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Reactions of maize towards drought and management implications

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- drought induced changes in maize
  - during vegetative growth
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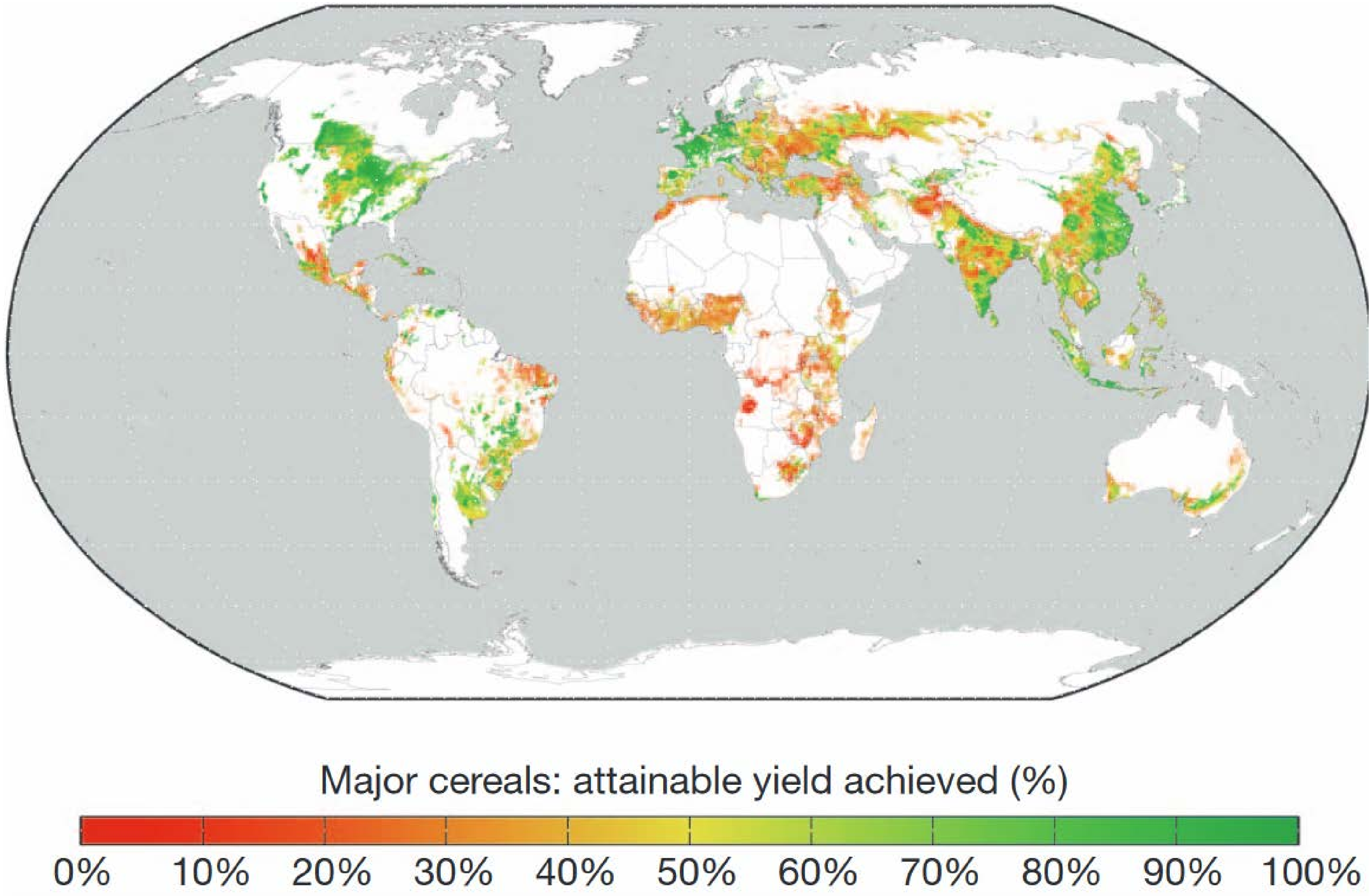
Closing global yield gaps



source: Mueller et al. (2012) Nature Vol. 490

heat wave 2018 (May – July)

temperature | precipitation

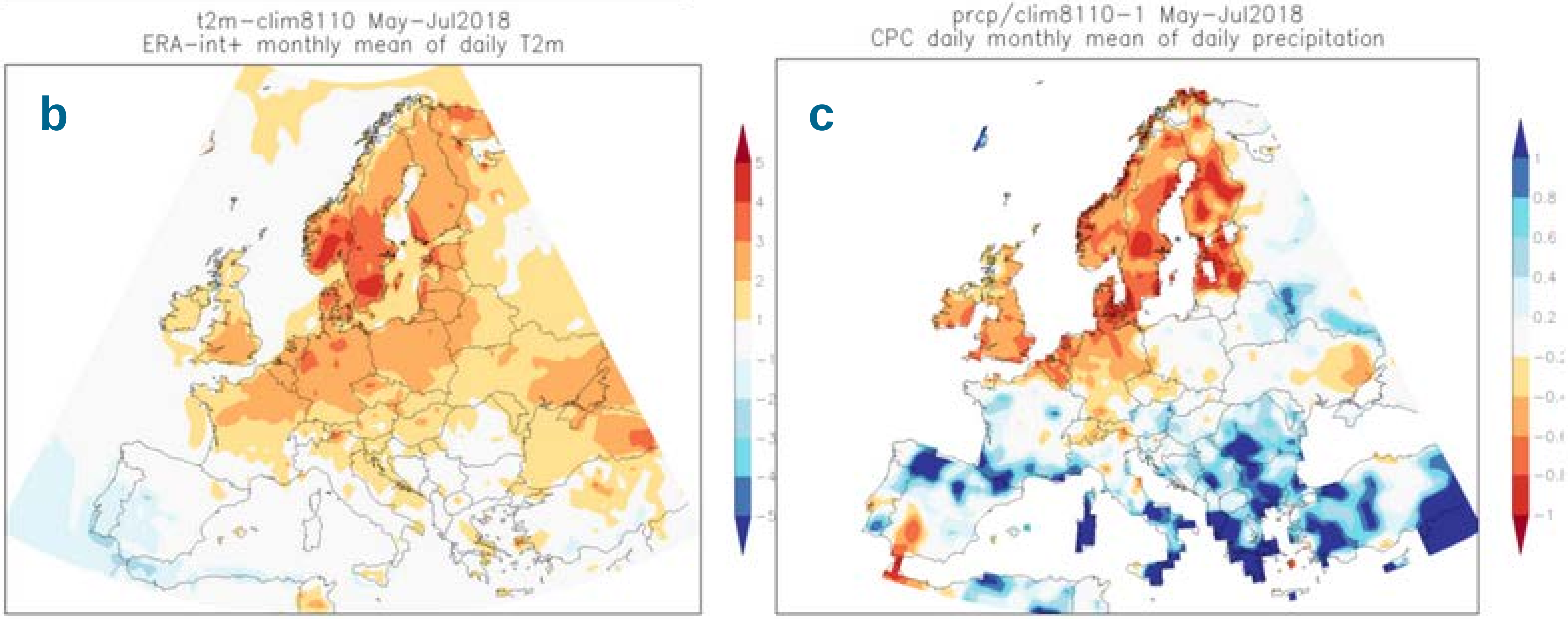
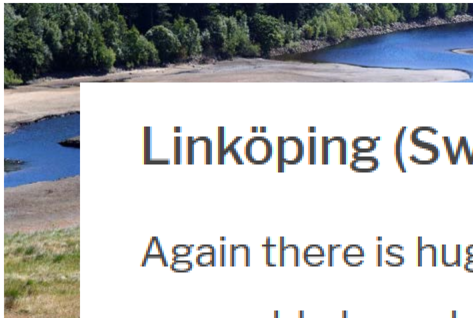
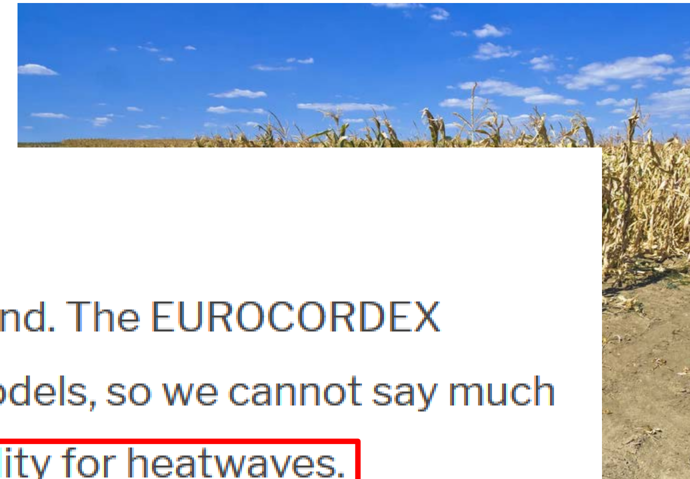


