Using crop model ensembles to design future climate-resilient barley cultivars

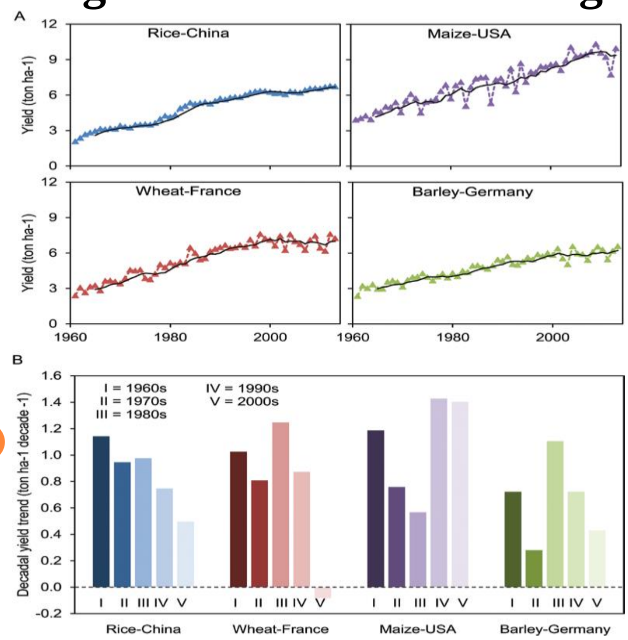
Fulu Tao[1,*], Reimund P. Rötter[1], Taru Palosuo[1], C. G. Hernández[2], M.I. Mínguez[2], Mikhail Semenov[3], Kurt Christian Kersebaum[4], Claas Nendel[4], Davide Cammarano[5], Holger Hoffmann[6], Frank Ewert[6], Anaelle Dambreville[7,8], Pierre Martre[7,8], Lucía Rodríguez[2], Margarita Ruiz-Ramos[2], Thomas Gaiser[6], Jukka G. Höhn[1], Tapio Salo[1], Roberto Ferrise[9], Marco Bindi[9] and Alan Schulman[10]

Challenges for food security in future

- Global demand for agricultural production is expected to roughly double by 2050.

- However, crop yield growth rates have been stagnating in the last decade in some important agricultural regions around the world

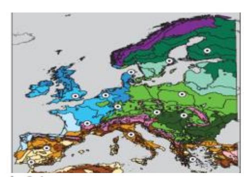
Crop yield growth rates become stagnated

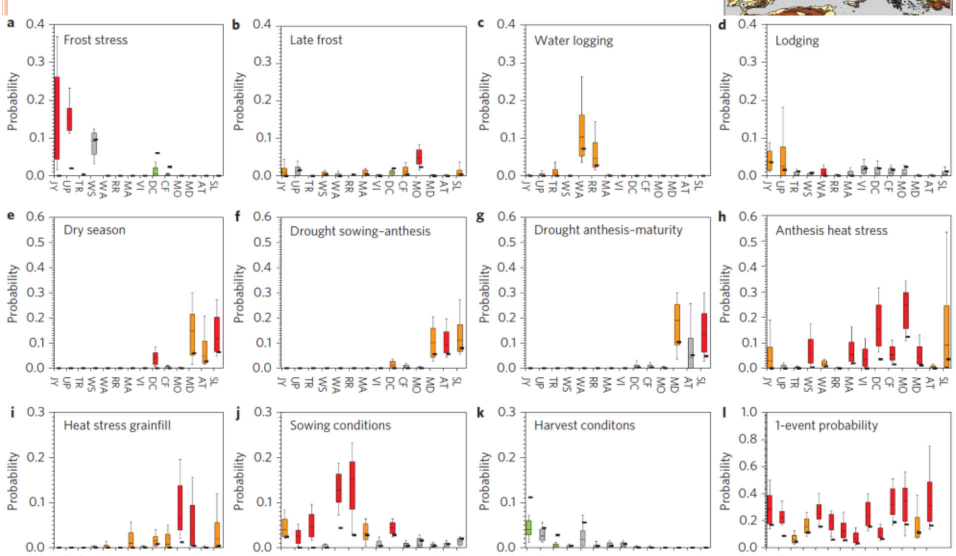


Lobell and Gourdji, 2012

Adverse weather conditions for European wheat production will become more frequent with climate change

Miroslav Trnka[1,2]*, Reimund P. Rötter[3], Margarita Ruiz-Ramos[4], Kurt Christian Kersebaum[5], Jørgen E. Olesen[6], Zdeněk Žalud[1,2] and Mikhail A. Semenov[7]





Adaptation Strategies

- Varieties development and improved agronomic practices are major climate change adaptation options in agriculture.

- Have proven track records in achieving more resilience to climate variability and extremes in the past decades.

