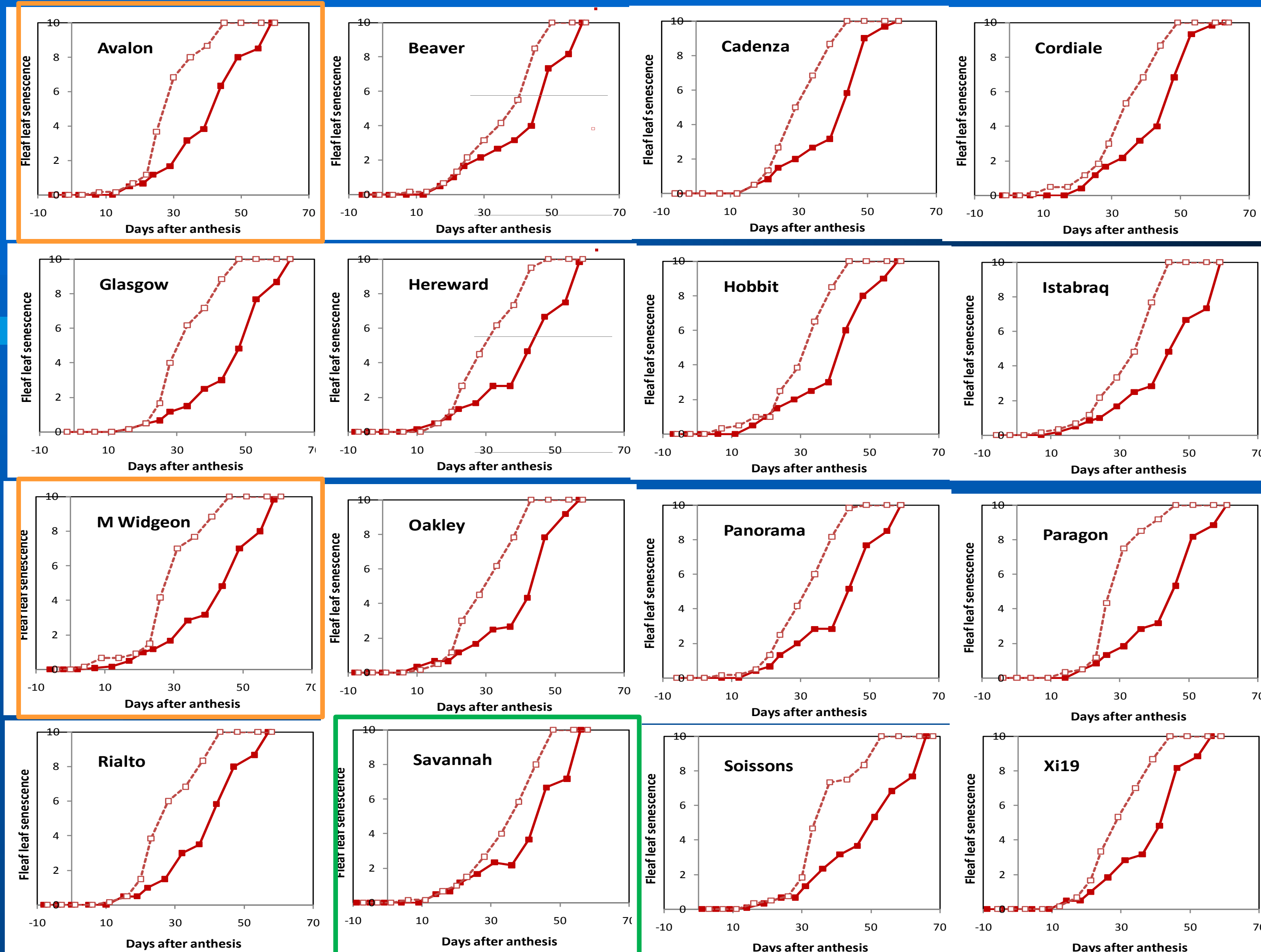
defra
Department for Environment Food and Rural Affairs