Figure 1: May-July averages of b) temperature anomalies and c) relative precipitation anomalies. a,b: ECMWF analyses and forecasts compared to ERA-interim, c: CPC analysis (up to 23 July).

https://www.worldweatherattribution.org/attribution-of-the-2018-heat-in-northern-europe/

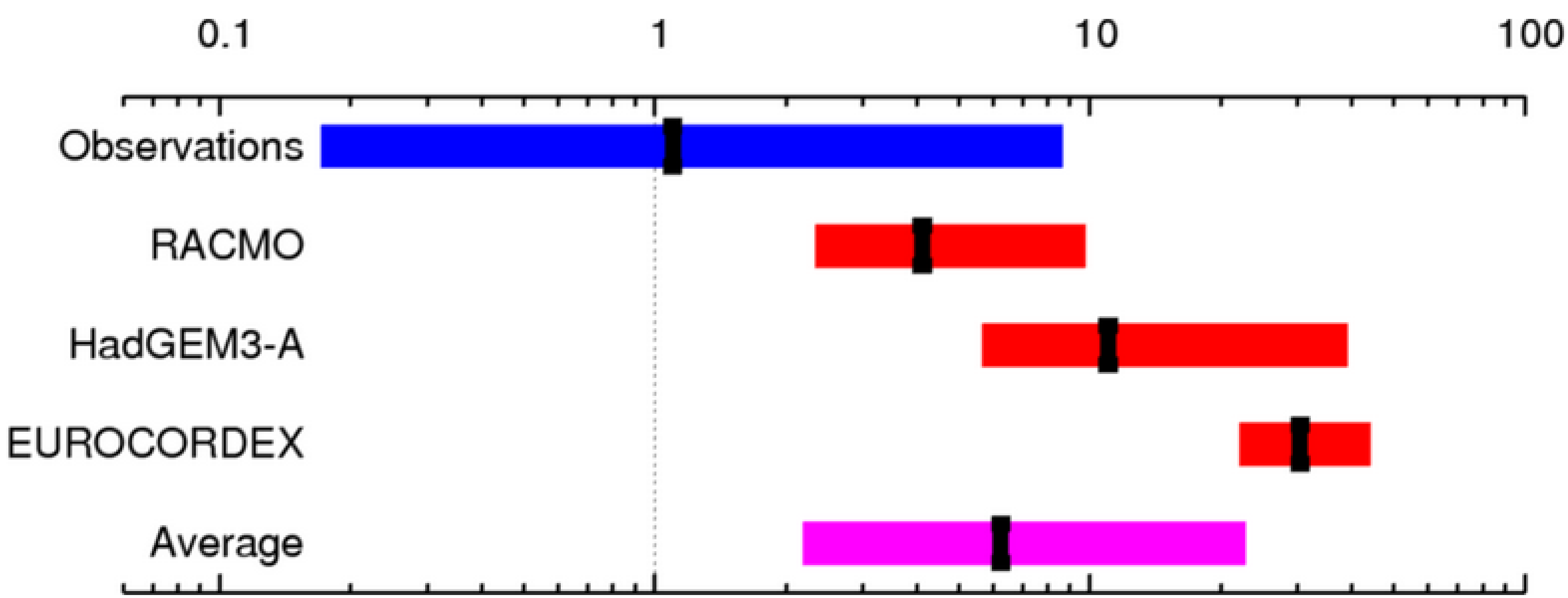
Drought stress – a problem for maize?





Linköping (Sweden)

Again there is huge uncertainty in the observed trend. The EUROCORDEX ensemble has a higher trend than the other two models, so we cannot say much more than there is definitely an increase in probability for heatwaves.



https://www.worldweatherattribution.org/attribution-of-the-2018-heat-in-northern-europe/

Consequence of drought on important crops

TABLE 1 | Yield losses in some major crops caused by drought and heat stress.

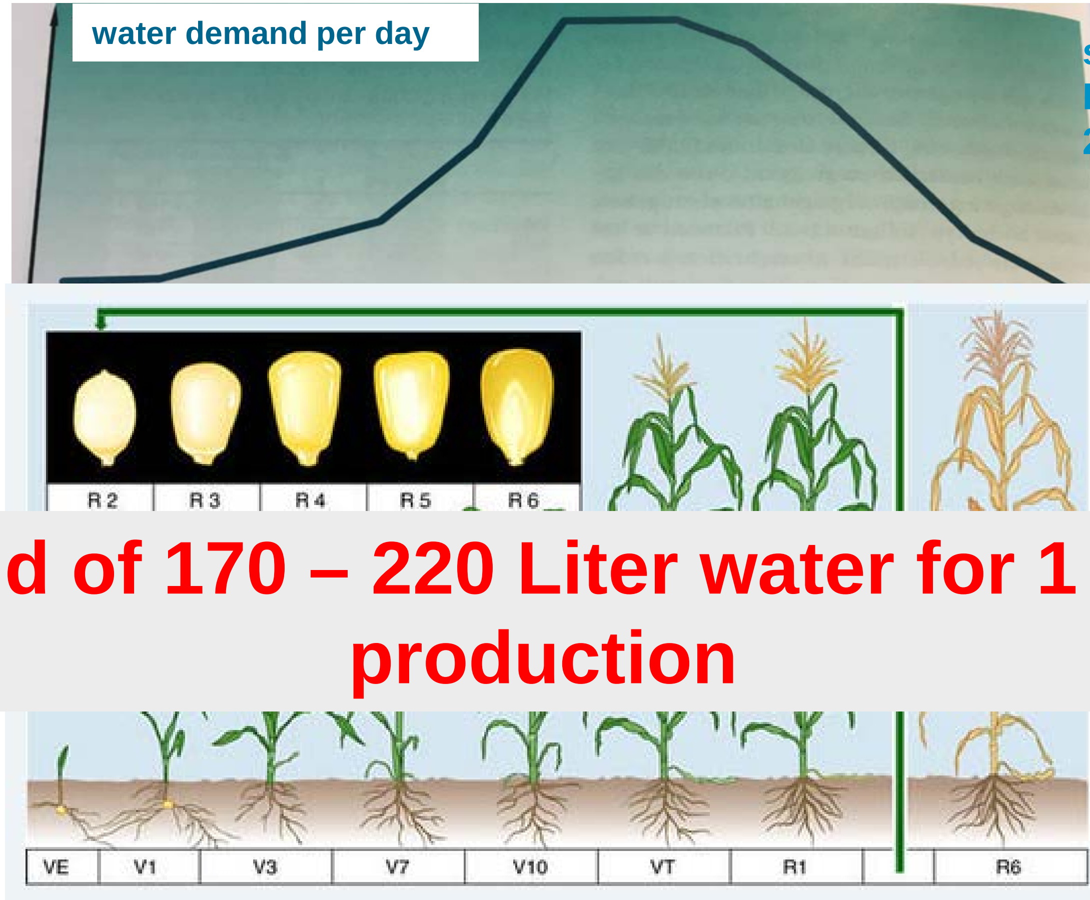
Crop species	Stress	Yield losses (%)	Reference
Maize (*Zea mays* L.)	Drought	63–87	Kamara et al., 2003
	Heat	42	Badu-Apraku et al., 1983
Wheat (*Triticum aestivum* L.)	Drought	57	Balla et al., 2011
	Heat	31	Balla et al., 2011
Rice (*Oryza sativa* L.)	Drought	53–92	Lafitte et al., 2007
	Heat	50	Li et al., 2010
Chickpea (*Cicer arietinum* L.)	Drought	45–69	Nayyar et al., 2006
Soybean (*Glycine max* L.)	Drought	46–71	Samarah et al., 2006
Sunflower (*Helianthus annuus* L.)	Drought	60	Mazahery-Laghab et al., 2003