  - Climate-smart crop varieties
  - Climate-smart agronomic management

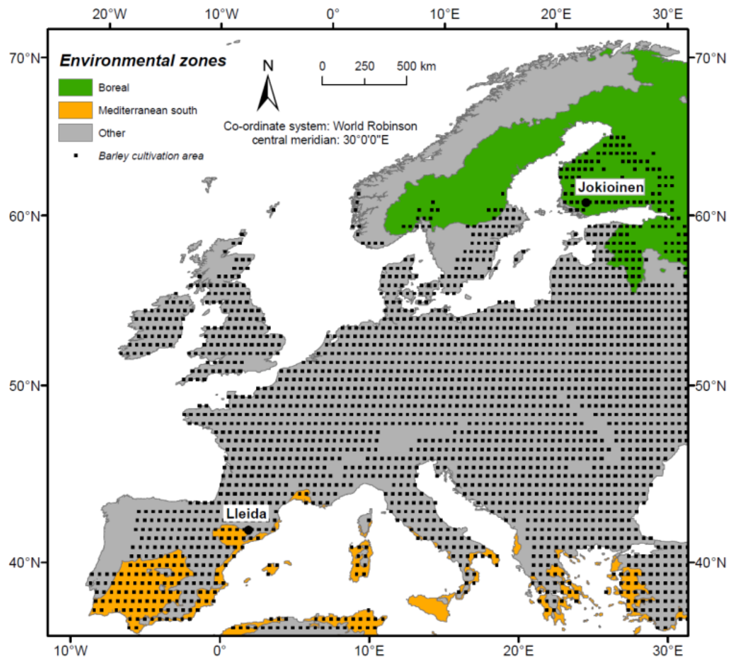
Barley Cultivar Design (BCD) study

- One of activities carried out in the context of CropM within the FACCE-MACSUR knowledge hub

- Take barley as an example because:
  - Barley is an important crop throughout the world;
  - It is emerging as a model crop for studying the genetics of stress adaptation.

- Designing future barley ideotypes using crop model ensemble, for the first time.

Study sites of the BCD study



Crop models involved

Model (version)	Reference	Documentation
APSIM (V.7.7)	Keating et al., 2003	http://www.apsim.info/Wiki/
CropSyst (V 3.02)	Stockle et al., 2003	http://www.bsyse.wsu.edu/CS_Suite/CropSyst/index.html
HERMES (V4.26)	Kersebaum, 2007, 2011	http://www.zalf.de/en/forschung/institute/lsa/forschung/oekomod/hermes
MCWLA (V2.0)	Tao et al., 2009, 2013	Request from fulu.tao@luke.fi
MONICA (V1.2.5)	Nendel et al., 2011	http://monica.agrosystem-models.com
SIMPLACE<Lintul2, Slim>	Addiscott and Whitmore, 1991; Angulo et al., 2013	www.simplace.net/, http://models.pps.wur.nl/models
SiriusQuality (V2.0)	Martre et al., 2006; Ferrise et al., 2010	Request from pierre.martre@clermont.inra.fr
WOFOST (V7.1)	Boogaard et al., 1998	http://www.wofost.wur.nl

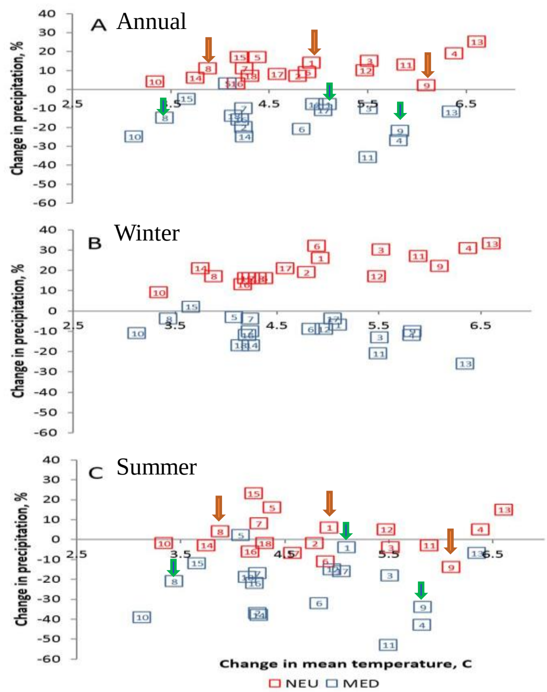
Three representative Climate scenarios:

GCMs:
ACCESS(1), (medium)
GISS(8), (cold)
HadGEM(9) (hot dry)

Time period:
2050s

Emission scenario:
RCP8.5,
$[CO_2]$ = 560ppm

➢ A reference for possible futures with high greenhouse gas emissions.