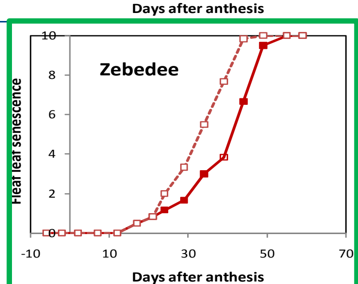
Wheat Genetic Improvement Network

WGIN Drought tolerance (2009-14)

OBJECTIVES

- **Identify traits for WUE and drought tolerance (DT) in elite winter wheat varieties. (*Yrs 1-2*)**
- **Identify QTLs for WUE and DT traits using one DH pop in an elite background. (*Yrs 2-3*)**
- **Develop one new DH pop for UK drought research. (*Yrs 2-4*)**





Flag leaf senescence

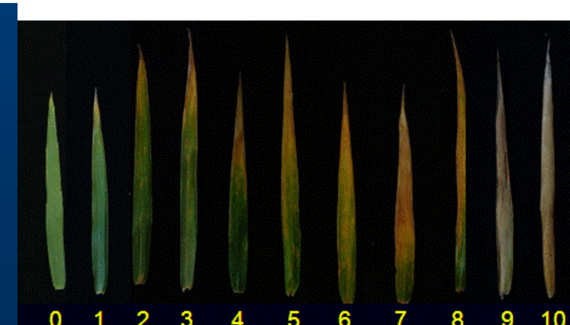
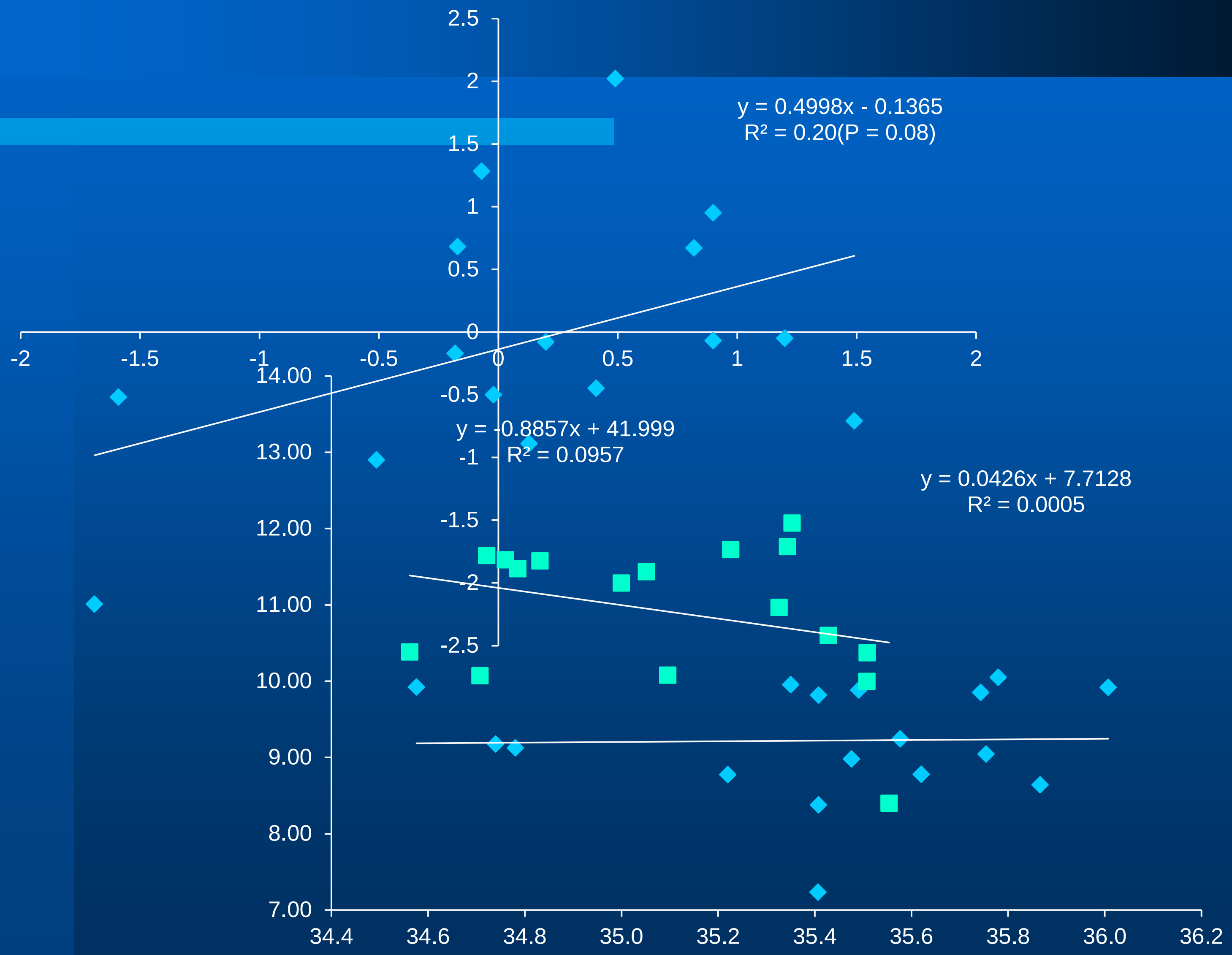