source: Fahad et al. (2017) Frontiers in Plant Science

Extent of drought-induced yield changes depend on

- stress intensity
- stress duration
- the moment of drought stress during the different developmental stages
- how the capacities of sinks and sources for assimilates are affected by drought
- the extent to which plants are able to recover from drought (resilience)

water demand of maize in relation to development



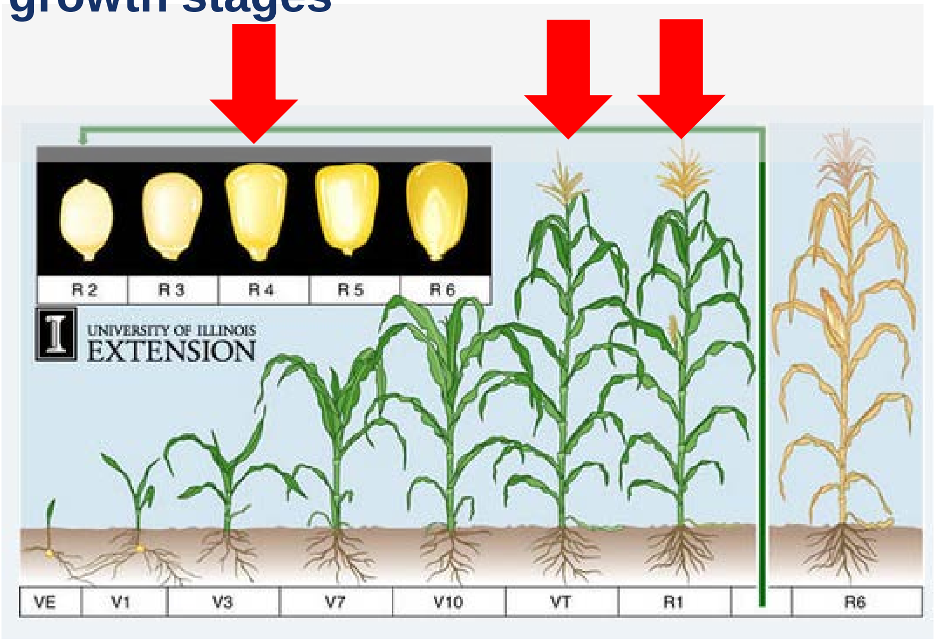
source: Handbuch Mais, 2013

demand of 170 – 220 Liter water for 1 kg DM production

https://odells.typepad.com/blog/corn-growth-stages.html

- **Veg. growth:** emerging (VE), leaf (Vn), tasseling (VT)
- **Gen. growth:** silking (R1), blister (R2), milk (R3), dough, dent, maturity (R6)

essential maize growth stages



https://odells.typepad.com/blog/corn-growth-stages.html

- yield formation: silage maize: % cob:remainder ~50:50
  - **number of kernel rows/cob**
  - **kernels per row**
    - *~between 750 and 1000 ovules are developed per cob*
    - *at harvest the kernel no. ~400 and 600 kernels/cob with 14-22 kernel rows and 30-50 kernels per row*

Drought beginning during vegetative growth: effects on biomass **Drought initiated 21 DAS**

DAS		Photosynthesis (μmol m^{-2} s^{-1})		Transpiration (mmol m^{-2} s^{-1})		Stomatal conductance (mmol m^{-2} s^{-1})		Leaf water potential (MPa)	
		Well-Watered	Ratio[a]	Well-Watered	Ratio[a]	Well-Watered	Ratio[a]	Well-Watered	Ratio[a]
55	Maize	39.6	0.80	6.1	0.77†	354.4	0.69†	−1.26	1.10
	Sorghum	33.6 ns	0.96†	5.0 ns	0.99	345.2 ns	1.04	−1.16 ns	1.09 ns
81	Maize	25.5	0.83	3.9	0.87	158.4	0.70	−0.97	1.32†
	Sorghum	31.4 ns	0.92 ns	4.1 ns	1.04 ns	226.6 ns	0.93 ns	−0.94 ns	1.21
95[c]	Maize	–	–	–	–	–	–	−1.15*	1.43*
	Sorghum	–	–	–	–	–	–	−0.65	1.20

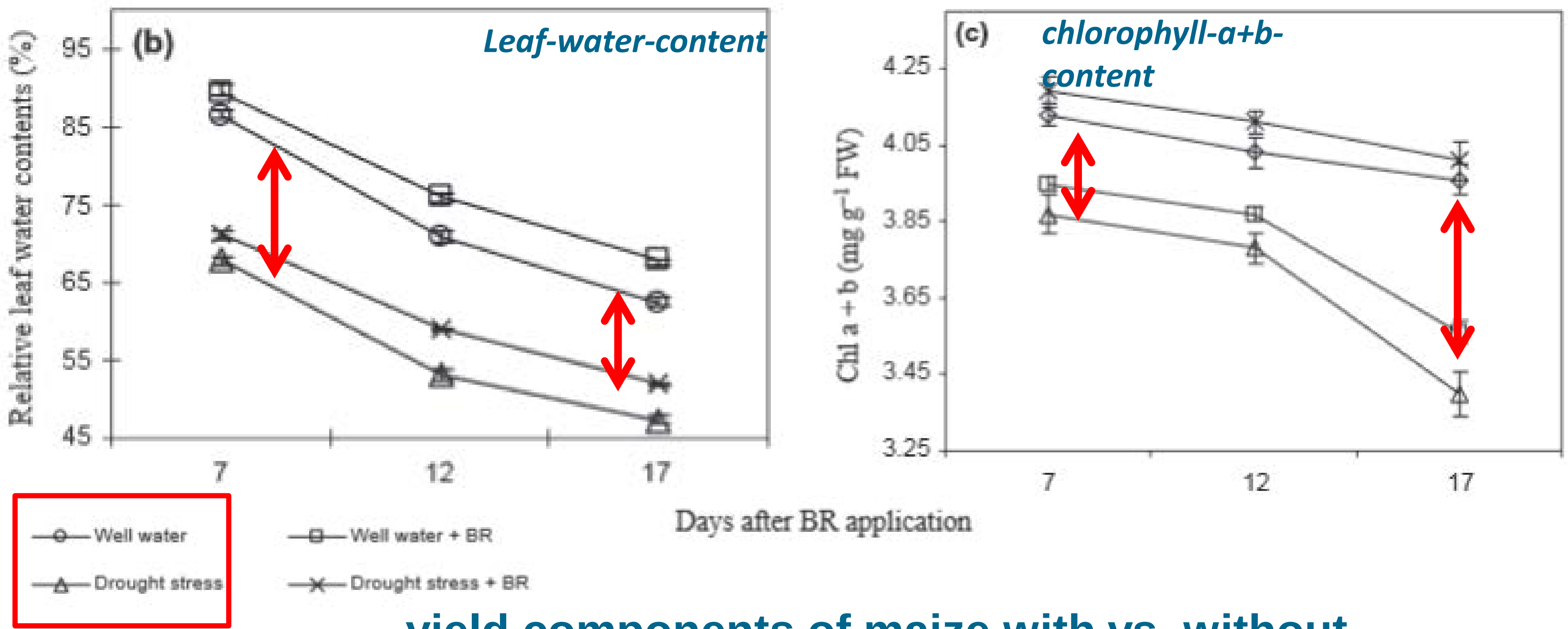
ratio: behaviour under drought in relation to irrigated treatment

