Sugarcane trait modelling at SASRI

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- Hypothesis
- Progress
  1. Initial exploration
  2. Model development
  3. Parameter estimation
  4. Trait impacts
  5. Model application: Ideotyping
- Conclusions

Trait modelling hypothesis

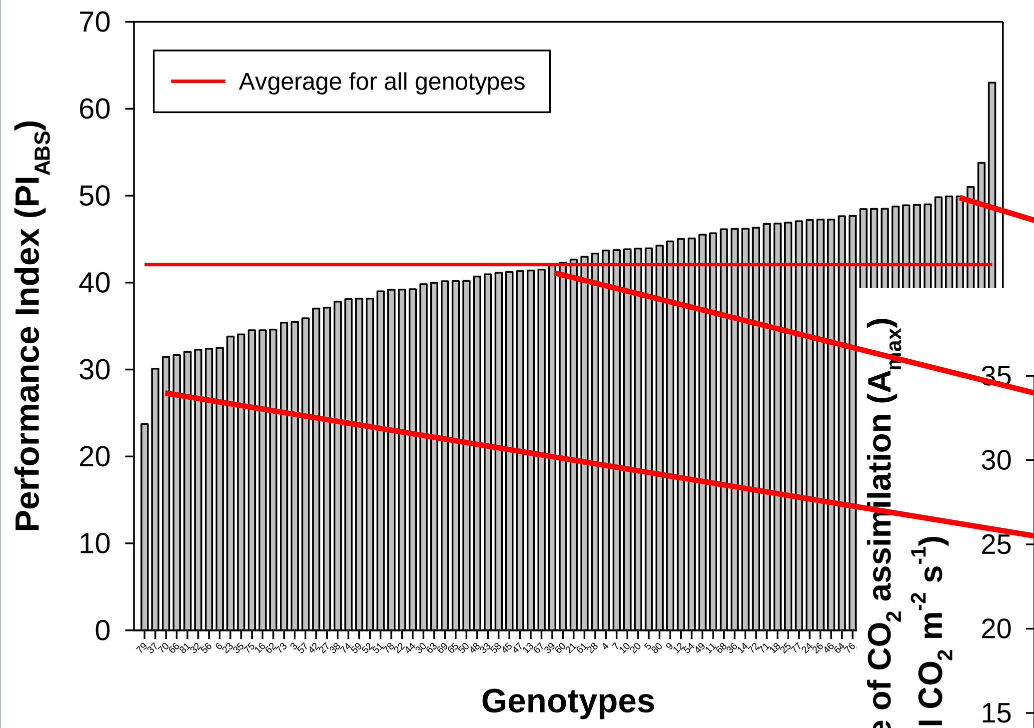
- Genotype performance (yield) can be predicted realistically by simulating the physiological response to environmental and management factors using genetic trait parameters and environmental data
- Genetic trait parameters can be defined well – predominantly capturing genetic effects
- Genetic trait parameter values can be estimated accurately from reliable and practical phenotypic measurements
- Realistic models with accurate trait parameter values can be used to identify important traits and their ideal values for given environments (including future climate)
- Enhancement of variety improvement programs: Crossing, selection and genetic engineering may be guided by desirable trait sets for target environments

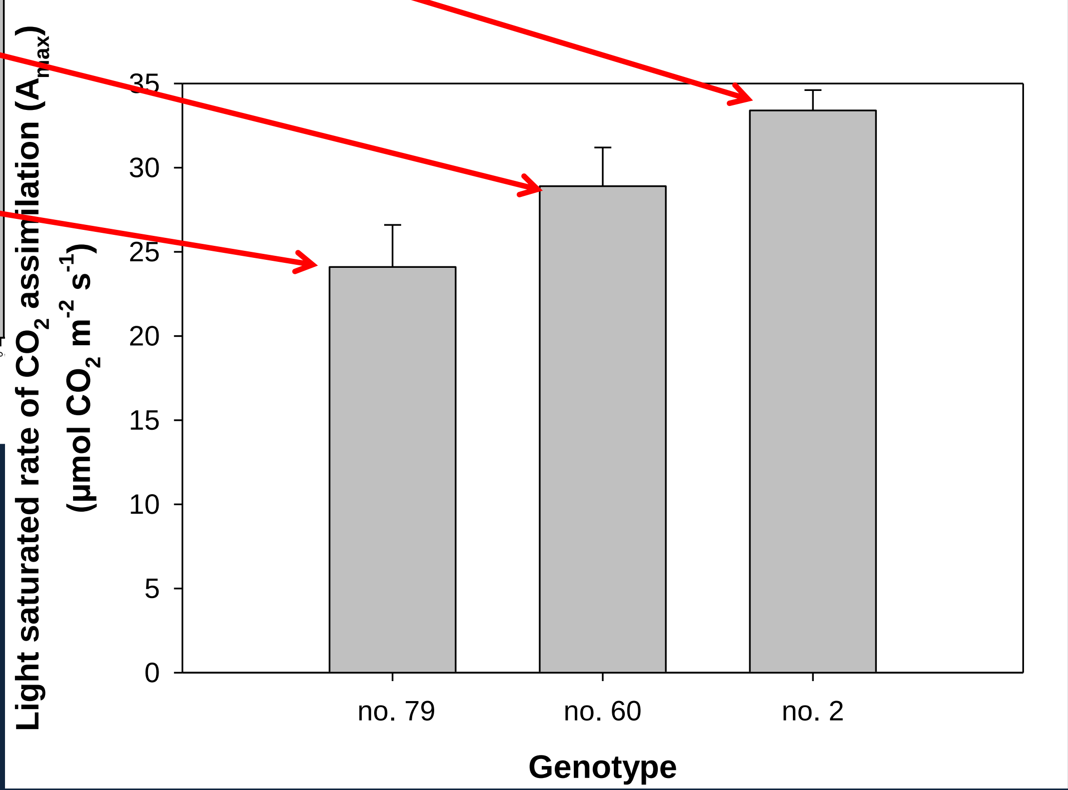
Progress: 1. Initial exploration

- Leaf level photosynthetic efficiency highly heritable, can be phenotyped conveniently with chlorophyll fluorescence (LD80 mapping population)
- Stable genetic markers identified for leaf size and photosynthetic efficiency.
- Trait modelling explores the value of traits **early stomatal closure** and **fast root growth**
- Potential value of approach demonstrated, research requirements identified

Roadmap for deducing Canegro genetic parameters from genomic information (1)

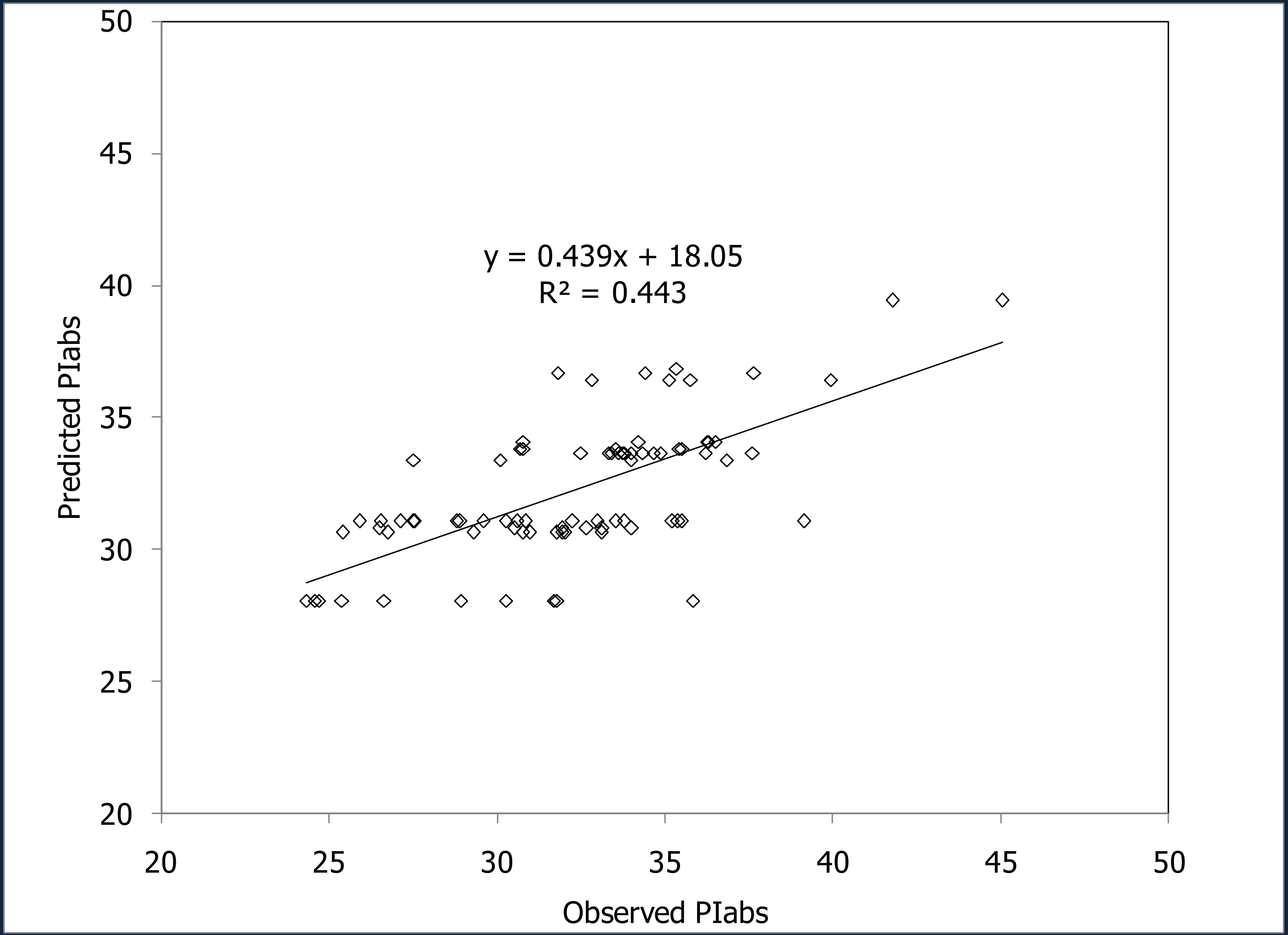
1. Photochemical light use efficiency (PI_{ABS}) determined through chlorophyll a fluorescence
2. Excellent agreement in PI_{ABS} ranking and photosynthetic capacity (P_{CAP}) ranking (as determined by CO_2 fixation response to light)





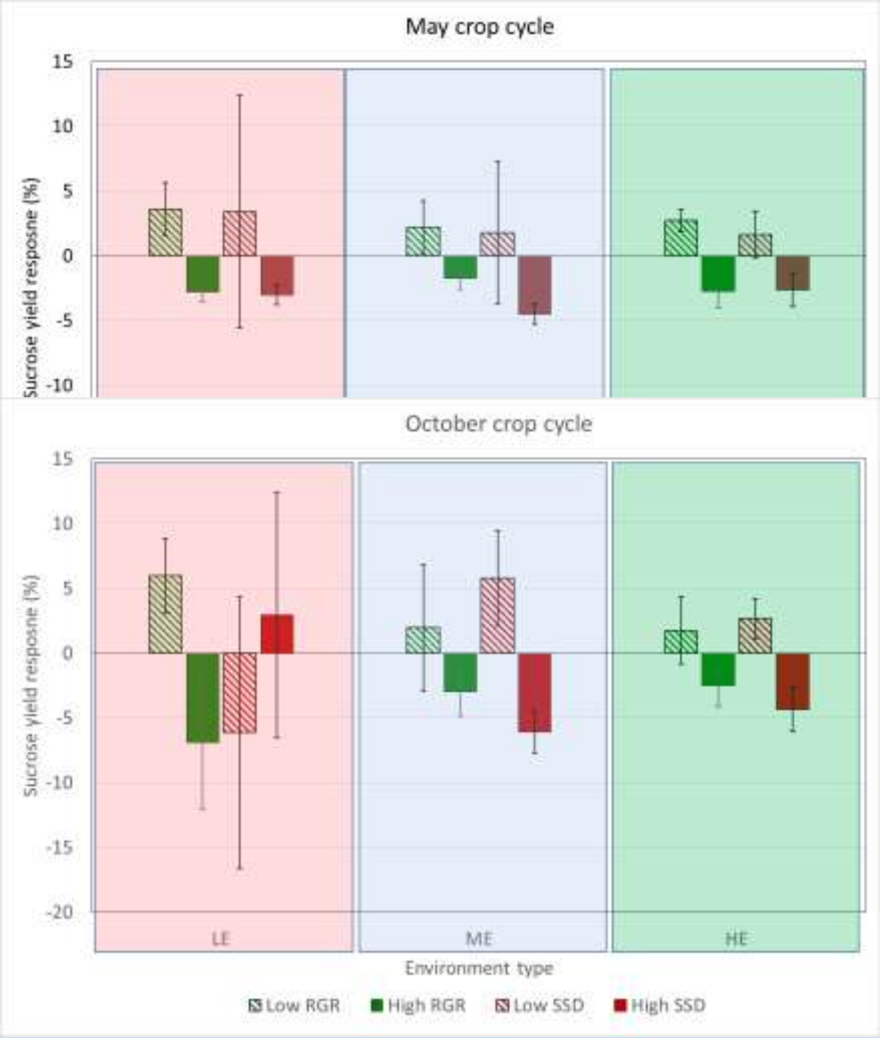
Roadmap for deducing Canegro genetic parameters from genomic information (2)