Field Experiment Data for Model Calibration and Validation

Experimental year	Jokioinen, May-Aug	Lleida, Nov-Jul
Mean growing season temperature	2002 (15.6) 2009 (14.0)	1997 (12.6) 1998 (11.9) 1999 (11.7)
Mean growing season precipitation	2002 (206.6) 2009 (200.7)	1997 (371.0) 1998 (191.9) 1999 (255.7)
Baseline		
Mean growing season temperature (°C)	13.6	11.5
Mean growing season precipitation (mm)	252.4	227.3
Climate change scenario		
Mean growing season temperature (°C)	ACCESS (16.2), GISS (16.1) HadGEM (17.0)	ACCESS (14.1) GISS (12.8) HadGEM (13.9)
Mean growing season precipitation (mm)	ACCESS (284.0) GISS (266.3) HadGEM (257.4)	ACCESS (185.8) GISS (225.9) HadGEM (225.3)

Analytical steps of the BCD study

Step 1. Define the most important crop parameters of the simulation model related to key growth and yield formation processes

Step 2. Define potential value ranges for each selected parameter based on what is considered to be possible within the given time frame.

Step 3. Perform simultaneous crop parameter perturbations using an orthogonal sampling approach

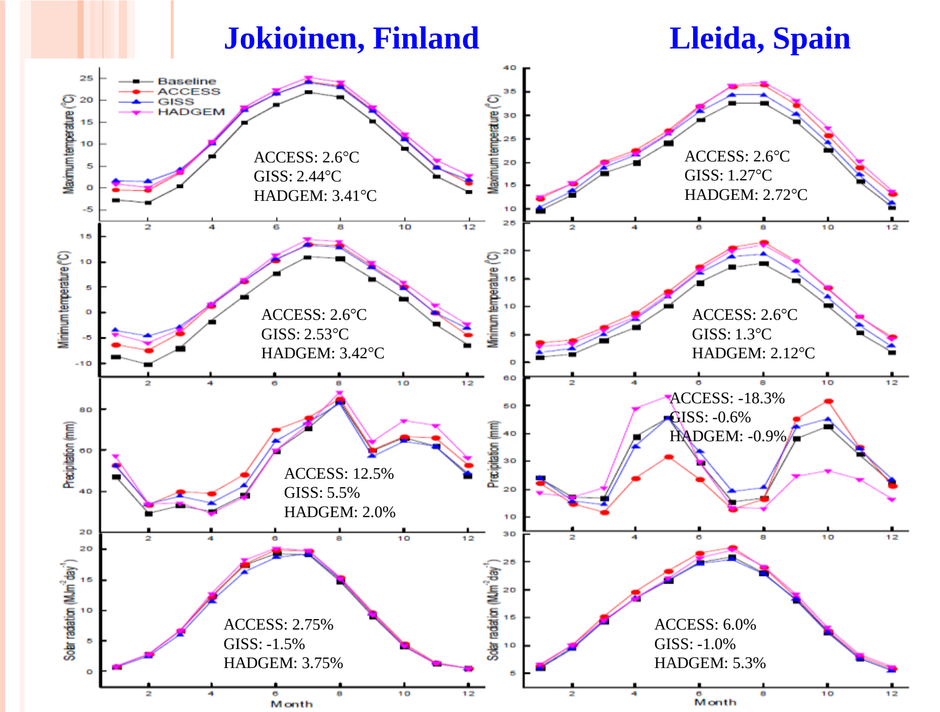
Step 4. Run simulations for baseline climate and for three different future climates using perturbed parameter sets.

Step 5. Optimize parameters: this leads to the identification of ideotypes.