*, † = sign. differences between maize and sorghum ($p \leq 0.05$ and $p \leq 0.1$)

- 55 DAS: tasseling
- 81 DAS: blister
- 95 DAS: dough

source: Zegada-Lizarazu et al. (2011) Plant and Soil

drought at tasseling

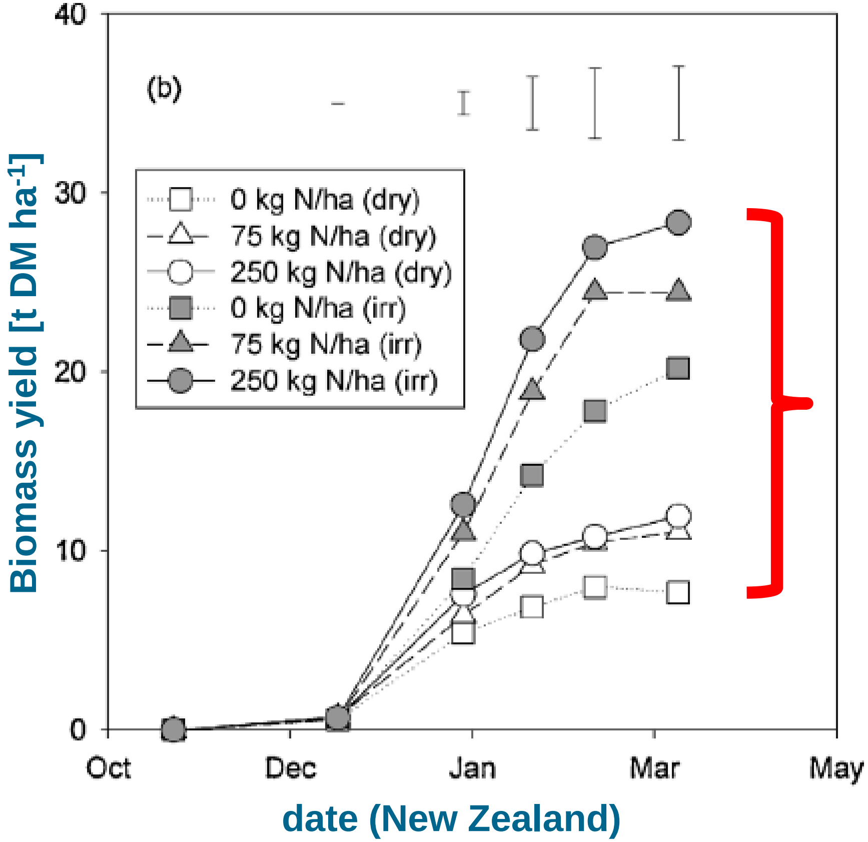


yield components of maize with vs. without drought stress

factor	rows/cob	kernel no./row	TKM [g]	kernels/ cob	harvest index [%]
No drought	14.9 ± 0.6 a	35.9 ± 1.0 a	31.2 ± 0.6 a	544.2 ± 3.5 a	54.9 ± 0.9 a
drought	14.2 ± 0.1 a	29.3 ± 1.4 b	25.5 ± 0.3 b	380.1 ± 3.0 b	52.3 ± 0.5 b