3. PI_{ABS} reliably predicted from marker data
4. Markers -> PI_{ABS} –> P_{CAP} (mol $CO^2/m^2/s$) -> Canegro PAR conversion efficiency (g/MJ)



Exploring the potential of crop modelling to assist variety improvement

- Trait modelling study suggest that:
  - Early stomatal closure during dry spells is not an advantage in low or high potential environments
  - Increased carbon investment required to accelerate root elongation was not adequately compensated by enhanced soil water capture and aboveground growth
- Potential value of approach demonstrated
- Research required to improve models and phenotyping procedures



Progress: 2. Model improvement

Canegro weaknesses partially addressed:

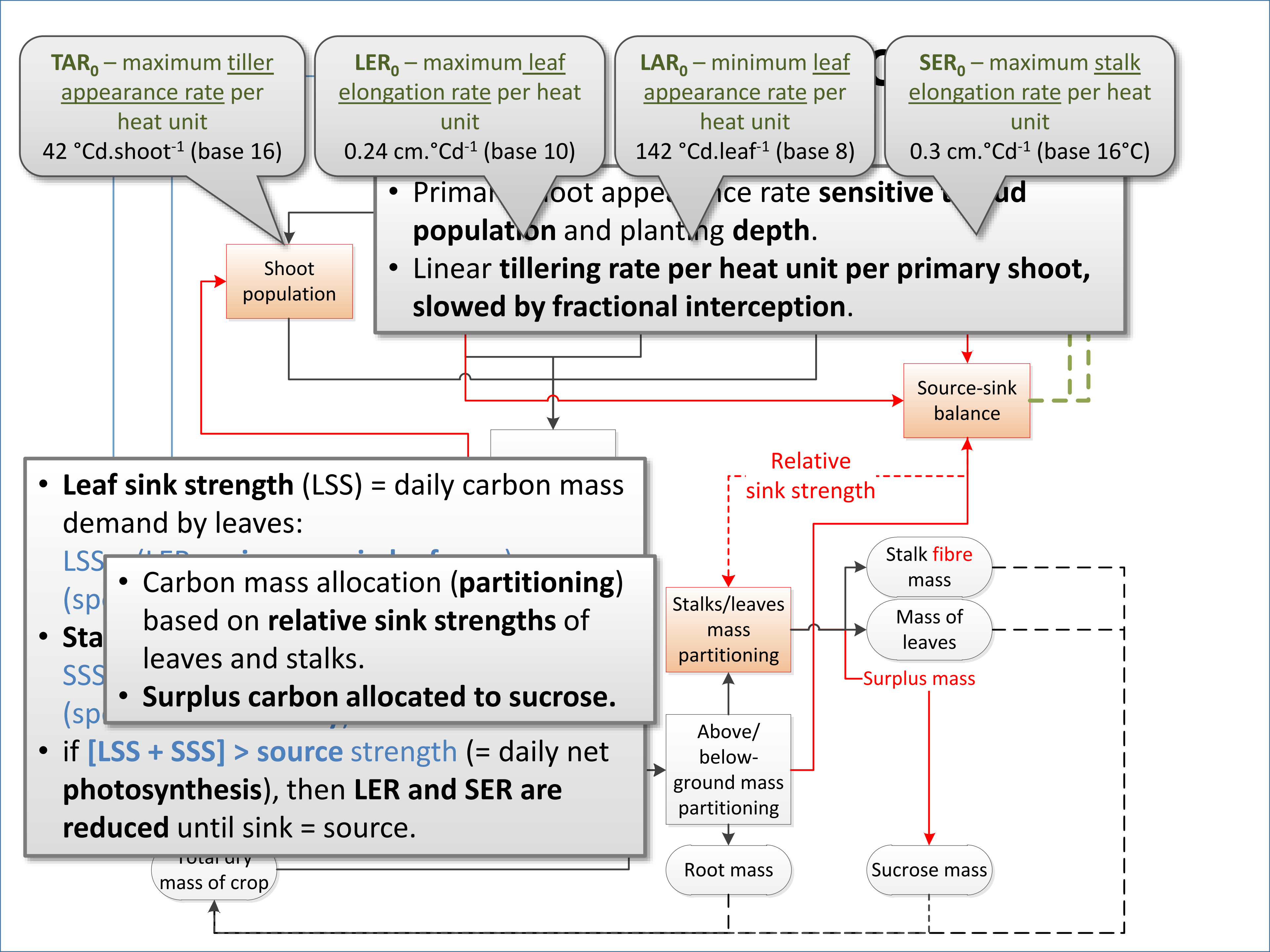
1. Inappropriate maintenance respiration algorithm fixed
2. Refine high temperature effects on growth and development
3. On-off CERES water uptake algorithm replaced by Aquacrop water uptake algorithm
4. Descriptive, non-dynamic nature of canopy development (shading effect).
5. Biomass partitioning not responsive to sink demands (disconnect between organ development and mass balance at the crop level)

Canesim model revamped

1. Similar changes to Canegro
2. Database of trait parameter values for all released varieties up to N52.

Development of GTP Canegro

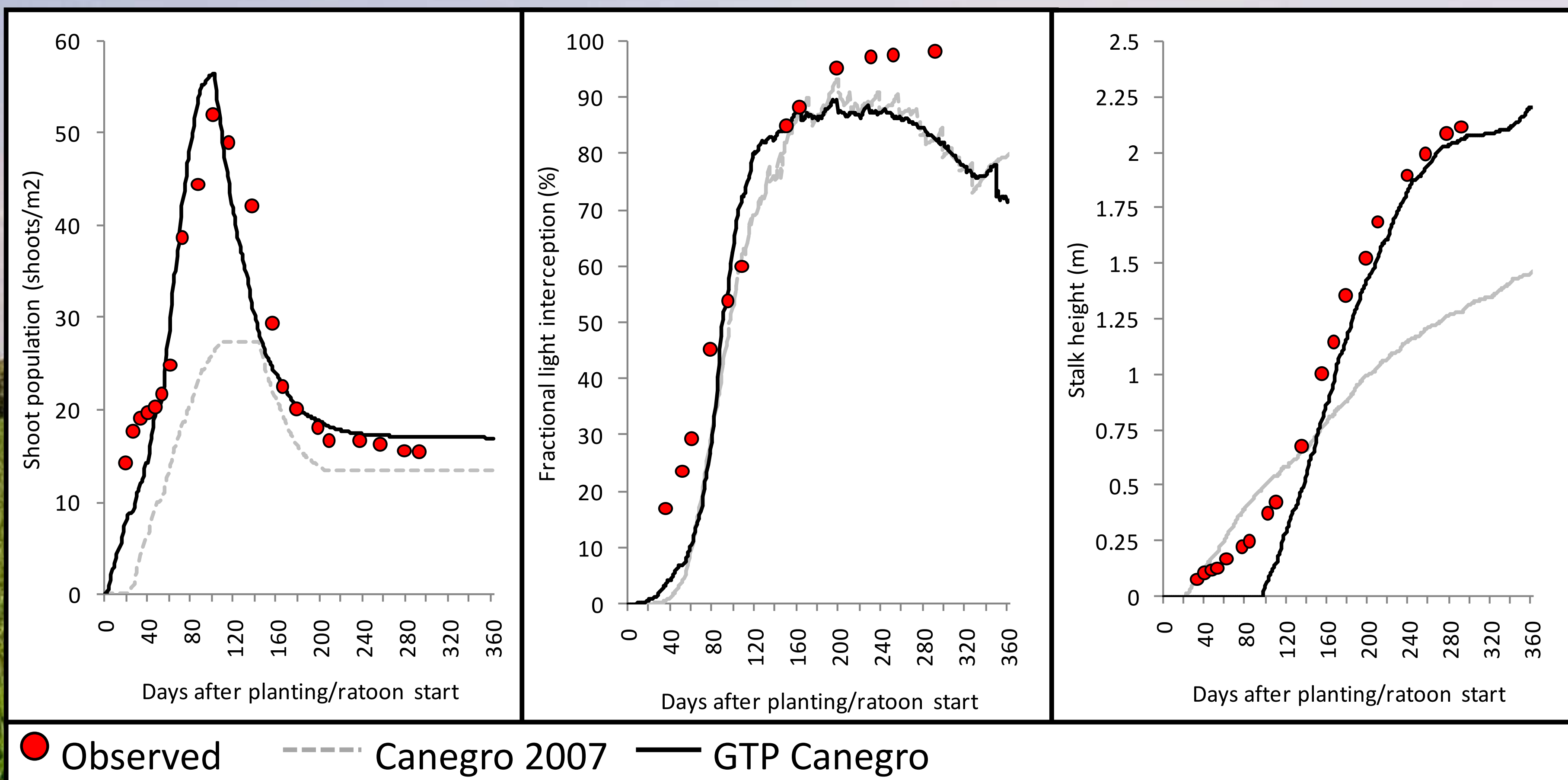
- Problem: Canegro v4.5 unsuitable for crop improvement support because
  - structural growth and development are not affected by carbon availability (source), and
  - carbon partitioning is largely unresponsive to changing demand of structural sinks.
- Objective: Modify Canegro to address these shortcomings and make it more suitable for gene-to-phenotype modelling.
- GTP Canegro
  - Shoot development: Affected by light interception feedback. Tillering slows as the canopy intercepts sunlight and shades the stools. Tillering is therefore sensitive to leaf appearance and dimensions, as well as genetic tillering characteristics
  - Source-sink dynamics: Partitioning of daily biomass increments determined by the carbohydrate demand for structural growth, which is driven by temperature and limited by water stress, and regulated by genetic trait parameters.
  - Structural growth responds to a shortfall of carbohydrate by reducing leaf and stalk elongation rates until the 'books are balanced', i.e. that carbohydrate demand for structural growth ('sink strength') is tempered to match carbohydrate supply form photosynthesis ('source strength')
  - When source strength exceeds sink strength, excess carbohydrate is allocated to sucrose storage in the stalk.
- Model calibrated against one data set and evaluated through sensitivity analysis