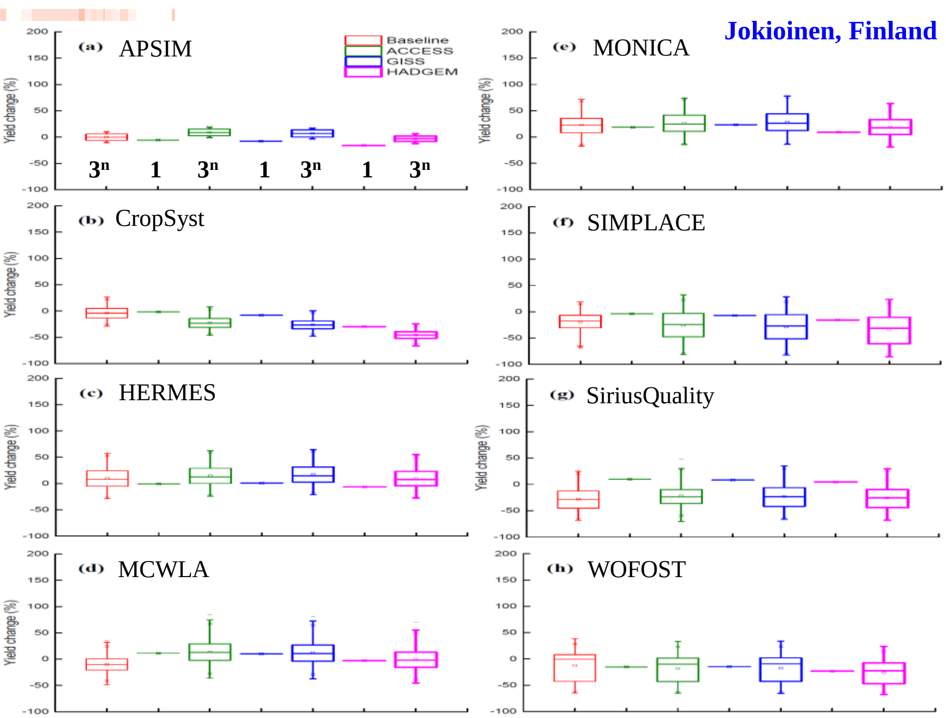
Step 6. Perform post-model synthesis: identify desirable ideotypes

Selected key parameters and their potential value ranges

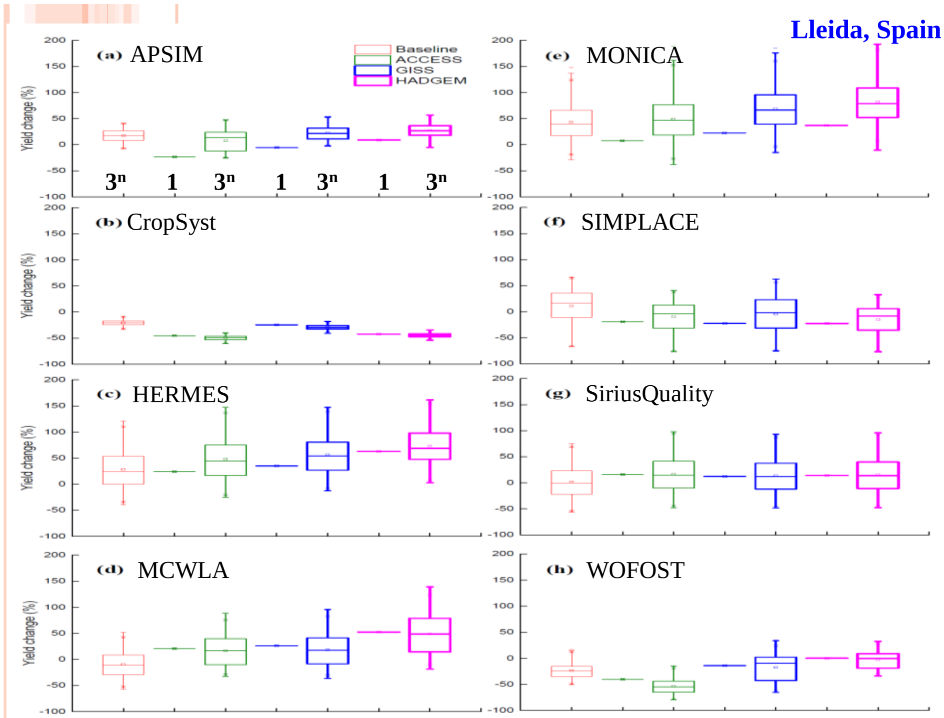
Model	Model parameters	Explainations of the parameters	Parameter value for Jokioinen		Parameter value for Lleida	
			Value range	Calibrated value for baseline	Value range	Calibrated value for baseline
APSIM	photop_sens	Photoperiod response	2.0-5.0	3.5	2.0-5.0	3.5
	vern_sens	Vernalization response	0.5-1.5	1	0.5-1.5	1
	y_node_app_rate(2)	node phyllochron	67.5-82.5	75	90-110	100
	y_rue(3)	Radiation use efficiency for each phenological stage	1.116-1.364	1.24	1.116-1.364	1.24
	y_co2_te_modifier(2)	Factor of CO_2 effects in C3 crops	1.233-1.507	1.37	1.233-1.507	1.37
	transp_eff_cf(3)	Transpiration efficiency coefficient	0.00525-0.00675	0.006	0.00525-0.00675	0.006
	max_grain_size	Maximum grain size	0.085-0.115	0.1	0.05525-0.07475	0.065
	grains_per_gram_stem	Grains per gram of stem	28-36	32	21.875-28.125	25