source: Anjum et al. (2011) J.Agron.Crop.Sci

No additional water from sowing onwards: final yield

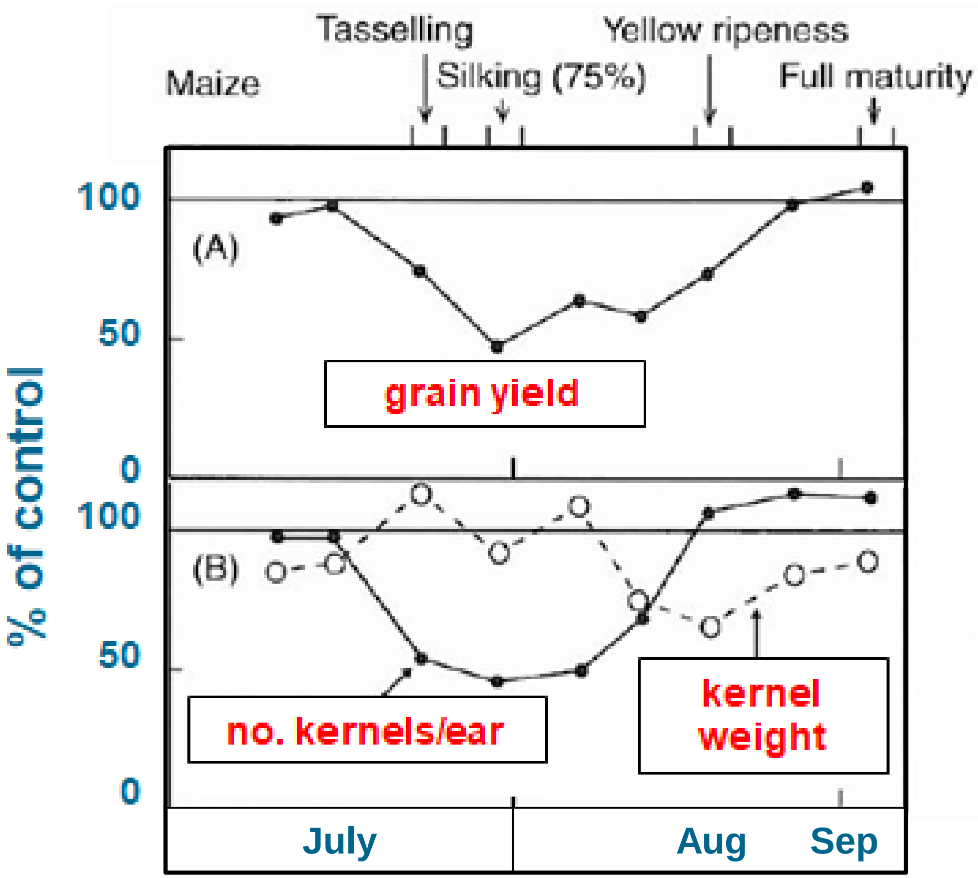


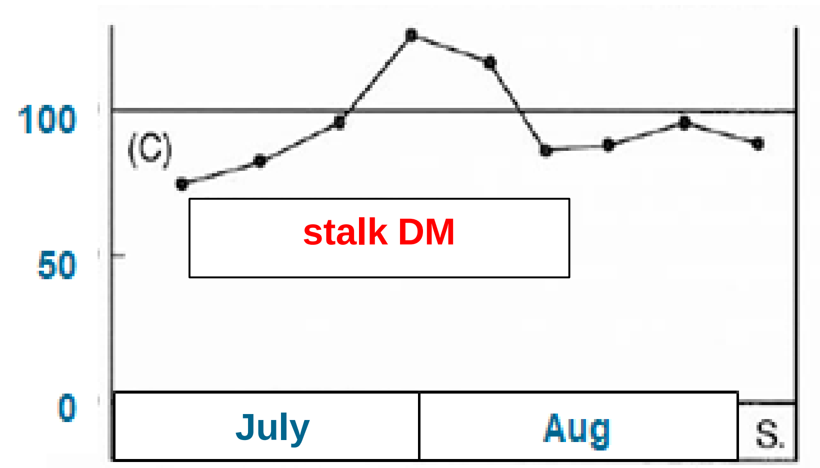
average yield loss 60%

deep soil with 190 mm water m^{-1} soil depth

source: Teixeira et al. (2014) Field Crops Res.

drought during different stages of development





from Claassen & Shaw, 1970a,b

consequences of drought

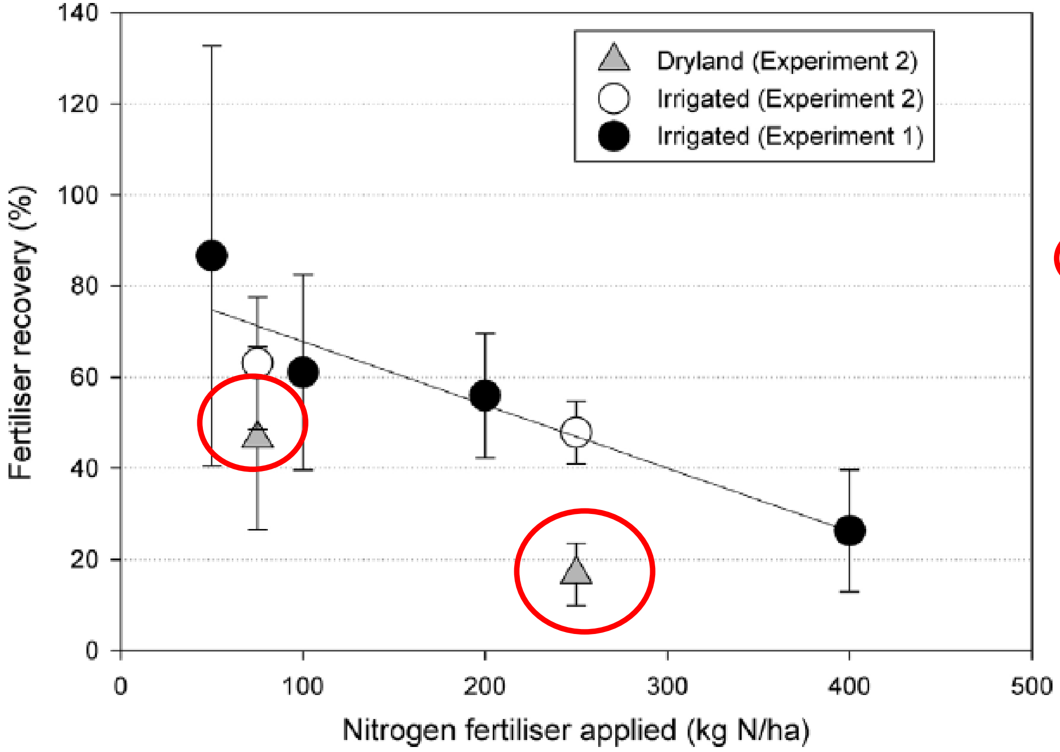
- pre-anthesis drought: → shortened vegetative growth (low stalk and leaf dev.)
- post-anthesis drought: → reduced grain filling (sink strength reduced)
    - reduced activity of sucrose-synthase, starch-synthase, starch-branching-enzyme & adenosine-diphosphate-glucose-pyrophosphorylase

Cause analysis of yield losses induced by drought

- leaf-water-potential decreases
- lower stomatal conductance → reduced transpiration
    - canopy-temperatures increase
    - reduced photosynthesis (PS)
    - reduced assimilate availability
    - low flagleaf development (50% of yield resources)
    - indirect nutrient insufficience + high residual soil N

source: Fahad et al. (2017) Frontiers in Plant Science

No additional water from sowing onwards:
N recovery in harvested biomass

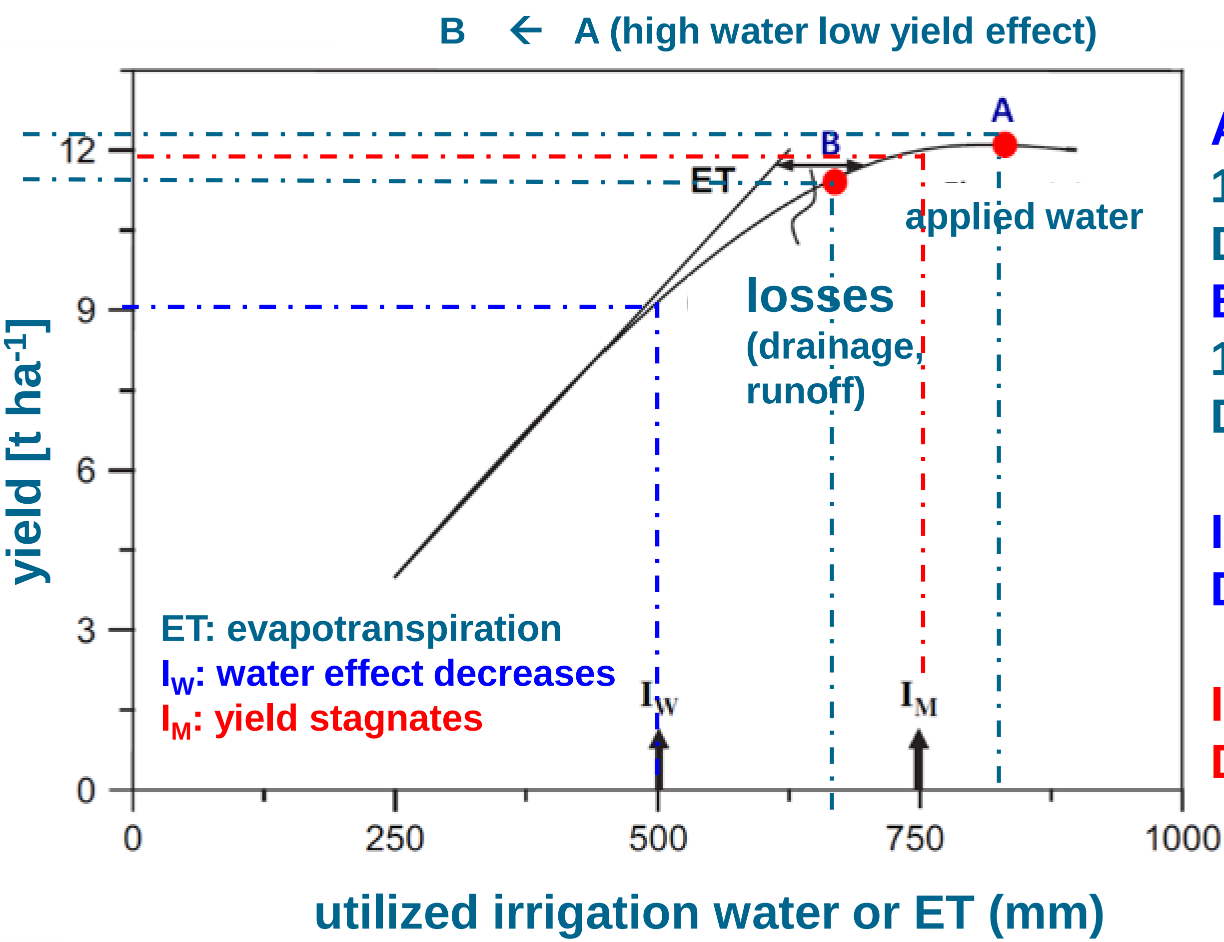


indicates drought stress treatment

low biomass production reduces N uptake and increases post-harvest soil N

source: Teixeira et al. (2014) Field Crops Res.