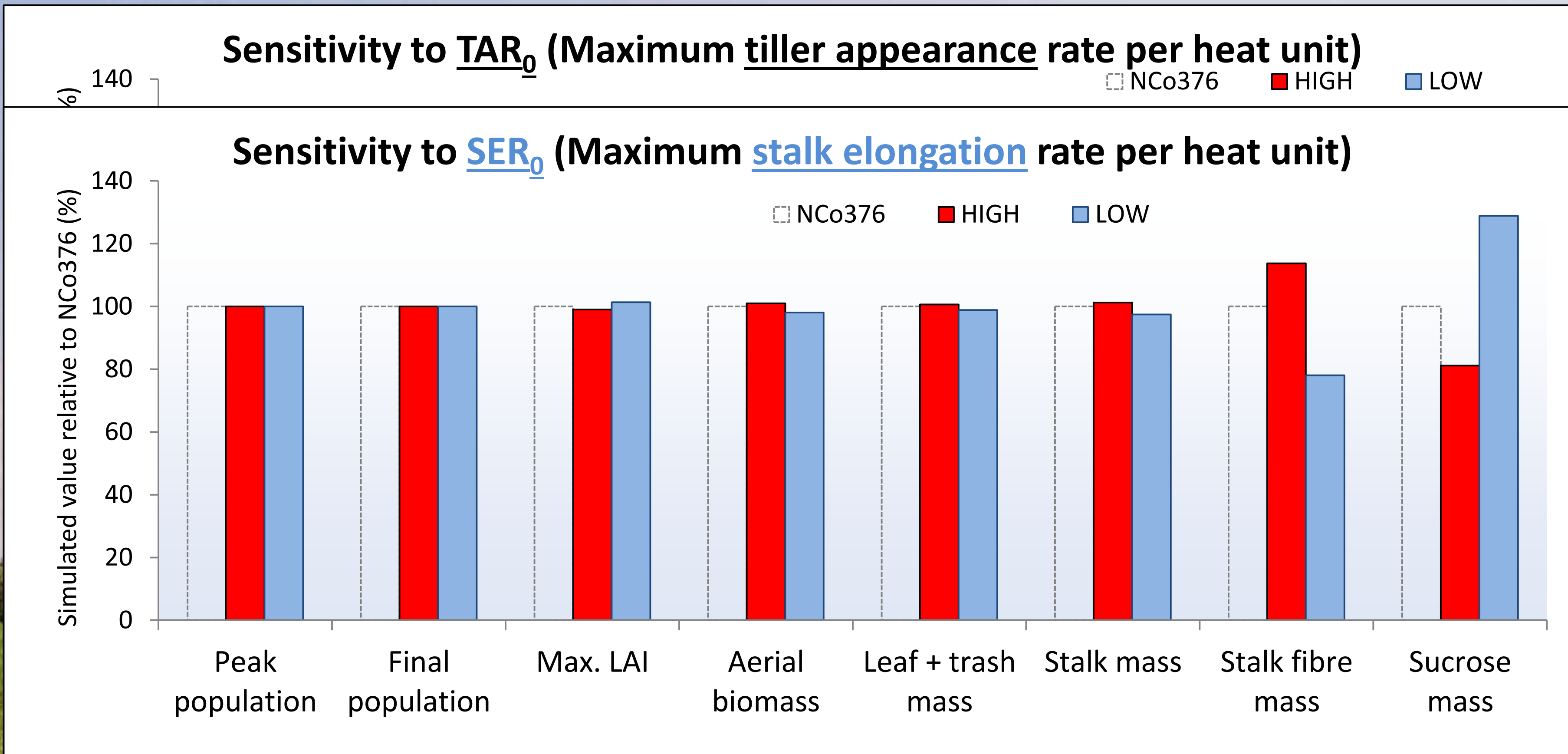
TAR0 – maximum tiller appearance rate per heat unit
42 °Cd.shoot-1 (base 16)
LER0 – maximum leaf elongation rate per heat unit
0.24 cm.°Cd-1 (base 10)
LAR0 – minimum leaf appearance rate per heat unit
142 °Cd.leaf-1 (base 8)
SER0 – maximum stalk elongation rate per heat unit
0.3 cm.°Cd-1 (base 16°C)
• Linear tillering rate per heat unit per primary shoot, slowed by fractional interception.
Shoot population
Source-sink balance
Relative sink strength
• Leaf sink strength (LSS) = daily carbon mass demand by leaves:
• if [LSS + SSS] > source strength (= daily net photosynthesis), then LER and SER are reduced until sink = source.
• Carbon mass allocation (partitioning) based on relative sink strengths of leaves and stalks.
• Surplus carbon allocated to sucrose.
Stalk fibre mass
Mass of leaves
Surplus mass
Stalks/leaves mass partitioning
Above/ below-ground mass partitioning
Root mass
Sucrose mass
mass of crop

Calibration results

- Model was calibrated on observations and Canegro 2007 simulations from Mount Edgecombe row-spacing trial

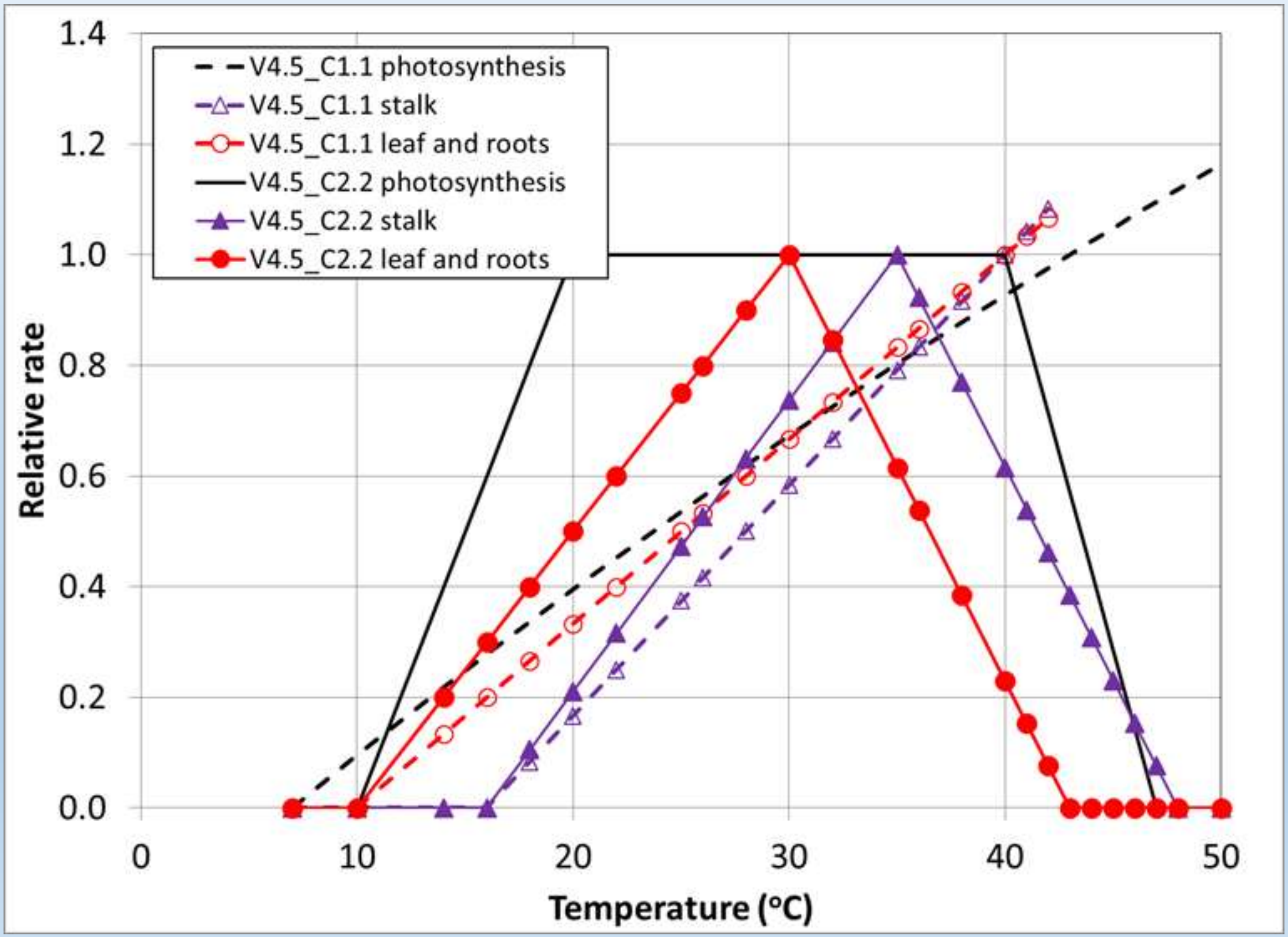


Sensitivity analysis results

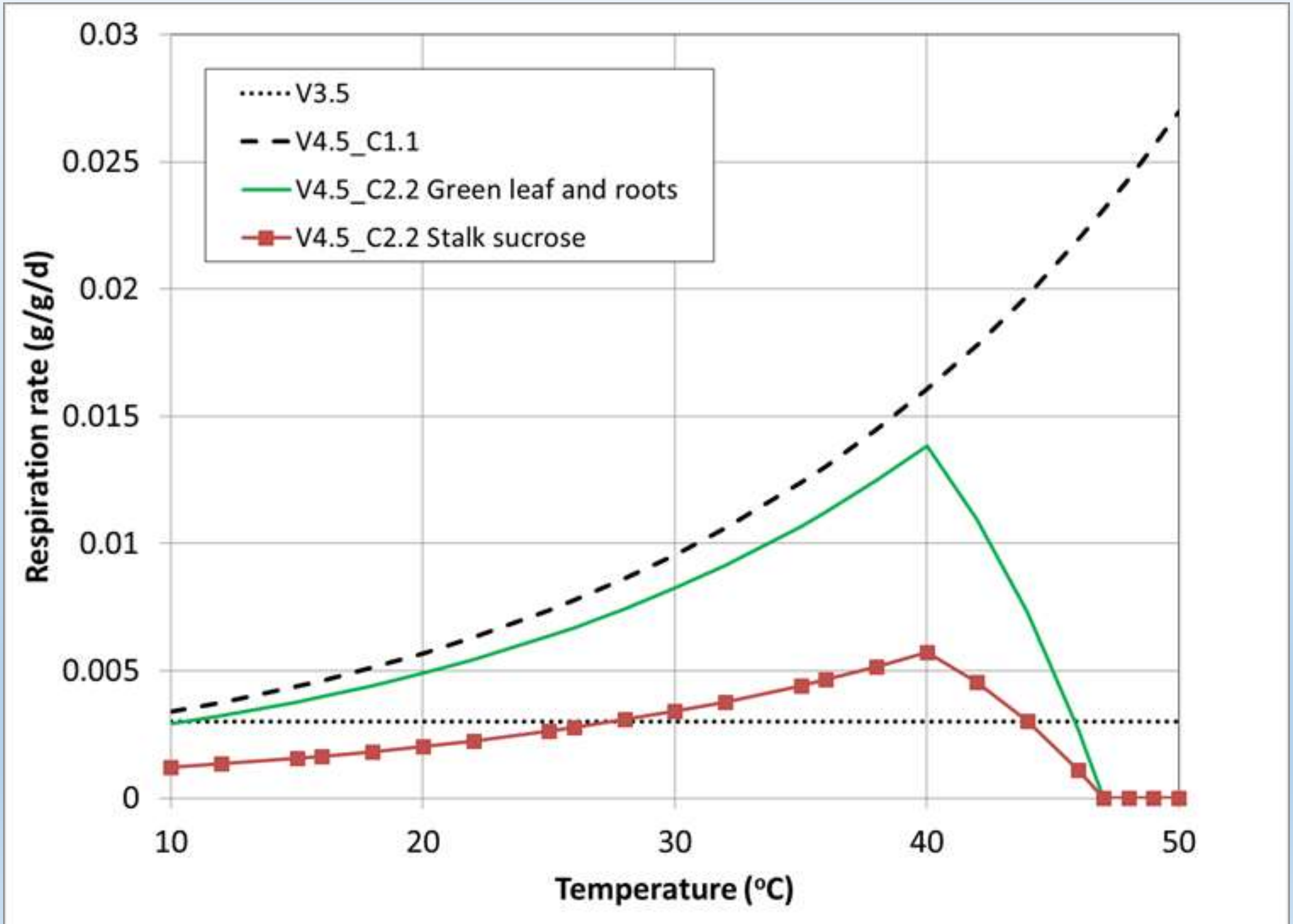


- Each series shows simulation results of a variety genetically-identical to **NCo376**, but with the "genes" responsible for, for e.g. Tiller appearance rate (**TAR_0**), modified to be faster (**HIGH**) or slower (**LOW**).