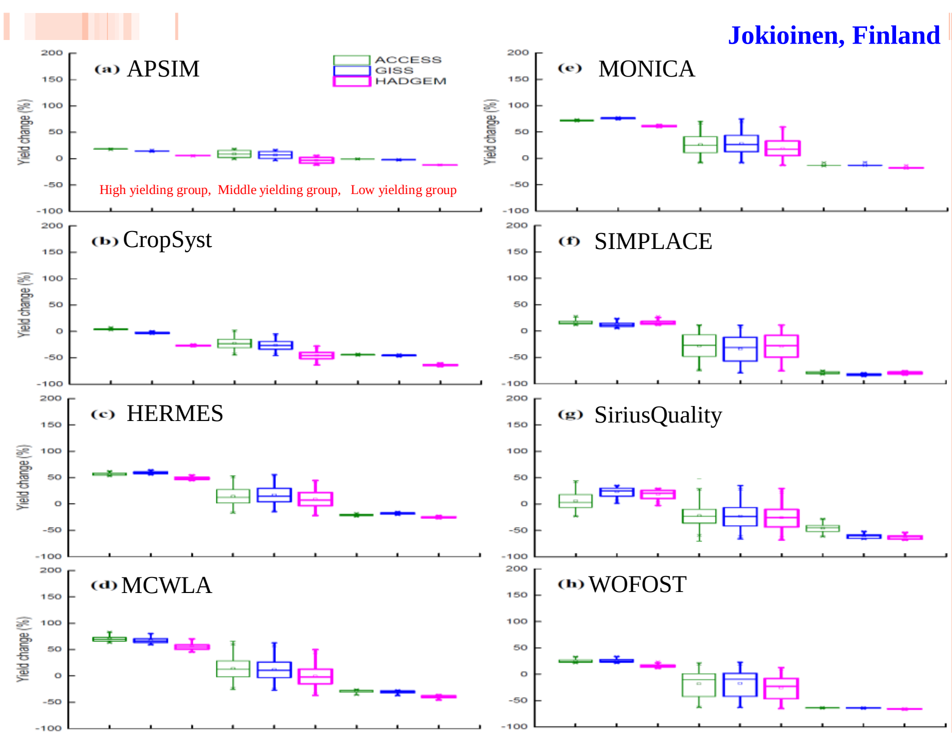


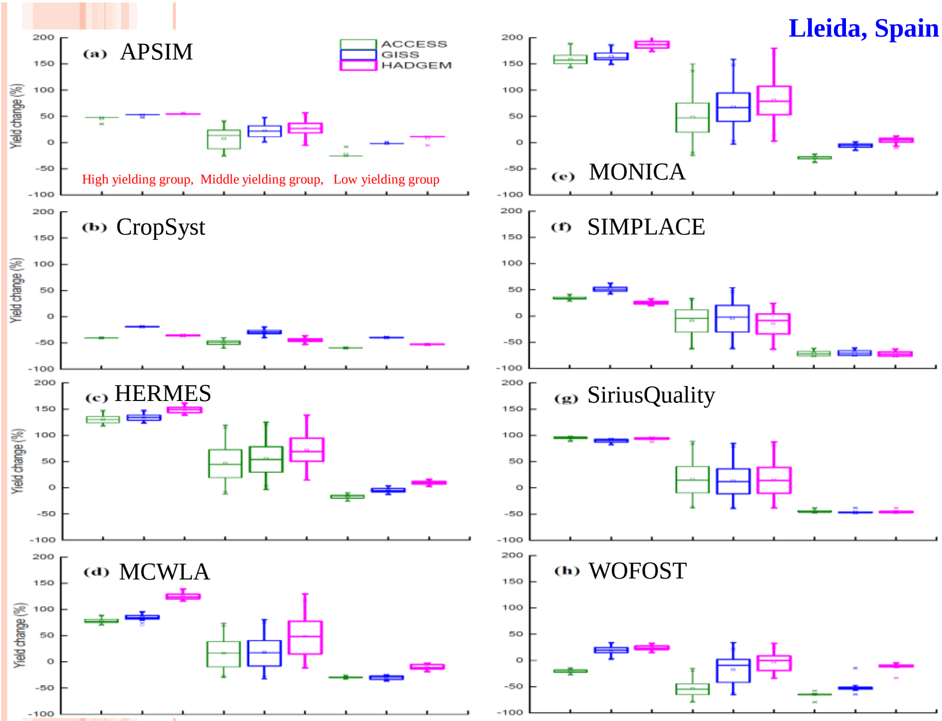
Jokioinen, Finland
Lleida, Spain
Baseline
ACCESS
GISS
HADGEM
ACCESS: 2.6°C
GISS: 2.44°C
HADGEM: 3.41°C
ACCESS: 2.6°C
GISS: 1.27°C
HADGEM: 2.72°C
ACCESS: 2.6°C
GISS: 2.53°C
HADGEM: 3.42°C
ACCESS: 2.6°C
GISS: 1.3°C
HADGEM: 2.12°C
ACCESS: 12.5%
GISS: 5.5%
HADGEM: 2.0%
ACCESS: -18.3%
GISS: -0.6%
HADGEM: -0.9%
ACCESS: 2.75%
GISS: -1.5%
HADGEM: 3.75%
ACCESS: 6.0%
GISS: -1.0%
HADGEM: 5.3%
Maximum temperature (°C)
Minimum temperature (°C)
Precipitation (mm)
Solar radiation (MJm⁻²day⁻¹)
Month