Irrigation to challenge drought



A:
12.000/875 = 13.7 kg DM/mm

B:
11.000/650 = 16.9 kg DM/mm

I_W: 9.000/500 = 18 kg DM/mm

I_M: 12.000/750 = 16 kg DM/mm

source: Schittenhelm et al. 2017; adapted from Fereres & Soriano (2007) and Schneekloth & Andales (2017)

Efficient irrigation practice long-known

- deficit irrigation (DI50) and partial-root-drying (PRD50)

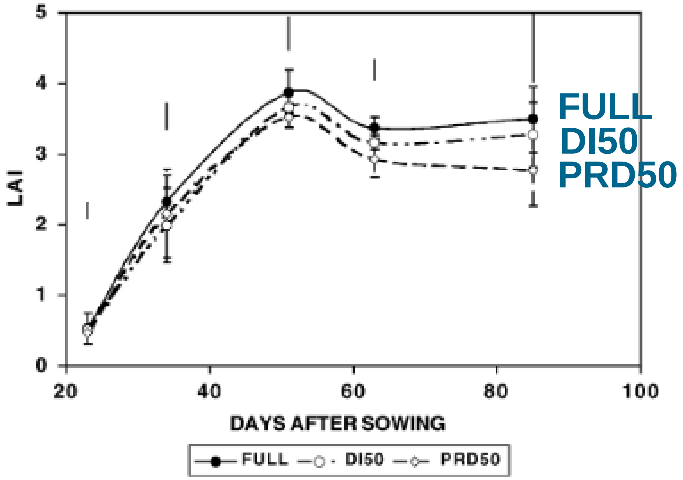
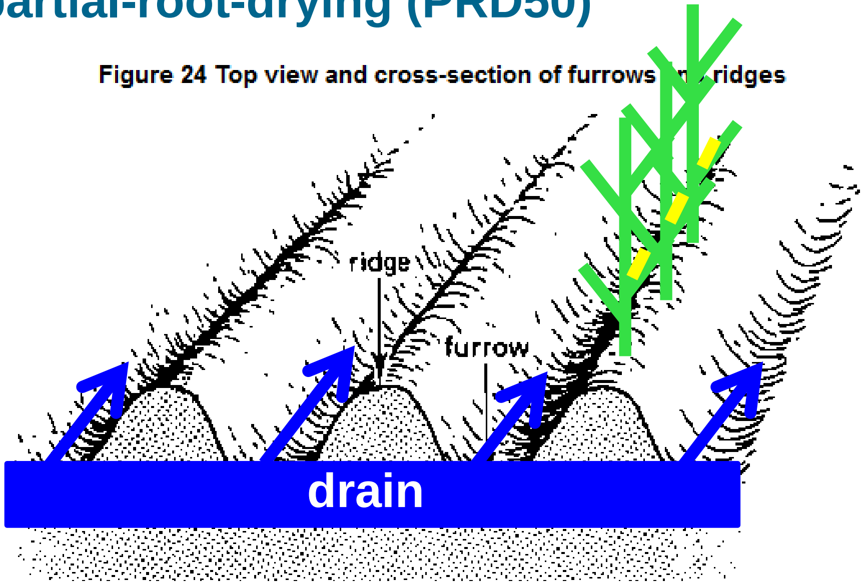


Fig. 3. Seasonal change of LAI of maize in 2002. Data points are means ($n = 4$) ± S.E. LSDs ($P = 0.05$) are presented as vertical line bars.



http://www.fao.org/docrep/S8684E/s8684e04.htm

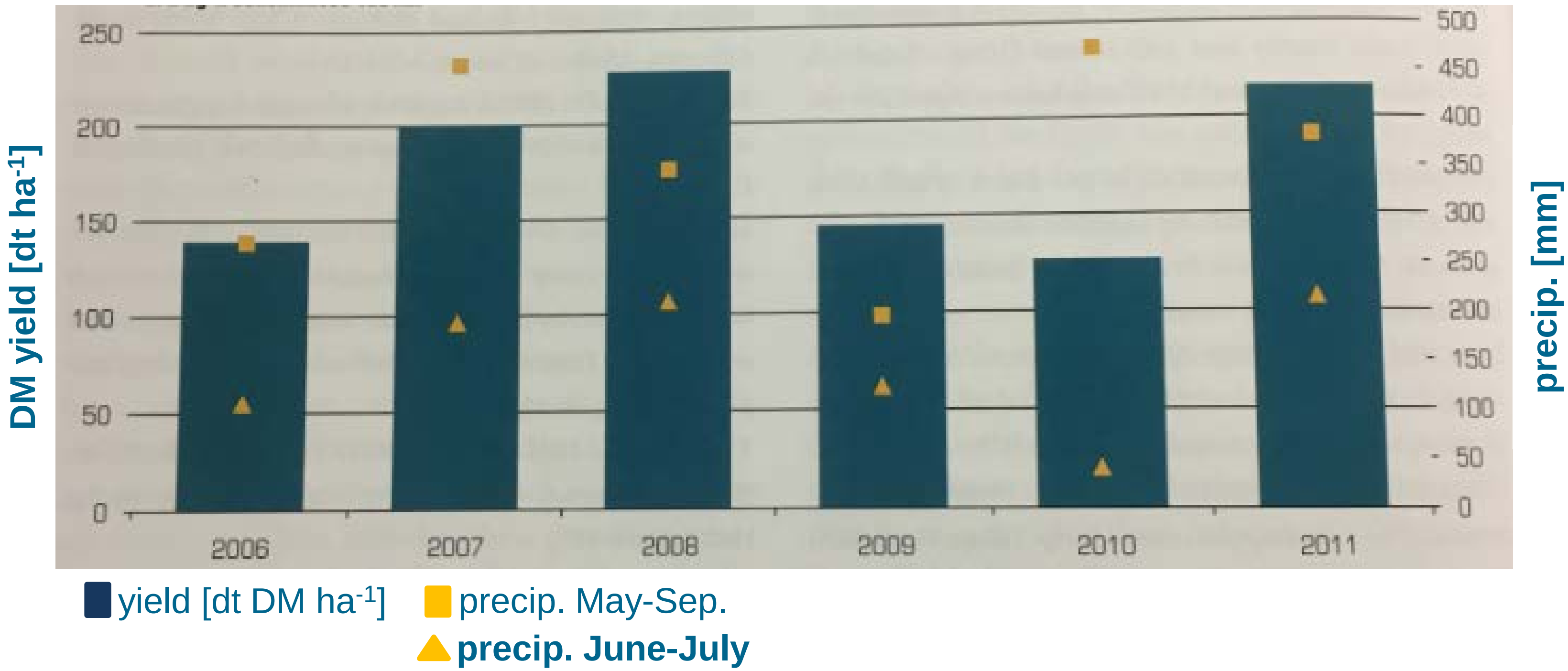
Table 2
Maize yield and irrigation water-use efficiency[a]