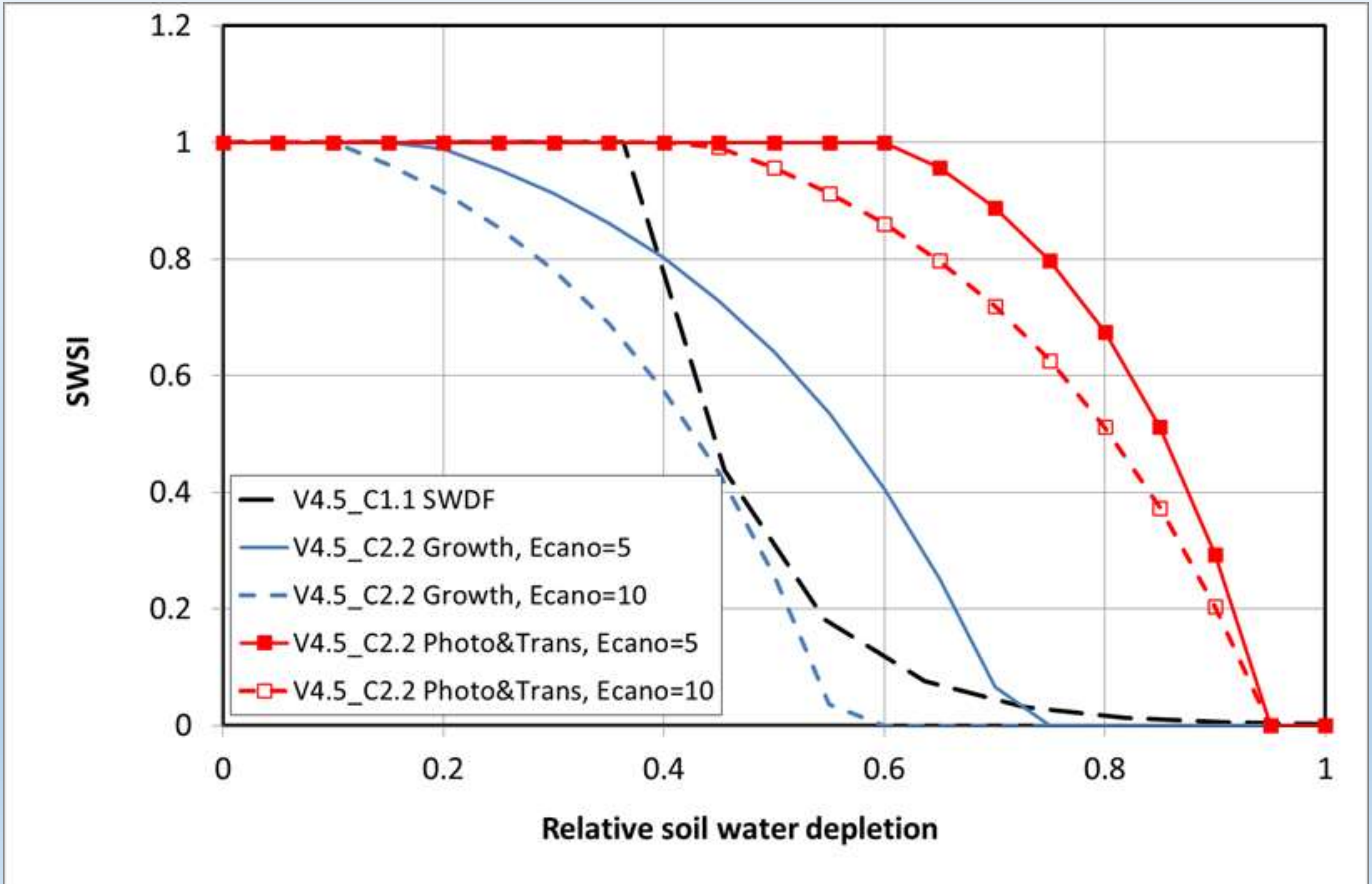
Canegro temperature control



Canegro respiration



Canegro water uptake



Progress: 3. Model parametrization

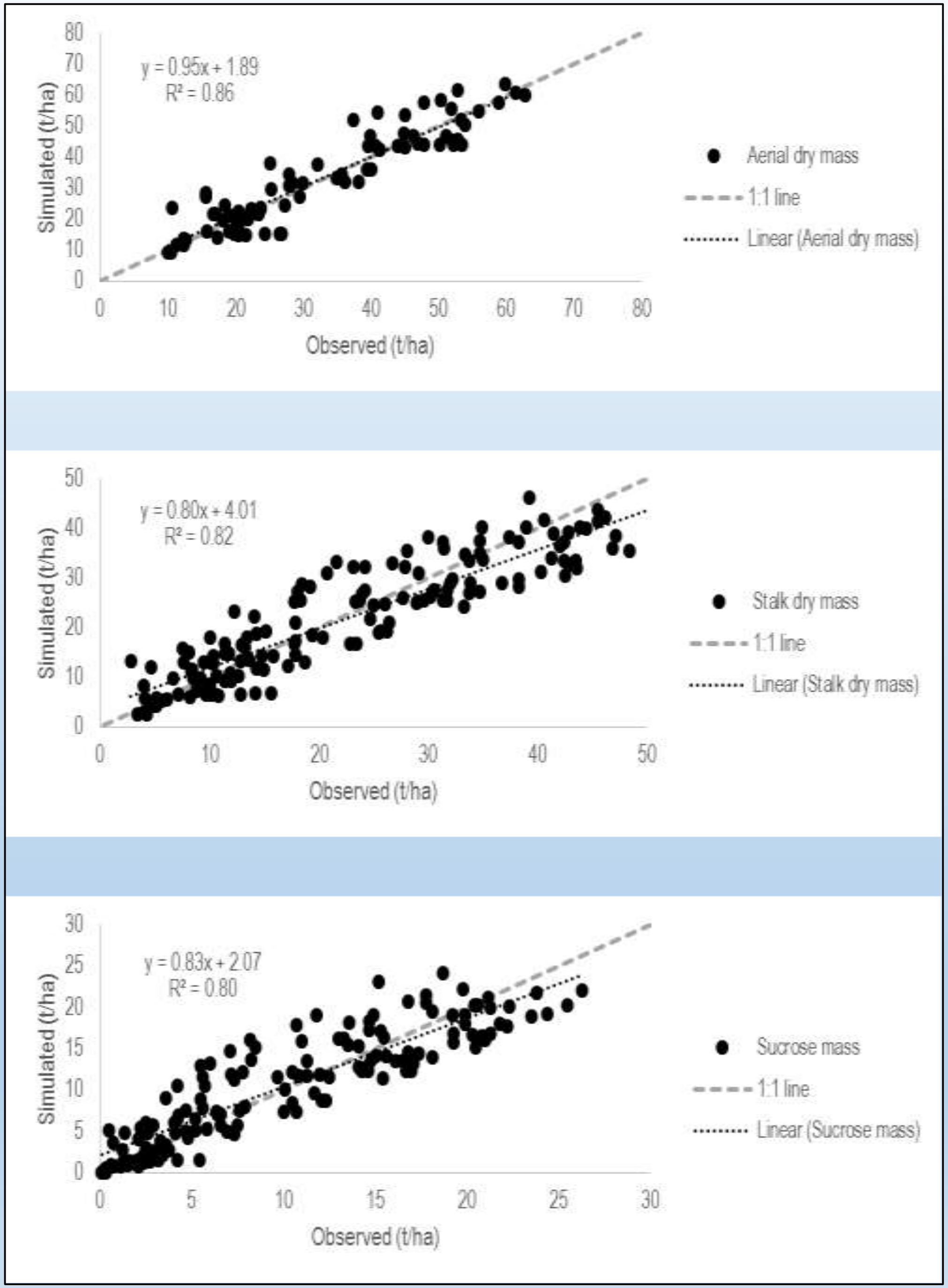
- M.Sc thesis completed
- Paper presented at iCropm 2016 in Berlin

Canegro trait parameters

Parameter	Description	NCo376	N19	G73	N31	HS	HF
MaxPARCE	Maximum (no stress) radiation conversion efficiency expressed as assimilate produced before respiration, per unit PAR. (g/MJ)	5.7	5.8	6.2	5.9	5.8	6.9
STKPFMAX	Fraction of daily aerial dry mass increments partitioned to stalk at high temperatures in a mature crop (t/t on a dry mass basis)	0.7	0.65	0.6	0.68	0.65	0.6
SUCA	Sucrose partitioning parameter: Maximum sucrose contents in the base of stalk (t/t)	0.58	0.63	0.30	0.53	0.63	0.30
MXLFARNO	Leaf number above which leaf area is limited to MXLFAREA	17	17	23	14	17	23
PI1	Phyllocron interval 1 (for leaf numbers below Pswitch, ^{o}C.d	70	50	59	90	50	59
PI2	Phyllocron interval 2 (for leaf numbers above Pswitch, ^{o}C.d	170	146	117	170	146	117
TAR0	The number of lower order tillers produced per higher order tiller per unit thermal time (/oCd) for unstressed crops	0.020	0.015	0.020	0.018	0.015	0.020
AQP_UP5	Drought sensitivity coefficient: The soil water depletion fraction below which transpiration and photosynthesis rates are reduced at the reference atmospheric evaporative demand of 5 mm/d	0.6	0.45	0.65	0.55	0.45	0.65

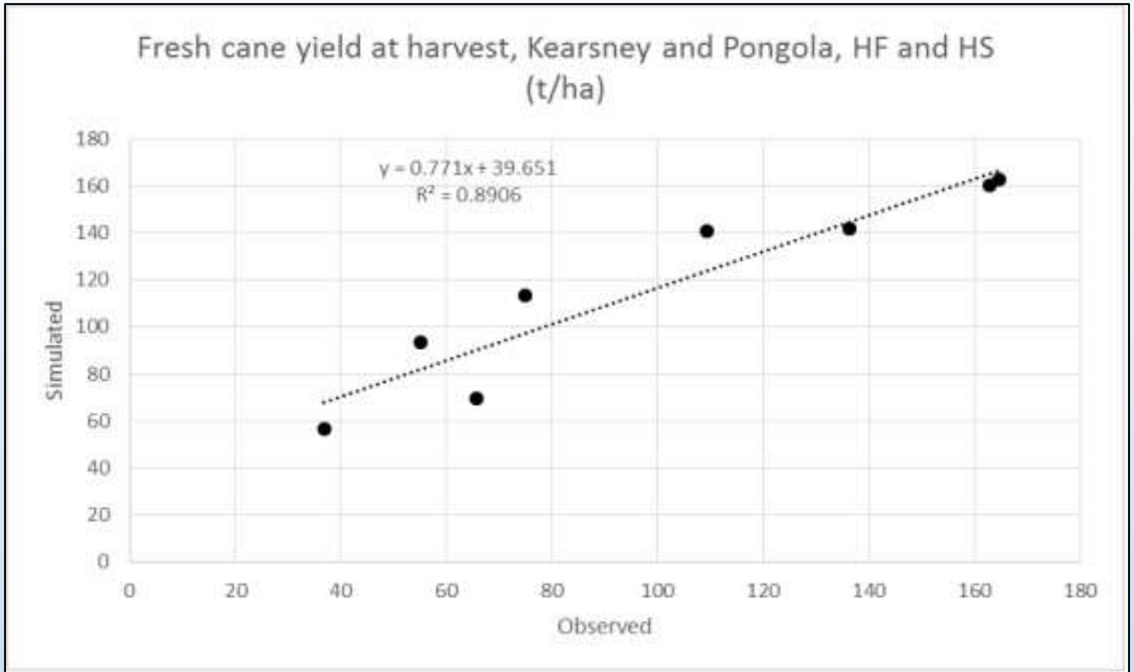
Model and parameter calibration

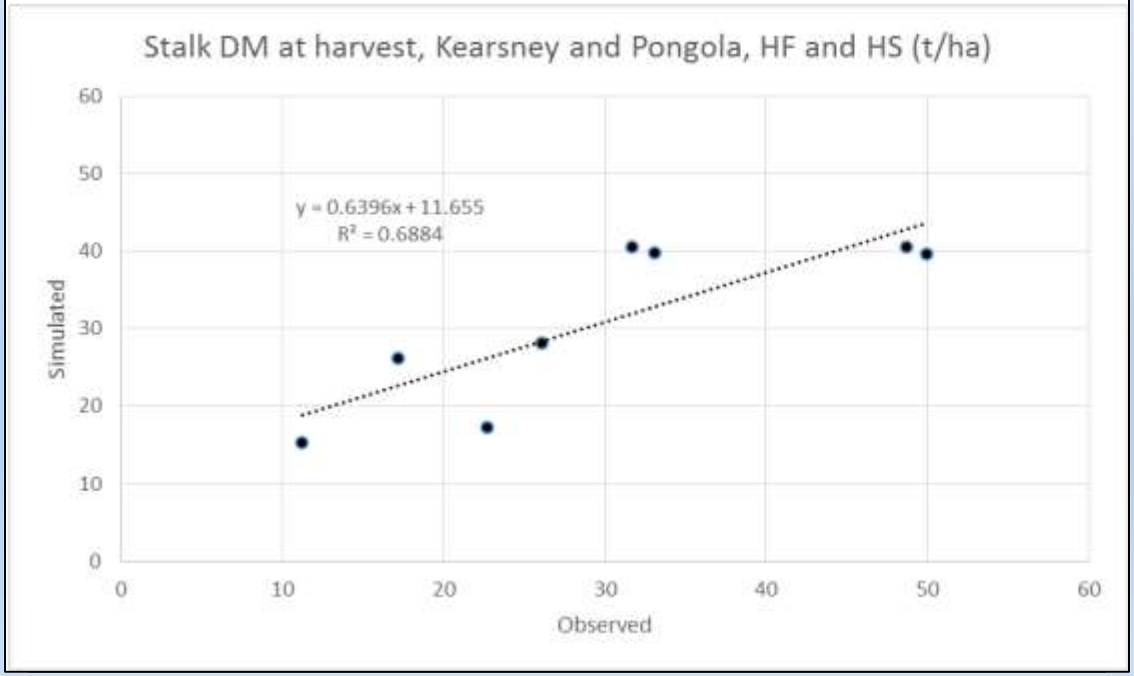
1. Calibrate refined model on standard NCo376 dataset