Jokioinen, Finland
(a) APSIM
(b) CropSyst
(c) HERMES
(d) MCWLA
(e) MONICA
(f) SIMPLACE
(g) SiriusQuality
(h) WOFOST
Baseline
ACCESS
GISS
HADGEM
3n
1
3n
1
3n
1
3n
Yield change (%)


Lleida, Spain
(a) APSIM
Baseline
ACCESS
GISS
HADGEM
3n 1 3n 1 3n 1 3n
(b) CropSyst
(c) HERMES
(d) MCWLA
(e) MONICA
(f) SIMPLACE
(g) SiriusQuality
(h) WOFOST
Yield change (%)


Jokioinen, Finland
(a) APSIM
ACCESS
GISS
HADGEM
High yielding group, Middle yielding group, Low yielding group
(b) CropSyst
(c) HERMES
(d) MCWLA
(e) MONICA
(f) SIMPLACE
(g) SiriusQuality
(h) WOFOST
Yield change (%)



Identifying the ideotypic traits under future climate scenarios, Finland

		High yielding group		Middle yielding group		Low yielding group		Baseline
	Parameter	Mean	Std	Mean	Std	Mean	Std	Mean
APSIM	photop_sens	4.0500	0.7437	3.4844	0.8155	3.9400	0.6247	3.5
	vern_sens	1.2937	0.1038	1.0005	0.2677	0.6733	0.0330	1
	y_node_app_rate(2)	77.7500	3.2079	74.9544	4.0774	75.1500	4.2909	75
	y_rue(3)	1.3227	0.0000	1.2400	0.0670	1.1606	0.0201	1.24
	y_co2_te_modifier(2)	1.3271	0.0629	1.3710	0.0746	1.3481	0.0676	1.37
	transp_eff_cf(3)	0.0060	0.0004	0.0060	0.0004	0.0060	0.0004	0.006
	max_grain_size	0.0999	0.0082	0.1000	0.0082	0.0998	0.0083	0.1
	grains_per_gram_stem	32.4801	2.2227	32.0126	2.1729	30.6665	1.9879	32
CropSyst	GDD_Flw	782.6684	16.7356	799.7485	27.1548	833.3300	0.0000	750
	GDD_Mty	1358.9910	27.5393	1349.9738	27.1540	1342.6740	27.0158	1350
	LAImax	5.9933	0.5484	6.0000	0.5444	6.0067	0.5484	5
	LWP_red	-1281.3130	80.1481	-1199.8533	108.6976	-1128.0180	87.6874	-1200
	RUE	2.8203	0.1041	2.6490	0.1903	2.5450	0.1637	2.8
	C_TB	6.6667	0.0000	6.1998	0.3782	5.7473	0.0800	6.7
	MWU	9.3734	0.4165	8.9982	0.5440	8.7400	0.4914	8.6
	HI	0.5667	0.0000	0.5000	0.0540	0.4333	0.0000	0.53
HERMES	Tsum1	128.4000	24.3385	135.0453	24.4115	140.7000	25.1161	148
	Tsum3	308.3300	0.0000	425.0000	92.8560	541.6700	0.0000	575
	Tsum4	154.6666	13.6069	155.0252	13.6161	154.8333	13.7127	130