Treatments	2001					2002				
	Yield (t ha^{-1})	I (mm)	ET (mm)	IWUE (kg ha^{-1} mm^{-1})		Yield (t ha^{-1})	I (mm)	ET (mm)	IWUE (kg ha^{-1} mm^{-1})	
FULL	9.19 ± 0.23 a	421	654	21.8 ± 0.53 b		10.79 ± 0.74 a	408	532	26.5 ± 0.90 b	
PRD50	8.22 ± 0.23 b	211	484	39.0 ± 1.06 a	+44%	8.61 ± 0.17 b	204	323	42.2 ± 0.41 a	+35%
DI50	8.30 ± 0.08 b	211	483	39.4 ± 0.39 a		8.04 ± 0.21 b	204	324	39.4 ± 0.52 a	
Tukey's CV	0.42			5.8		1.35			3.8	
P	0.01	–	–	0.05		0.01	–	–	0.01	

[a] Rows of data within a column, followed with different letters, are significantly different at shown significance levels, based on Tukey's mean range test.

source: Kirda et al. 2005

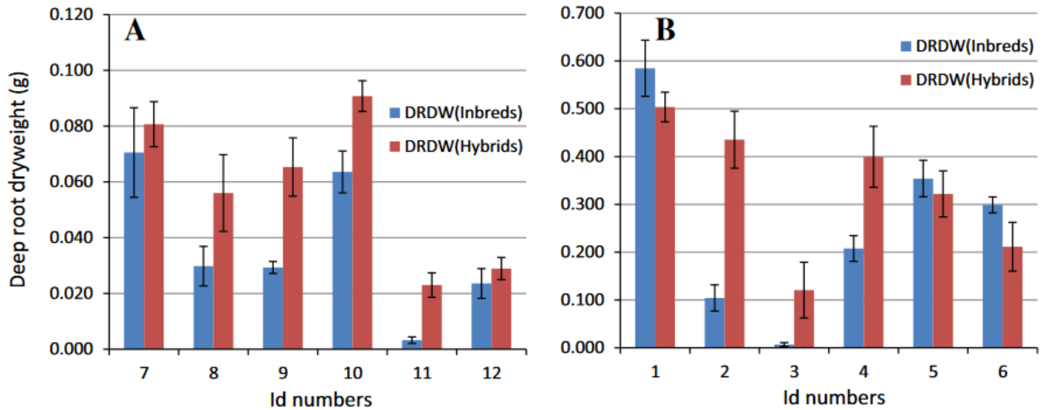
Time point of irrigation

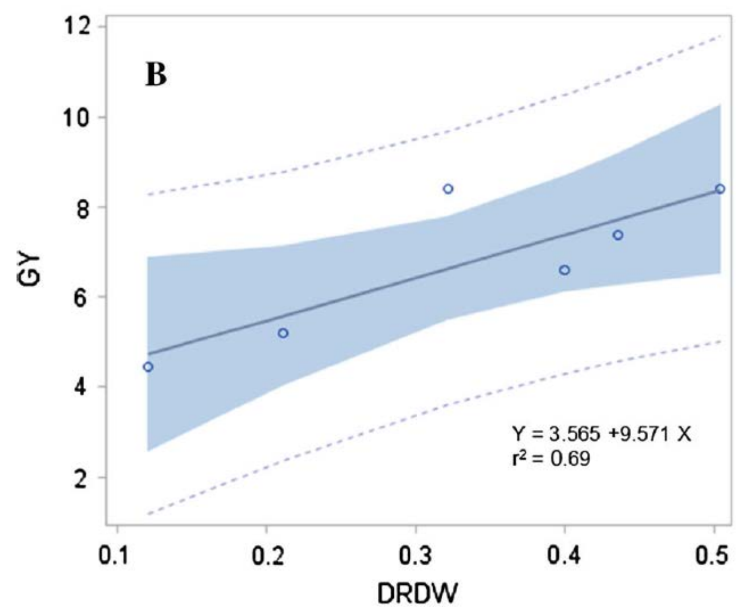


source: Fricke und Riedel 2012

Genotypic variation of root traits: deep rooting

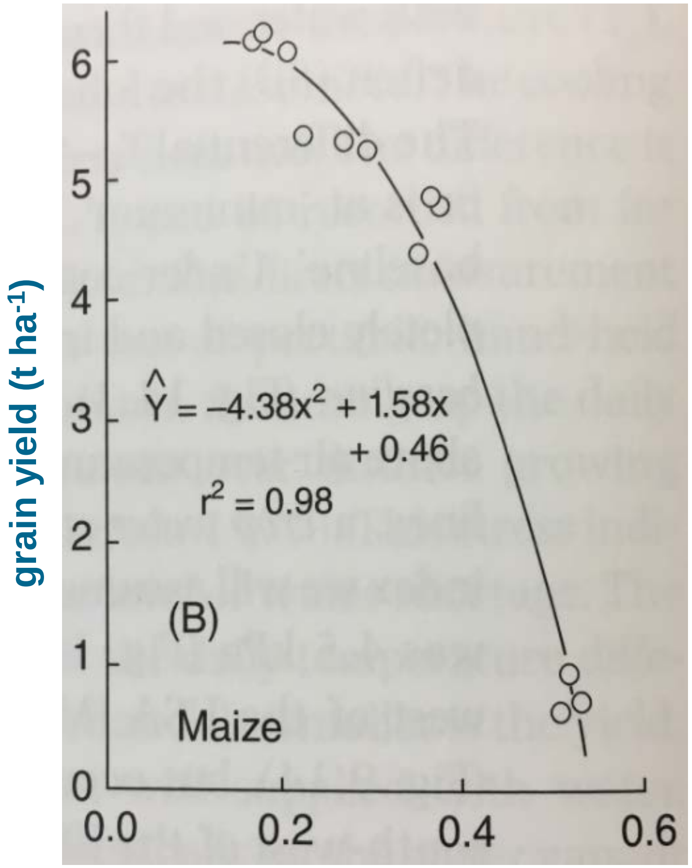
Scales!