Model and parameter calibration

1. Calibrate refined model on standard NCo376 dataset
2. Parameterize using (a) HF growth analysis data as well as (b) Plant Breeding data





Sugarcane phenotyping issues

- Difficulty in estimating parameter values
  - Often derived indirectly from experimental data (and theory)
  - Need for reference conditions in experiments to minimize environmental impacts
  - Precision, repeatability, ease, cost
- Scarcity of phenotypic data hinders trait modelling progress

Unlocking the potential of sugarcane

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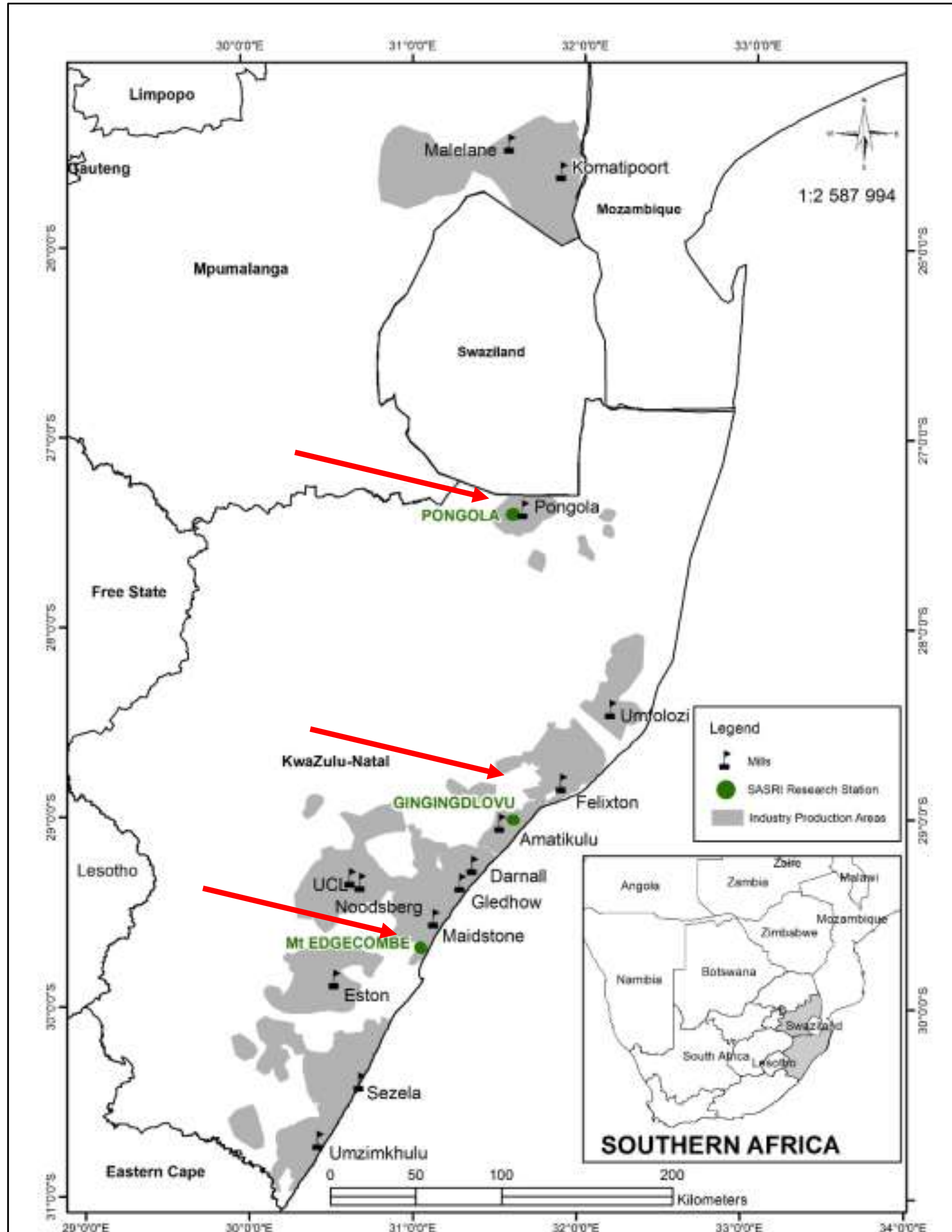
Overview

1. Model and trait parameters
2. Parameter estimation
   - Mount Edgecombe pot trial
   - Expert ratings from variety trials
3. Parameter values
4. Field validation
   - Pongola, Gingindlovu
5. Conclusions



Trait parameter estimation

Trait	Para-meter	Description
Canopy development rate	TT50	Thermal time to 50% canopy cover (^oCd)
Onset of stalk growth	TTsg	Thermal time to start of stalk growth (^oCd)
Maximum photosynthetic efficiency	RUEo	Gross photosynthate produced per unit of shortwave radiation intercepted under ideal condition (g/MJ)
Drought tolerance	Estress	Relative available soil water threshold below which transpiration is reduced below the potential rate (at AED=5mm/d)

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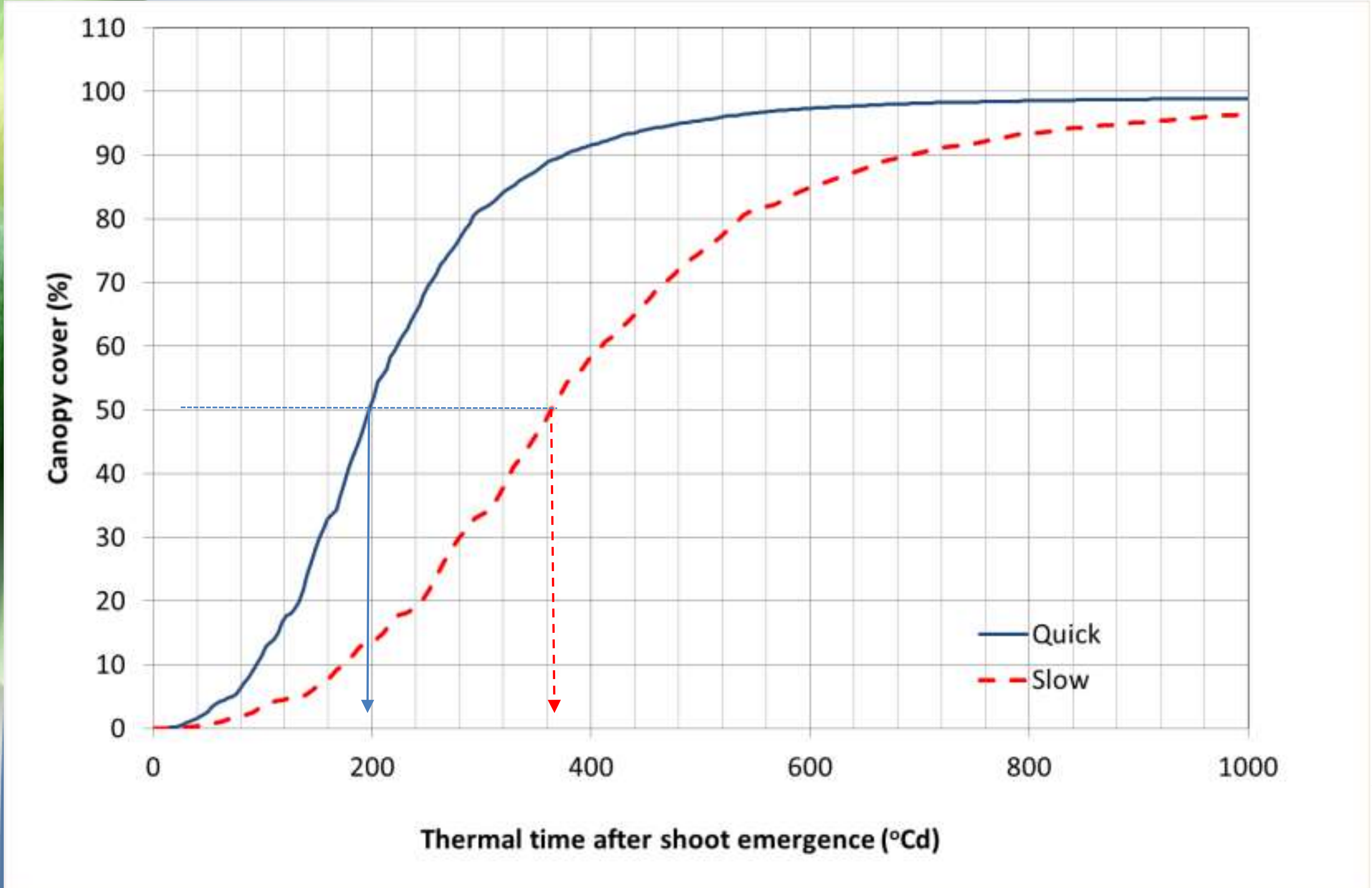
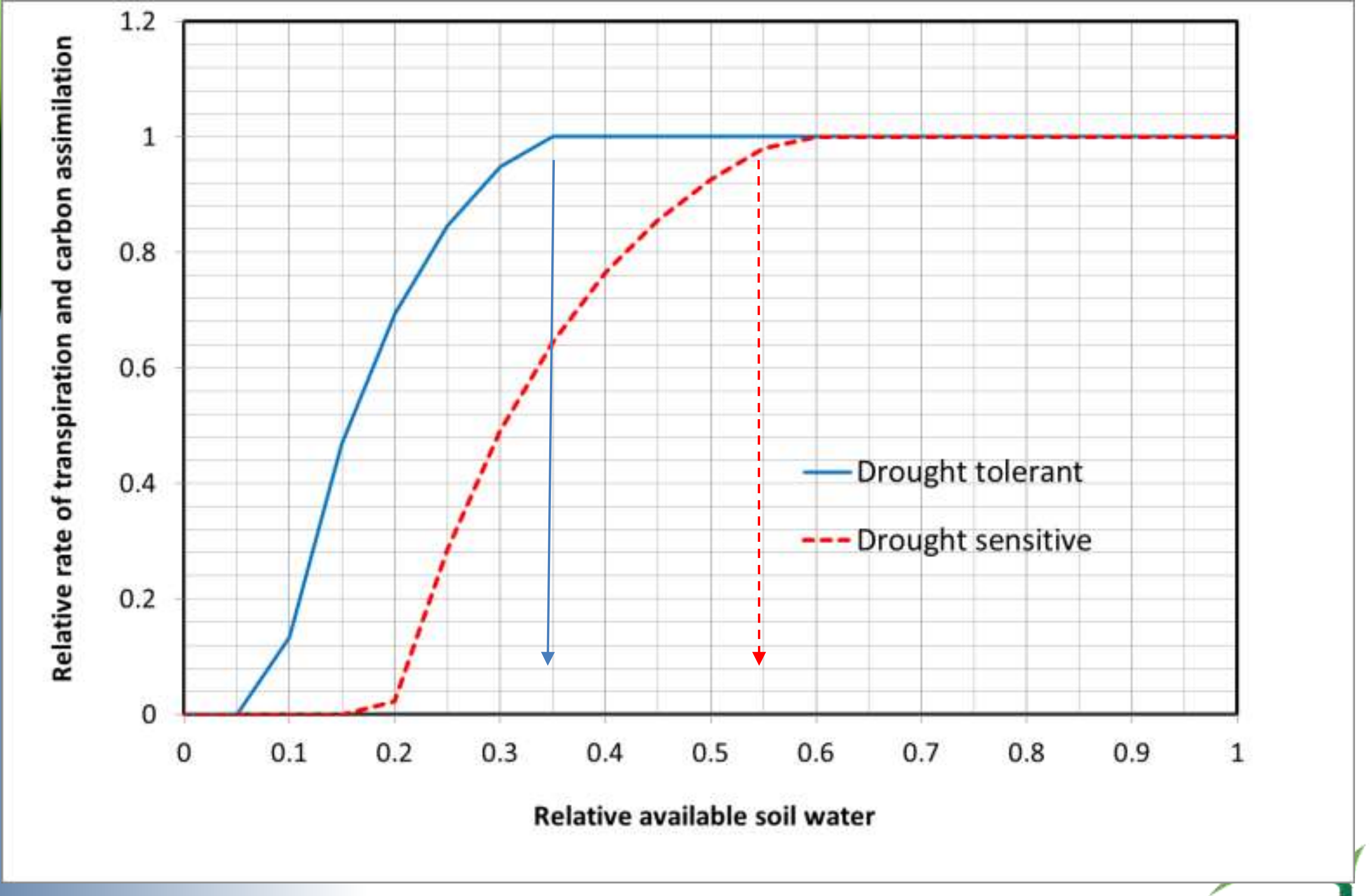
Canopy formation: TT_{50}