Table 7.1. Commonly used spectral reflectance indices (SRI) for wheat canopy analysis where index types are: VI – vegetation index; PI – pigment related index; WI – water index.

Index	Name	Physiological process	Type	Calculation
NDVI	Normalized difference vegetation index	Green area, photosynthetic capacity, N status	VI	$[R_{900}-R_{680}]/[R_{900}+R_{680}]$
R-NDVI	Red normalized difference vegetation index	Green area, photosynthetic capacity, N status	VI	$[R_{780}-R_{670}]/[R_{780}+R_{670}]$
G-NDVI	Green normalized difference vegetation index	Green area, photosynthetic capacity, N status	VI	$[R_{780}-R_{550}]/[R_{780}+R_{550}]$
SRa	Simple Ratio	Green biomass	VI	$[R_{800}/R_{680}]$ and $[R_{900}/R_{680}]$
$RARS_a$	Ratio analysis of reflectance spectra chlorophyll a	Chlorophyll a content	PI	$[R_{675}/R_{700}]$
$RARS_b$	Ratio analysis of reflectance spectra chlorophyll b	Chlorophyll b content	PI	$R_{675}/[R_{650}*R_{700}]$
$RARS_c$	Ratio analysis of reflectance spectra carotenoid	Carotenoid content	PI	$[R_{760}/R_{500}]$
NPQI	Normalized pheophytinization index	Normal chlorophyll degradation; can be used to estimate phenology, pest and diseases	PI	$[R_{415}-R_{435}]/[R_{415}+R_{435}]$
SIPI	Structural independent pigment index	Senescence related to stress	PI	$[R_{800}-R_{435}]/[R_{415}+R_{435}]$
PRI	Photochemical reflectance index	Dissipation of excess radiation	PI	$[R_{531}-R_{570}]/[R_{531}+R_{570}]$
WI	Water index	Plant water status	WI	$[R_{970}/R_{900}]$
NWI-1	Normalized water index 1	Plant water status	WI	$[R_{970}-R_{900}]/[R_{970}+R_{900}]$
NWI-2	Normalized water index 2	Plant water status	WI	$[R_{970}-R_{850}]/[R_{970}+R_{850}]$
NWI-3	Normalized water index 3	Plant water status	WI	$[R_{970}-R_{880}]/[R_{970}+R_{880}]$
NWI-4	Normalized water index 4	Plant water status	WI	$[R_{970}-R_{920}]/[R_{970}+R_{920}]$