	Tsum5	453.3300	0.0000	360.0000	74.2800	266.6700	0.0000	240
	DL	16.9603	0.5550	17.9980	1.0781	19.0797	0.5256	20
	A_{max}	50.7167	1.3331	50.4933	1.3621	50.4167	1.3688	48
	Scr(5)	0.4940	0.0545	0.5000	0.0545	0.5040	0.0543	0.6
MCWLA	R_{maxwg2}	0.0287	0.0072	0.0380	0.0108	0.0482	0.0056	0.038
	R_{maxg}	0.0288	0.0013	0.0420	0.0108	0.0545	0.0032	0.042
	L_{AImax}	7.0300	0.2725	7.0001	0.2722	6.9667	0.2701	7
	L_{AIdg}	0.5400	0.0994	0.5002	0.1088	0.4454	0.1004	0.5
	T_{Tmax}	6.7520	0.5723	5.7418	1.0844	4.5254	0.3835	5.7387
	α (Intrinsic quantum efficiency of CO_2 uptake)	0.0851	0.0029	0.0800	0.0055	0.0762	0.0043	0.08
	S_{cr}	0.4887	0.0553	0.5000	0.0544	0.5113	0.0537	0.4667
	HI	0.6054	0.0094	0.5400	0.0541	0.4760	0.0131	0.54
MONICA	Tsum3	233.3300	0.0000	300.0000	54.0105	366.6700	0.0000	280
	Tsum5	431.0000	39.4277	349.9371	81.3603	273.0000	48.9382	290
	LAI3	0.0025	0.0007	0.0023	0.0007	0.0021	0.0007	0.0019
	A_{max}	46.7000	5.3286	39.9607	8.1523	35.8000	7.5452	30
	kc3	0.6770	0.0863	0.9496	0.2433	1.2500	0.0000	1
	kc5	0.8030	0.2110	0.9506	0.2448	1.0580	0.2237	0.8
	Scr3	0.6477	0.1919	0.6499	0.1905	0.6593	0.1903	0.8
	Scr5	0.4820	0.1199	0.6495	0.1898	0.8483	0.0837	0.6
SIMPLACE	AirTemperatureSumAnthesis	911.6790	80.8889	855.2949	135.8408	683.3300	0.0000	861.5
	AirTemperatureSumMaturity	1509.3060	51.4702	1394.9015	108.1418	1392.0020	108.5418	1440
	RGRL	0.0221	0.0020	0.0201	0.0027	0.0167	0.0000	0.02

Identifying the ideotypic traits under future climate scenarios, Spain

		High yielding group		Middle yielding group		Low yielding group		Baseline
	Parameter	Mean	Std	Mean	Std	Mean	Std	Mean
APSIM	photop_sens	2.6900	0.3943	3.5030	0.8120	4.1200	0.7886	3.5
	vern_sens	0.9802	0.2604	0.9998	0.2697	1.0297	0.2616	1
	y_node_app_rate(2)	101.8016	5.5150	99.9821	5.4422	99.4008	5.2853	75
	y_rue(3)	1.2971	0.0584	1.2403	0.0671	1.1614	0.0181	1.24
	y_co2_te_modifier(2)	1.3727	0.0751	1.3700	0.0746	1.3691	0.0740	1.37
	transp_eff_cf(3)	0.0060	0.0004	0.0060	0.0004	0.0060	0.0004	0.006
	max_grain_size	0.0687	0.0048	0.0650	0.0053	0.0592	0.0028	0.065
	grains_per_gram_stem	26.1040	1.5513	25.0115	1.6913	23.1253	0.8632	25
CropSyst	GDD_Flw	1193.9970	54.5387	1199.7169	54.4660	1224.0120	48.8214	1600
	GDD_Mty	2272.4810	49.1813	2225.0393	67.9740	2175.0200	50.2318	2270
	LAImax	5.9867	0.5442	6.0001	0.5444	6.0067	0.5484	6
	LWP_red	-1598.0000	131.7942	-1499.3083	163.2593	-1446.0000	157.9029	-1200
	RUE	2.8833	0.0000	2.6500	0.1890	2.4167	0.0000	2.56
	C_TB	6.6667	0.0000	6.2000	0.3781	5.7333	0.0000	6.7
	MWU	9.1133	0.5530	9.0005	0.5439	8.8533	0.5409	8.5
	HI	0.4667	0.0000	0.4000	0.0540	0.3333	0.0000	0.42
HERMES	Tsum1	129.9000	24.5153	135.0302	24.4579	139.5000	24.6337	110
	Tsum3	308.3300	0.0000	425.0000	92.8560	541.6700	0.0000	285
	Tsum4	154.1665	13.6881	155.0336	13.6110	155.1667	13.7127	145
	Tsum5	453.3300	0.0000	360.0000	74.2800	266.6700	0.0000	425