Drought sensitivity: Estress



Canopy formation

Expert Rating		Genotypes	TT_{50} (°Cd)
VL	1		370
L	2	N12, N24, N26, N27	340
LM	3		310
M	4	N28, N39, N41, N47	280
MH	5	CP66, N25, NCo376	250
H	6	N14 , N16, N19, N21, N22, N23, N29, N30, N31 , N32, N33, N35, N36, N37 , N40, N42, N43, N44, N45, N46, N48, N52, G73	220
VH	7		190

Experimental data

Inman-Bamber (1994):	Data on NCo376, N12
Singels & Donaldson (2000):	Data on NCo376, N25, N26
Singels et al. (2005):	Data on CP66, NCo376
Olivier & Singels (2006):	Data on N14
Rossler (2013):	Data on N41
Olivier et al. (2015a):	Data on N14, N26
Zhou et al. (2003):	Data on N14, NCo376
Olivier et al. (2015b); Weigel et al. (2014)	Data on N19, N31, G73

Drought tolerance

Expert Rating	Genotypes	Estress
1		0.65
2		0.60
3	CP66/1043, N14, N19, N22, N24, N26, N28, N30, N32, N35, N37	0.55
4	N16, N23, N25, N36, N40, N52	0.50
5	N12, NCo376	0.45
6	N21, N27, N31, N33, N39, N41, 04G0073	0.35
7		0.30

Experimental data

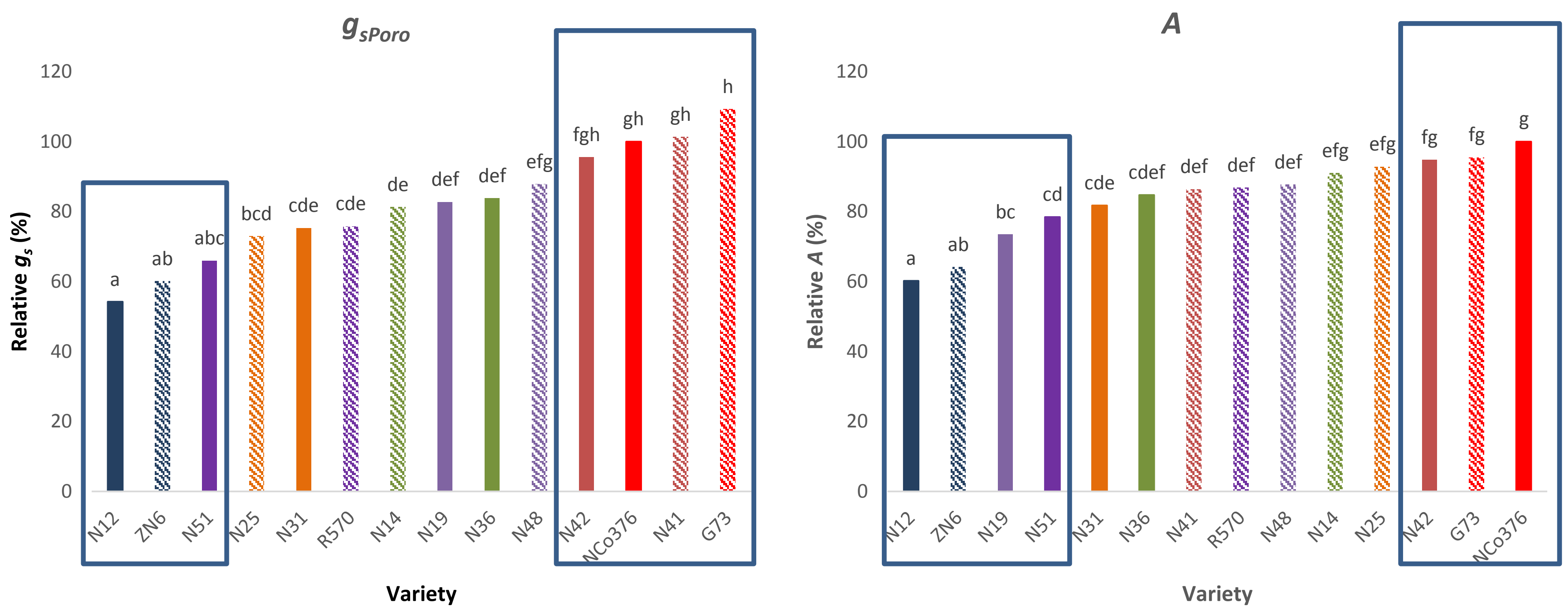
Eksteen *et al.* (2014): Data on N19 and 04G0073

Smit& Singels (2006): Data on NCo376 and N22

Singels *et al.* (2002); Singels *et al.* (2010): Data on NCo376

Trait parameter estimation: Pot trial data

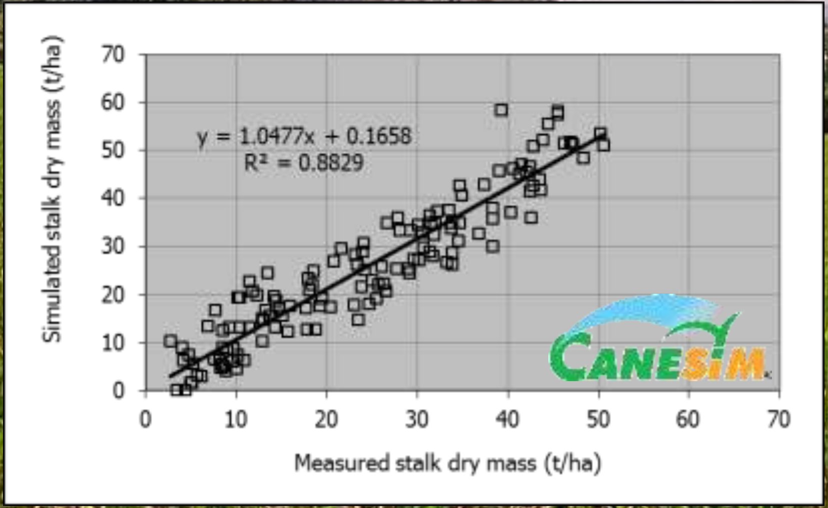
RUEo from leaf level *A* and g_s measurements (Hoffman et al., 2015)



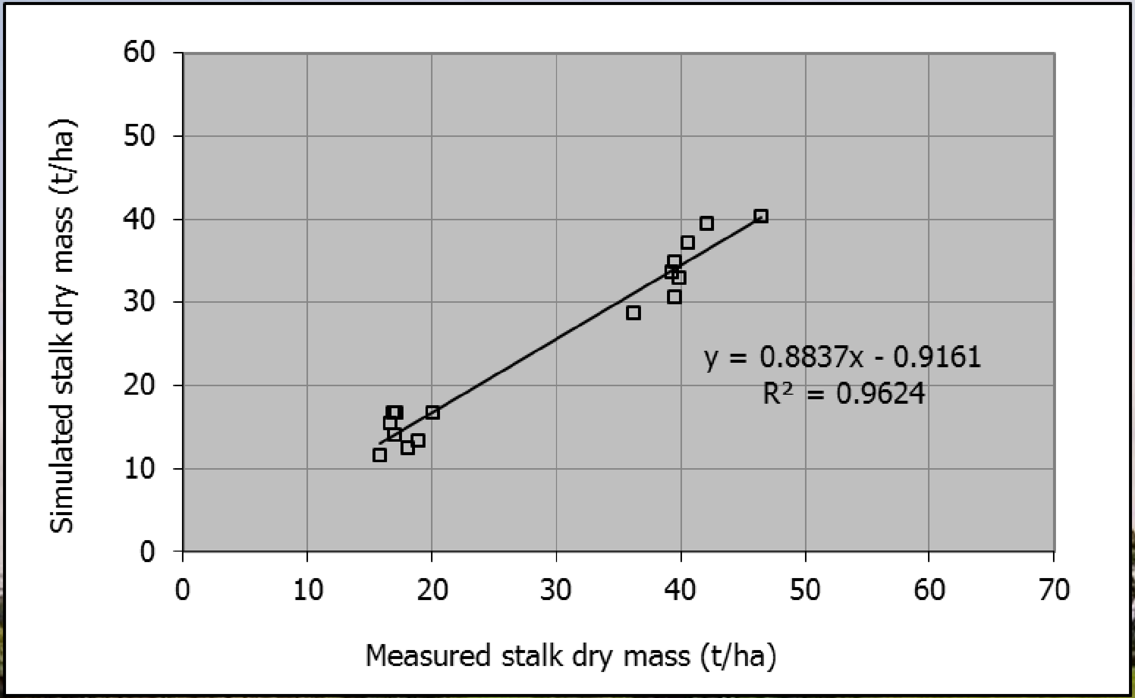
- Good agreement between *A* and g_{sporo} values (R^2=0.62) and rankings (R^2=0.48)
- Large genetic variation

Trait parameter estimation

Variety	NCo376
TT50 (^oCd)	250
TTsg (^oCd)	1000
RUEo (g/MJ)	2.25
Estress	0.45



Field validation: Stalk dry mass



	Observations			Simulations		Rank R
Field trial	Ave (t/ha)	Range (t/ha)	LSD (t/ha)	Ave (t/ha)	Range (t/ha)	
Pongola	40.4	10.2	6.0	37.6	14.5	0.74*
Gingindlovu	17.6	4.2	4.9	13.8	4.1	0.15

Trait impacts on stalk yield

	Pongola		Gingindlovu	
	Obs	Sim	Obs	Sim
TT50	-0.376	-0.467	-0.728*	-0.301
TTsg	-0.603	-0.841*	-0.449	-0.786*
RUEo	0.809*	0.993*	0.275	0.991*
Estress	0.122	-0.007	0.523	-0.125