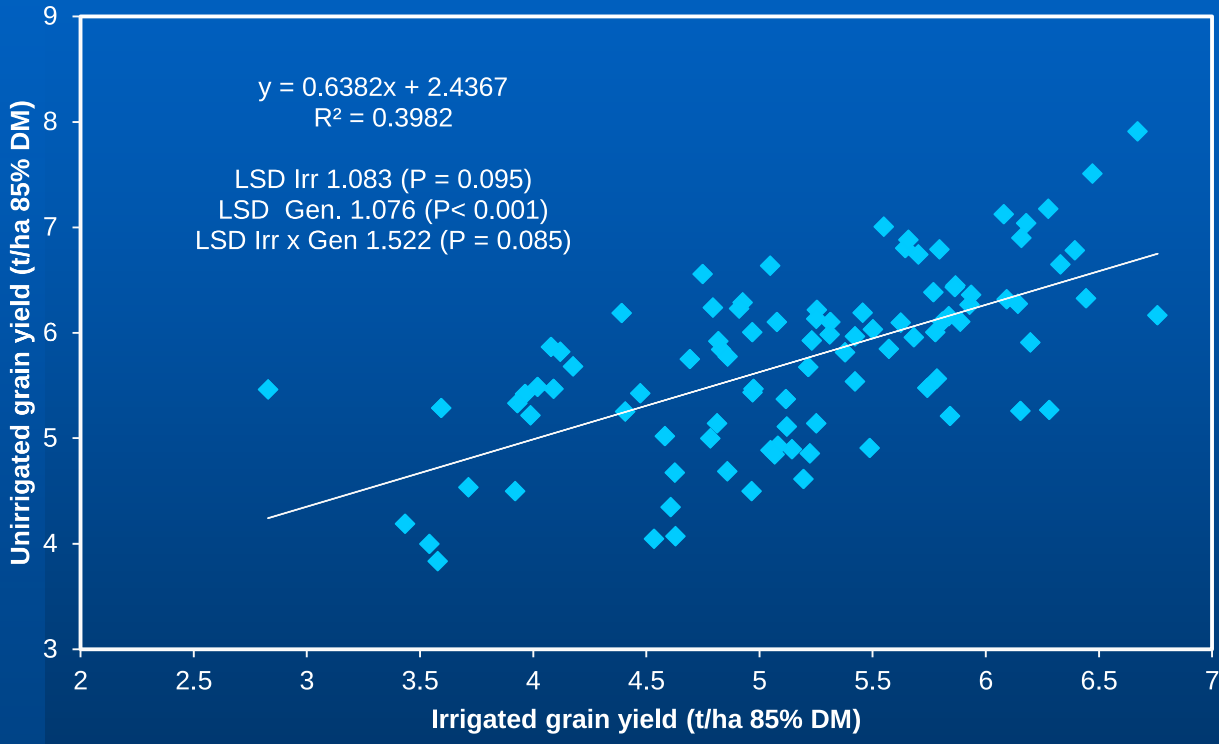

y = 0.4998x - 0.1365
R² = 0.20(P = 0.08)
y = -0.8857x + 41.999
R² = 0.0957
y = 0.0426x + 7.7128
R² = 0.0005
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
14.00
13.00
12.00
11.00
10.00
9.00
8.00
7.00
34.4
34.6
34.8
35.0
35.2
35.4
35.6
35.8
36.0
36.2

WGIN 2 (9.3 Develop new SSD pop)

	Project Month	Milestone
31/03/2012	40	Act 9 Obj3. Complete development of one new SSD population in an elite modern background segregating for drought-tolerance traits.

- Candidate F1(s) made at JIC informed by data analysis from LK0986 project
- Population segregating for *Ppd1a*:
  - use WGIN resource to select against *PpdD1a* - ie make the pop photoperiod sensitive.
  - keep the pop large, so we can have flowering time strata and perform analysis within them
- F3 sown in October 2012, population is in excess of 350 lines

Rialto x Savannah DH exp 2011-12



• Conflicting results obtained in various crops under different growing conditions on the association between 12/13C and yield - range from no relationship between delta and yield to negative or positive relationships, depending on the crop and the environment.