	DL	16.9336	0.5359	17.9993	1.0772	19.0797	0.5256	17
	A_{max}	50.6167	1.3664	50.4992	1.3616	50.4000	1.3574	48
	Scr(5)	0.4913	0.0542	0.4999	0.0545	0.5087	0.0542	0.5
MCWLA	R_{maxvg2}	0.0261	0.0051	0.0219	0.0082	0.0225	0.0095	0.022
	R_{maxrg}	0.0288	0.0027	0.0380	0.0081	0.0457	0.0049	0.038
	L_{AImax}	7.0200	0.2755	7.0000	0.2721	6.9800	0.2714	7
	L_{AIdg}	0.5560	0.0988	0.5000	0.1087	0.4454	0.1022	0.5
	T_{Tmax}	6.8853	0.4650	5.7412	1.0822	4.4321	0.1876	5.7387
	α (Intrinsic quantum efficiency of CO_2 uptake)	0.0907	0.0030	0.0857	0.0055	0.0799	0.0023	0.0857
	S_{cr}	0.4873	0.0525	0.5000	0.0545	0.5133	0.0545	0.4667
	HI	0.3067	0.0000	0.2400	0.0540	0.1733	0.0000	0.24
MONICA	Tsum3	233.3300	0.0000	300.1677	54.1137	356.0028	24.5648	360
	Tsum5	450.0000	0.0000	350.0000	81.0117	250.0000	0.0000	290
	LAI3	0.0029	0.0003	0.0023	0.0007	0.0014	0.0002	0.0019
	A_{max}	50.0000	0.0000	40.0000	8.1012	30.0000	0.0000	30
	kc3	0.8810	0.2369	0.9502	0.2448	1.0070	0.2512	1
	kc5	0.8990	0.2414	0.9504	0.2449	0.9770	0.2490	0.8
	Scr3	0.6477	0.1919	0.6500	0.1905	0.6523	0.1919	0.8
	Scr5	0.6220	0.1884	0.6500	0.1905	0.6710	0.1936	0.6
SIMPLACE	AirTemperatureSumAnthesis	1219.9950	58.0114	1204.6289	109.9270	1088.0280	49.1148	1221
	AirTemperatureSumMaturity	1715.8450	81.8918	1673.5904	95.4904	1662.1630	95.1334	1677
	RGRL	0.0048	0.0007	0.0040	0.0011	0.0027	0.0000	0.004
	SLA	0.0319	0.0016	0.0275	0.0040	0.0227	0.0009	0.023
	LUE	3.0053	0.0546	2.8960	0.1080	2.8747	0.1116	2.9

Future climate resilient barley ideotype

For Boreal climatic zones

Phenology:

- a larger thermal time from anthesis to physiological maturity.
- have a smaller thermal time before anthesis.
- have a small photoperiod and high vernalization sensitivity

Leaf area: a large SLA, maximum LAI, and low senescence rate

Photosynthesis: have a larger A_{max} or RUE

Drought resistance: have a higher water use efficiency, drought stress resistance, and maximum rooting depth

Yield formation: have a larger grain number, grain size and HI

Future climate resilient barley ideotype
For Mediterranean climatic zones

Phenology:

- a larger thermal time from anthesis to physiological maturity.
- have a smaller thermal time before anthesis.
- A small photoperiod and vernalization sensitivity at Lleida.

Leaf area: a large SLA, maximum LAI, and low senescence rate

Photosynthesis: have a larger A_{max} or RUE

Drought resistance: have a higher water use efficiency, drought stress resistance, and maximum rooting depth. Drought-resistant trait is more desirable at Lleida in comparison with Jokioinen.

Future development

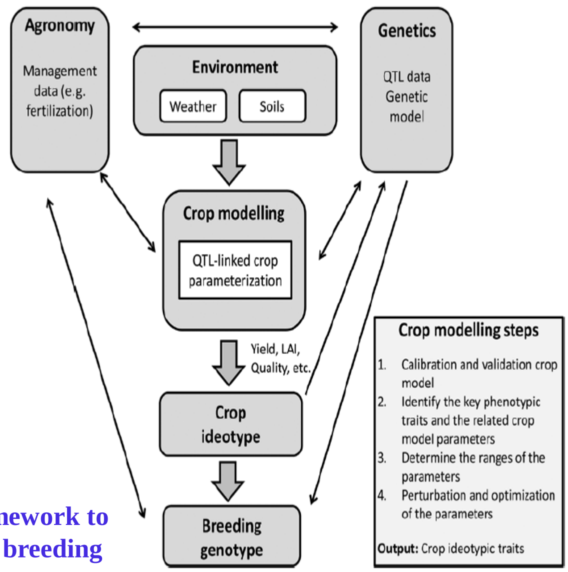
- Improving simulation models to better account for some key cultivar traits, such as three-dimensional canopy structure, heat, frost and water-logging stress resistance
- The interactions between genotype, management and environment (G×M×E).
- The challenges are the integrations between agronomists, genetics, breeders and crop modelers

Journal of Experimental Botany, Vol. 66, No. 12 pp. 3463–3476, 2015
doi:10.1093/jxb/erv098 Advance Access publication 20 March 2015

REVIEW PAPER

Use of crop simulation modelling to aid ideotype design of future cereal cultivars

R. P. Rötter*, F. Tao, J. G. Höhn and T. Palosuo
Natural Resources Institute Finland (Luke), 00790 Helsinki, Finland



Model-based framework to support effective breeding

Thanks for attention !