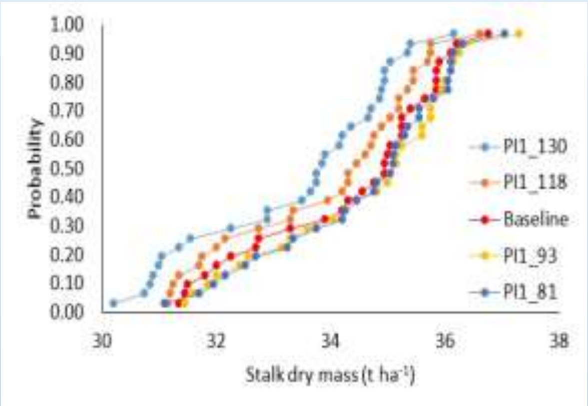
- Observed yields correlate with RUEo (well-watered) and TT50 (water stressed)
- Simulated yields correlated strongly with RUEo and TTsg

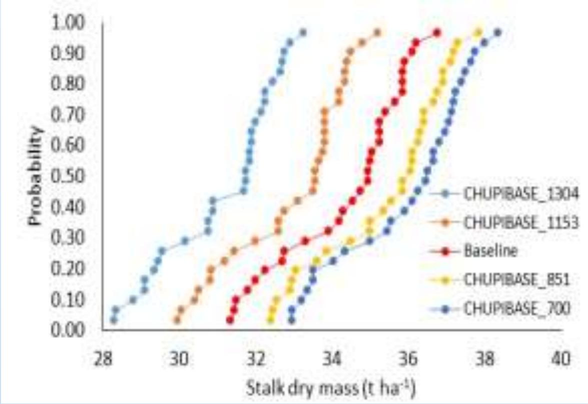
Canesim parameterization: Conclusions

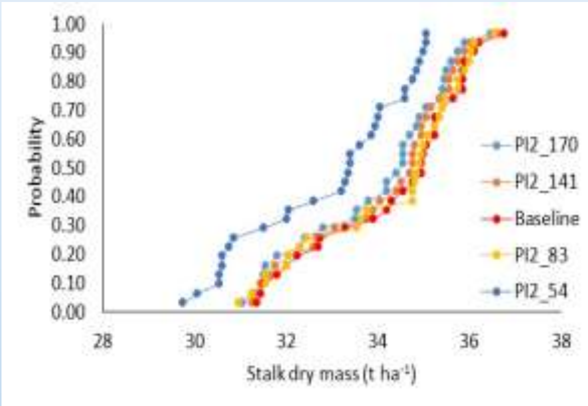
- Genotype yield differences under well-watered conditions predicted well from independent trait parameter estimations
- The validity of drought coping traits could not be assessed reliably
- Phenotyping approach (combining experimental measurements with subjective observations) holds promise
- Better grasp of ranges for key parameters
- Canopy development and photosynthetic efficiency are potential traits for screening genotypes for irrigated environments

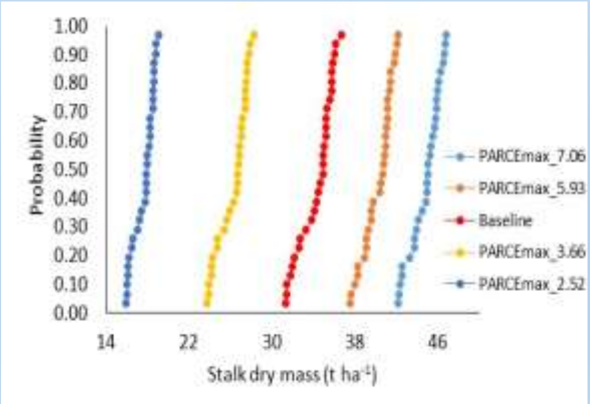
Model application: 4.Ideotyping

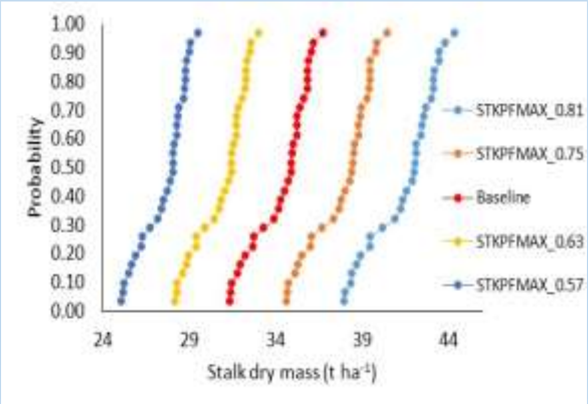
(Hoffman)

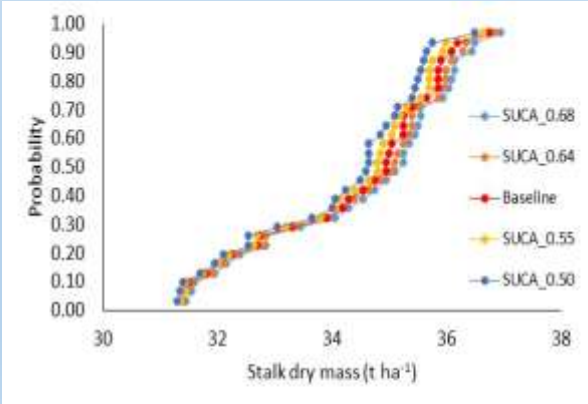








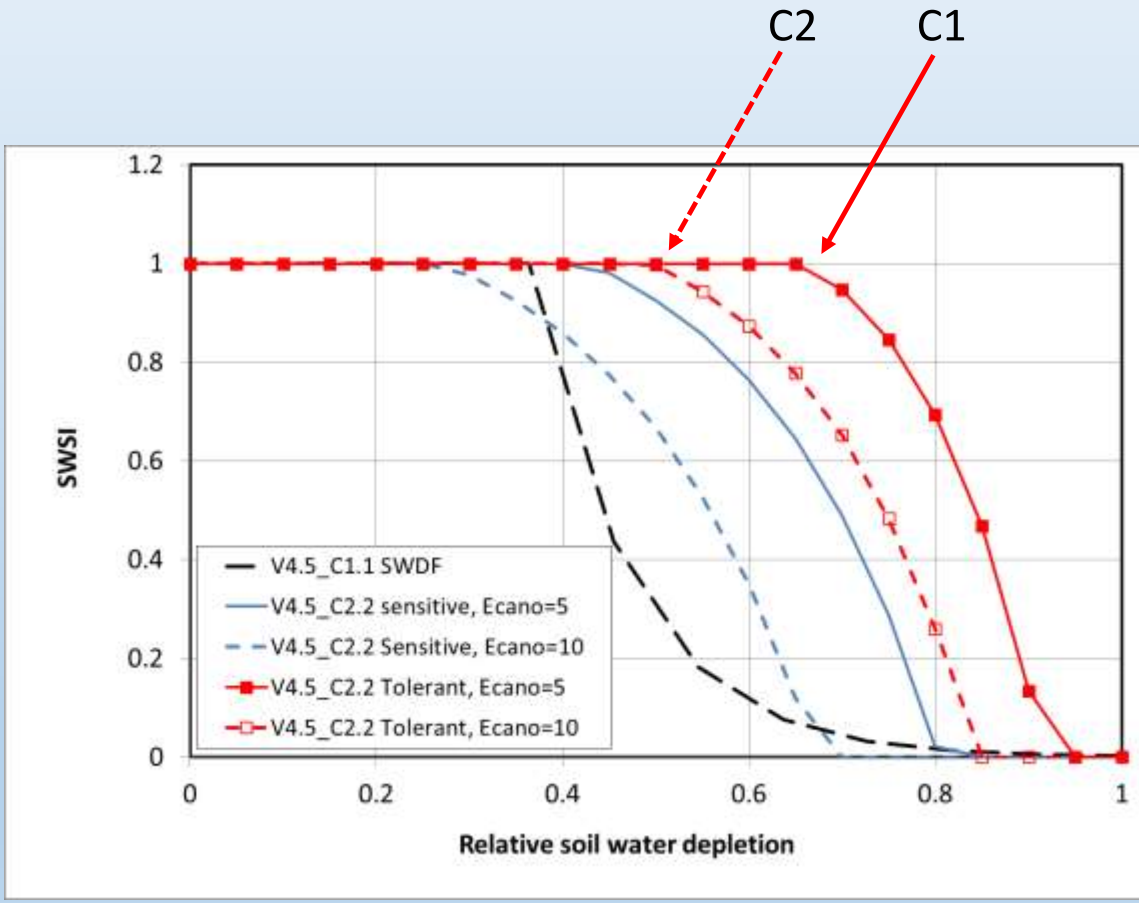




Model application: Ideotyping for the future

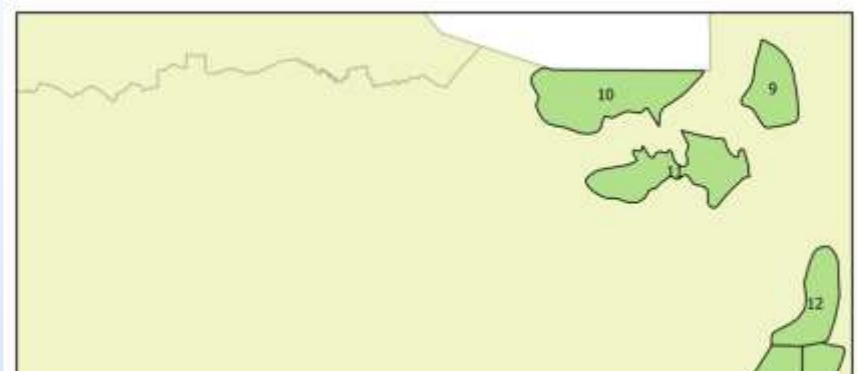
Jones

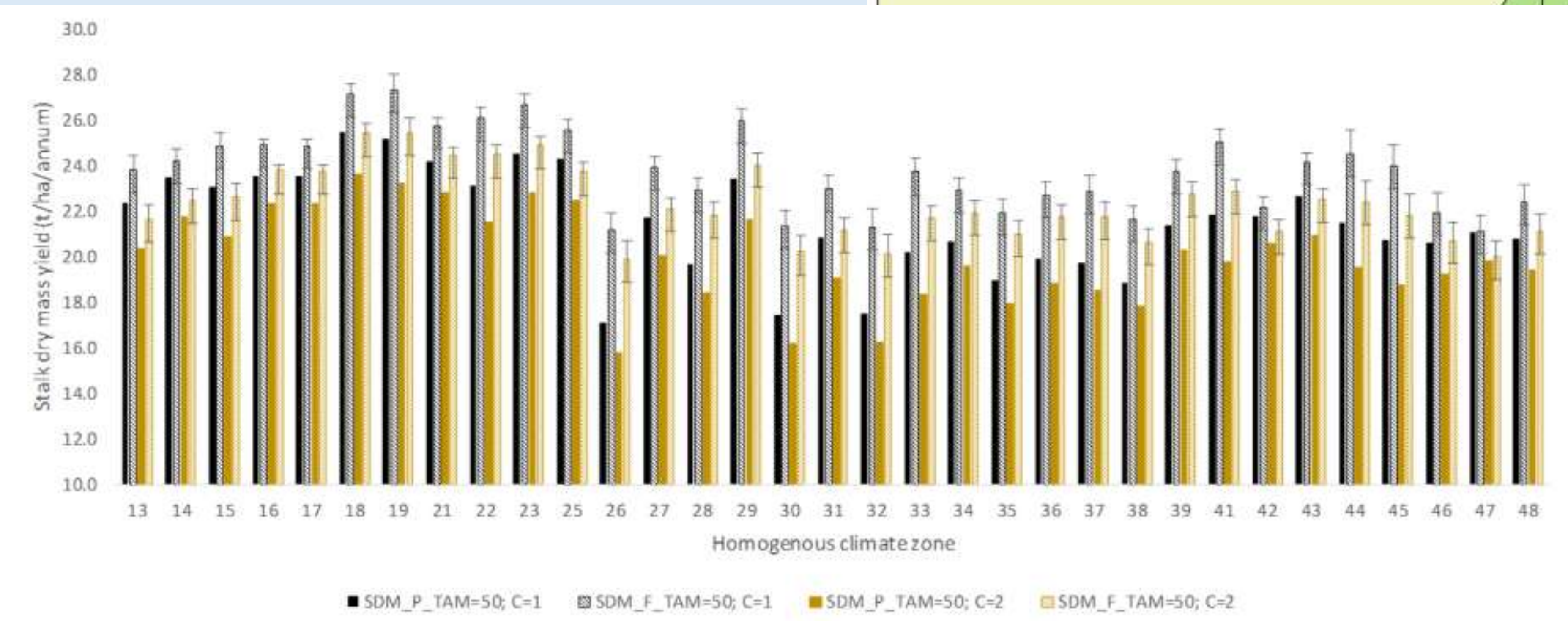
- What is the ideal drought coping trait values for different agro-climatic situations in South Africa?
- Drought sensitivity coefficient: The soil water depletion fraction below which transpiration and photosynthesis rates are reduced at the reference atmospheric evaporative demand of 5 mm/d
- C1 (tolerant)
  - AQP_UP5=0.65
- C2 (sensitive)
  - AQP_UP5=0.45