• Deep or dense root system which would promote soil moisture capture and WU is correlated across genotypes with low WUE (Pinheiro et al., 2005; Kobata et al., 1996) but high ability to

• Favorable genotypic plant waterstatus under drought stress as reflected in measurements of canopy temperature is correlated with lowWUE across genotypes (Araus et al., 1993; Frank et al., 1997; Read et al., 1991; Zong et al., 2008).

• Genotypic variation in WUE under limited water regimes is affected more by variation in the denominator (WU) rather than by variation in the nominator (biomass) (Blum, 2005).

• The successful and widely cited case for dryland wheat grain yield improvement with selection for high WUE (low carbon isotope discrimination) in NSW Australia (Condon et al., 2002) can be explained by the fact that wheat is grown there mainly on stored soil moisture. (Fig. 6 in Condon et al., 2002).

5. Drought resistance was found to be associated with low WUE when analyzed by delta under limited water supply (e.g.Araus et al., 2003; Morgan et al., 1993; Ngugi et al., 1994; Solomon and Labuschagne, 2004).

"water uptake (WU), water-use efficiency (WUE), and harvest index (HI) are drivers of yield." Whereas HI is also largely influenced by WU and plant water status, it can be concluded that WU alone is the main (not the exclusive) driver of yield under drought stress.

The $^{13}C/^{12}C$ ratios (R) of leaves grains analysed using an elemental analyser (Carlo Erba 2100) interfaced to an isotope ratio mass spectrometer.
Results expressed as $\delta^{13}C$ values, using a secondary standard calibrated against Vienna Pee Dee Belemnite calcium carbonate (VPDB).

$$\delta^{13}C = (R\text{sample} - R\text{standard}) - 1$$

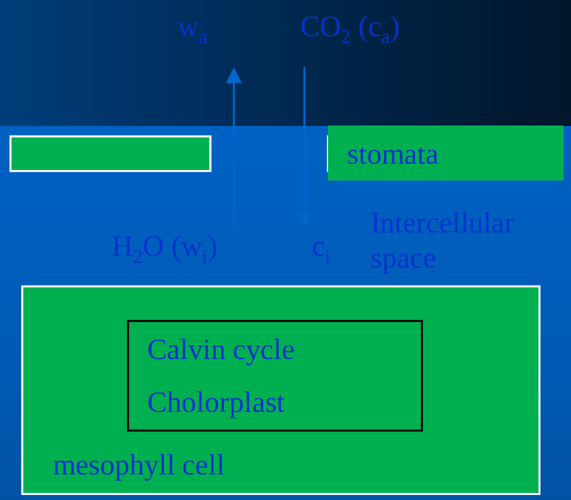
The C isotope discrimination (Δ 13C) of plant parts is then calculated as:

$$\Delta 13C = (\delta^{13}Ca - \delta^{13}Cp) /[1 +(\delta^{13}Cp/1000)]$$

where $\delta^{13}Ca$ and $\delta^{13}Cp$ refer to air and plant C isotope compositions, respectively.
d13C of free atmospheric CO_2 taken as -8‰ (Farquhar et al., 1989).

Effects of leaf activity traits on WUE

- ***Stomatal conductance:***. Lower conductance ↓ ci hence ↑ WUE.
- ***N or Rubisco content per unit leaf area:*** Greater photosynthetic activity ↓ c_i , hence ↑ WUE.



The 18O/16O ratios (R) of irrigation water were determined by the CO_2/H_2O equilibration technique and using an isotope ratio mass spectrometer

Results were expressed as δ18O values, using two secondary standards (IAEA 601 and IAEA 602) calibrated against to the Vienna Standard Mean Oceanic Water (VSMOW)

$\delta^{18}O = (\delta R_{sample} / \delta R_{standard} - 1)$

Then, the 18O enrichment in grains (Δ18O) was calculated as:

$\Delta^{18}O = (\delta^{18}O_p - \delta^{18}O_w) / [1 + \delta^{18}O_w/1000)]$

where d18Op and d18Ow refer to the oxygen isotope compositions of plant sample and rain water, respectively (d18O rain water was approx. 210.78 ‰).