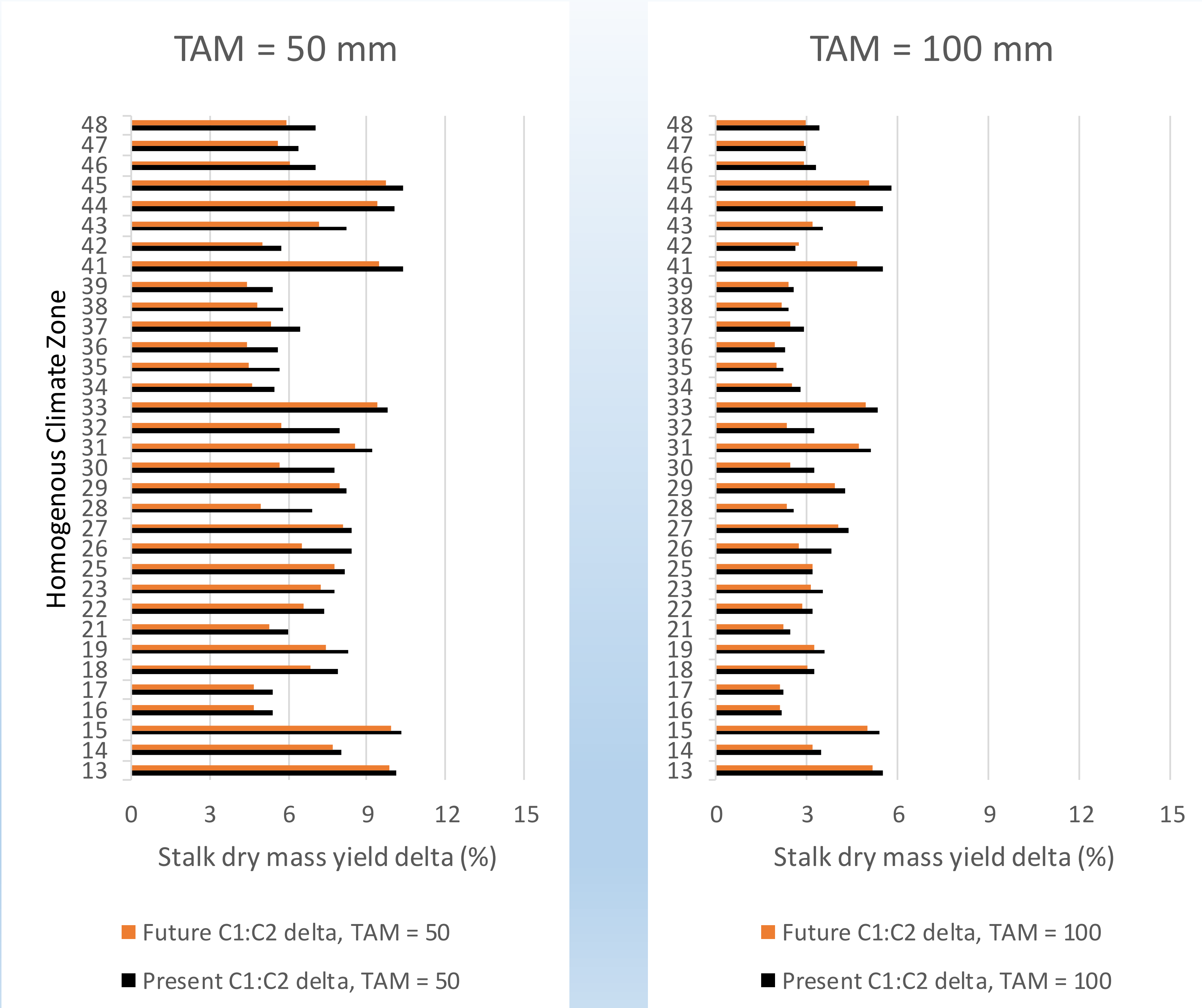


Model application: Ideotyping for the future

Jones







TAM = 50 mm
Homogenous Climate Zone
48
47
46
45
44
43
42
41
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38
37
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33
32
31
30
29
28
27
26
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21
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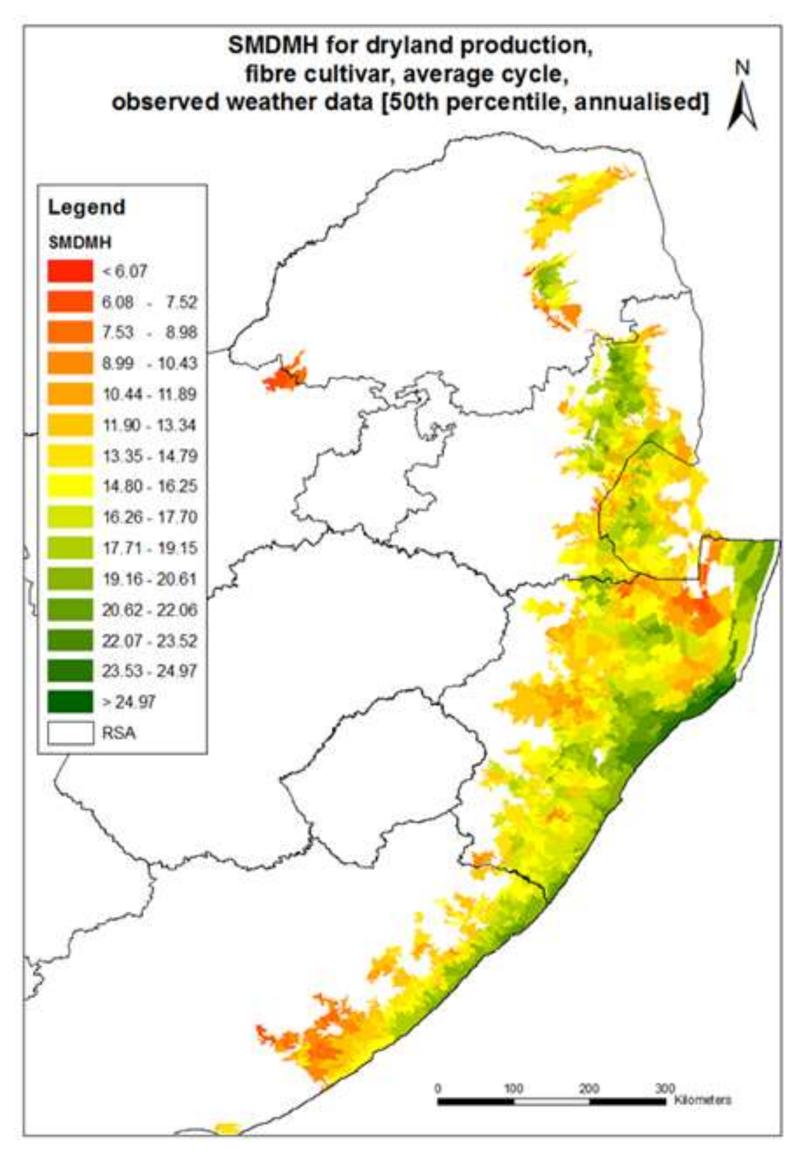
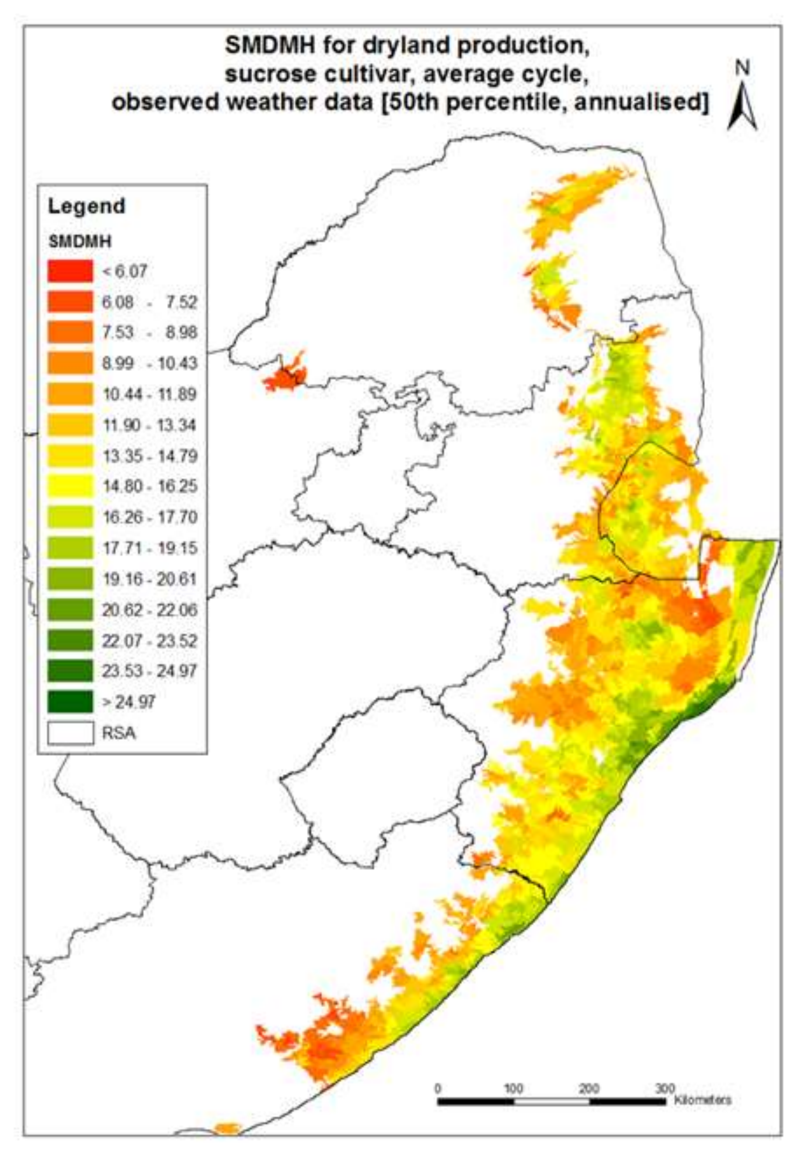
18
17
16
15
14
13
0
3
6
9
12
15
Stalk dry mass yield delta (%)
Future C1:C2 delta, TAM = 50
Present C1:C2 delta, TAM = 50
TAM = 100 mm
0
3
6
9
12
15
Stalk dry mass yield delta (%)
Future C1:C2 delta, TAM = 100
Present C1:C2 delta, TAM = 100

Model application
High fibre (Drought tolerant, high RUE) vs High sucrose





SASRI trait modelling: Conclusions

- Potential value demonstrated
- Models improved but requires further refinement to realize full potential for breeding support
- Key traits identified
- Promise of rapid phenotyping for RUE

CANESIM®

- Model features
  - Canopy cover driven by thermal time and crop water status
  - Multi-layered soil water balance with Penman evapotranspiration and Aquacrop water stress approach
  - Biomass growth based on intercepted radiation conversion and crop water status
  - Biomass partitioning based on development stage, temperature and crop water status
- Inputs
  - Daily weather data
  - Soil water holding capacity and drainage properties
  - Cropping dates, row spacing, ratoon class, soil cover, irrigation data
  - Trait parameters: Thermal time requirements (3), RUEo, biomass partition fractions (3), drought tolerance (1), lodging tolerance (1)

http://www.canesim.co.za/

Unlocking the potential of sugarcane

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Aim

Question

Can trait parameter values derived from experimental data and subjective observations predict field performance of sugarcane genotypes?

Objective

Use the Canesim model with parameter values estimated from experimental data and expert ratings

to

predict stalk dry mass for eight genotypes in two environments in South Africa