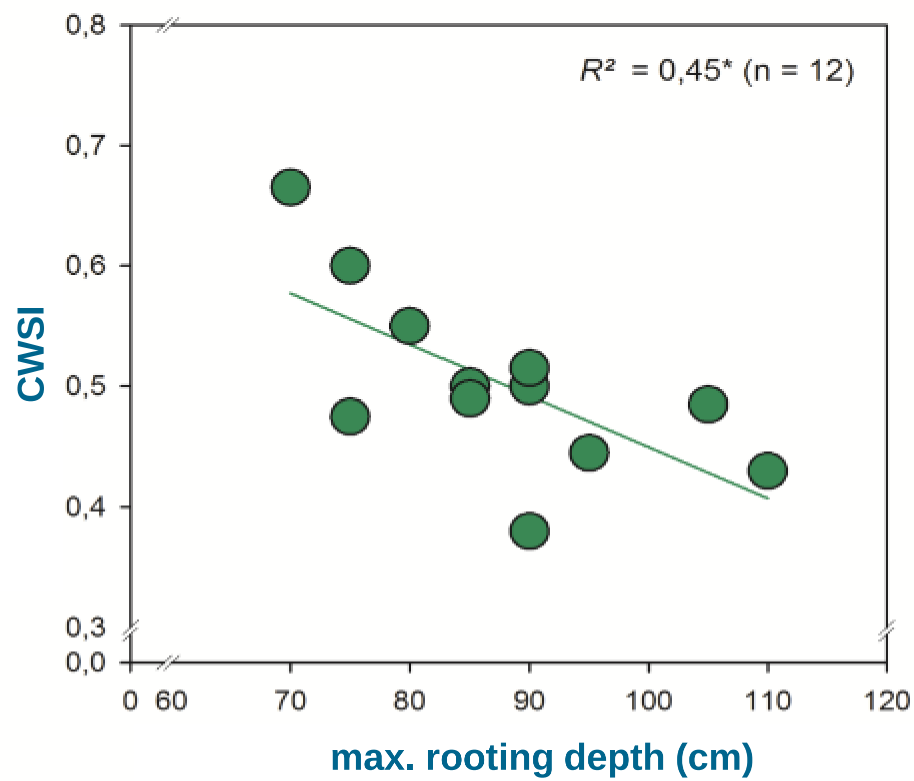


source: Ali et al. 2016

Screening genotypes



CWSI – Crop water stress Index



daily CWSI values are provided averaged from early pollination to mid-Sep

source: Kottmann, 2017

Abdul-Jabbar et al. 1985; Irmak et al. 2000

conclusions

- drought stress during transition from vegetative to generative growth harmful (tasseling → post-silking)
- adaptation by efficient irrigation
- deep rooting associated with higher yields under drought
- root measurements are labor intensive → indirect measurements required, i.e. CWSI

Thank you for your attention!

https://www.vanislewater.com/Understanding-Drought-Levels-and-Water-Restrictions

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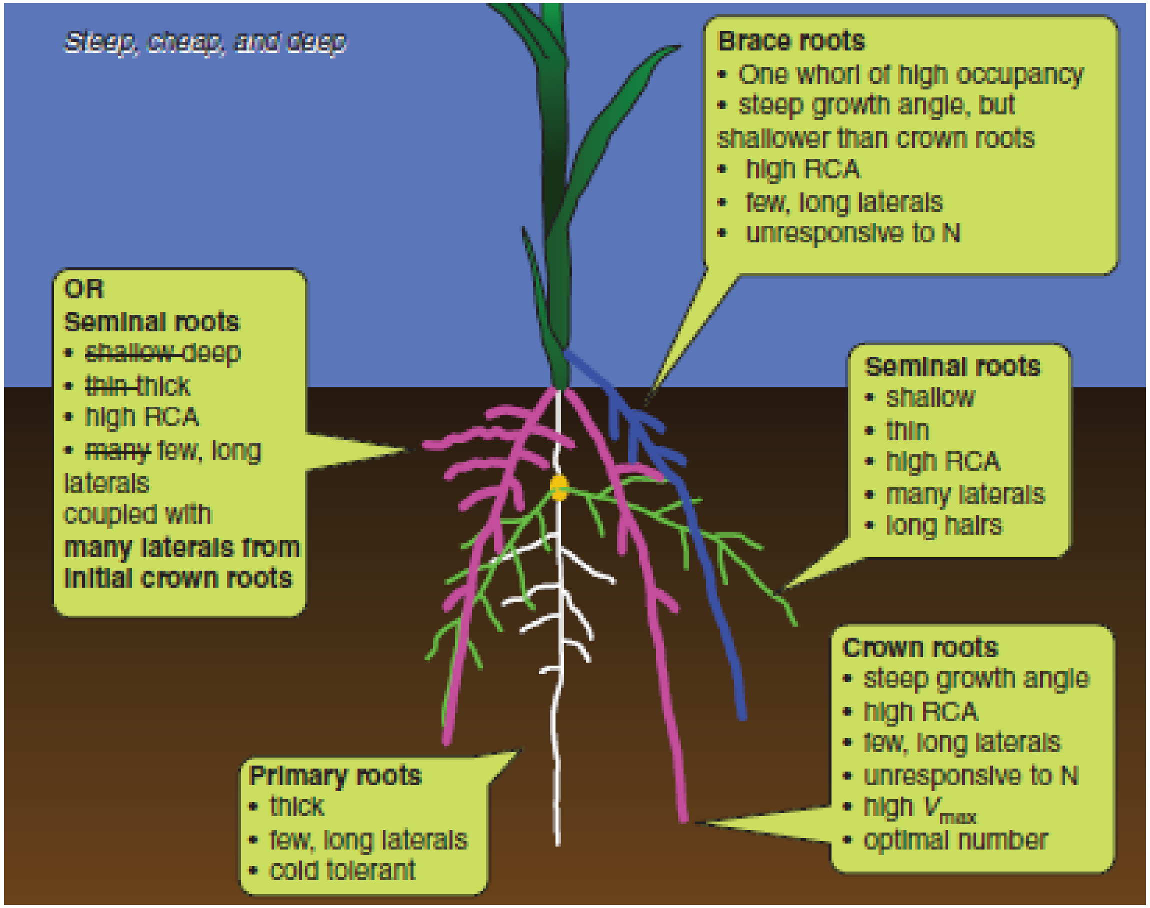
The steep, cheap and deep root ideotype



source: Lynch, 2013

GMO

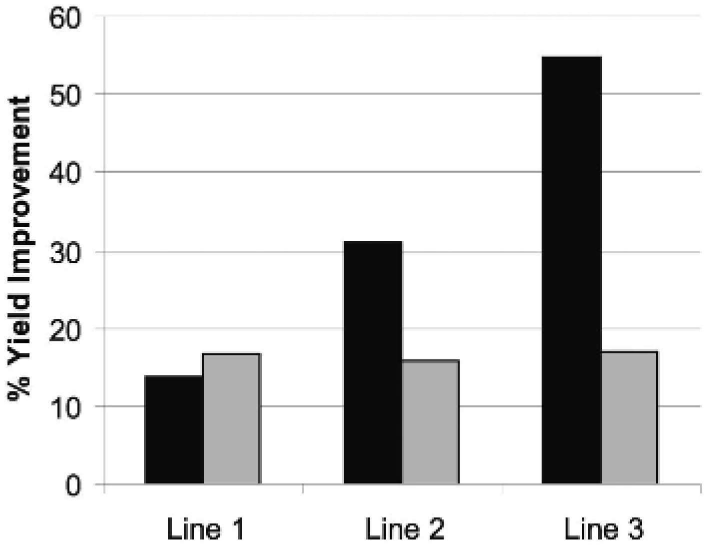


Fig. 6. Three transgenic maize lines demonstrate improved yield in 2 years of yield testing. Values plotted are increase on a percentage basis of transgenics over controls. All differences plotted are significant at $P < 0.1$. Data from three independent lines are shown with side-by-side comparison of 2 years' results. Base yield (yield of controls) was 4.6 metric tons/hectare (74 bushels/acre) in Year 1 and 6.4 metric tons/hectare (102 bushels/acre) in Year 2.

Fig. 5. Transgenic maize plants in greenhouse and field have visually observable improved drought tolerance. In both photographs, controls are in the left flat or row, and transgenics expressing ZmNF-YB2 are in the right flat or row.

- results based on transcription factor (ZmNF-YB2)
- GMO maize with increased expression show higher chlorophyll contents, stomatal conductance, leaf temperature, reduced wilting and PS maintenance under drought

source: Nelson et al. 2007; PNAS

root morphology

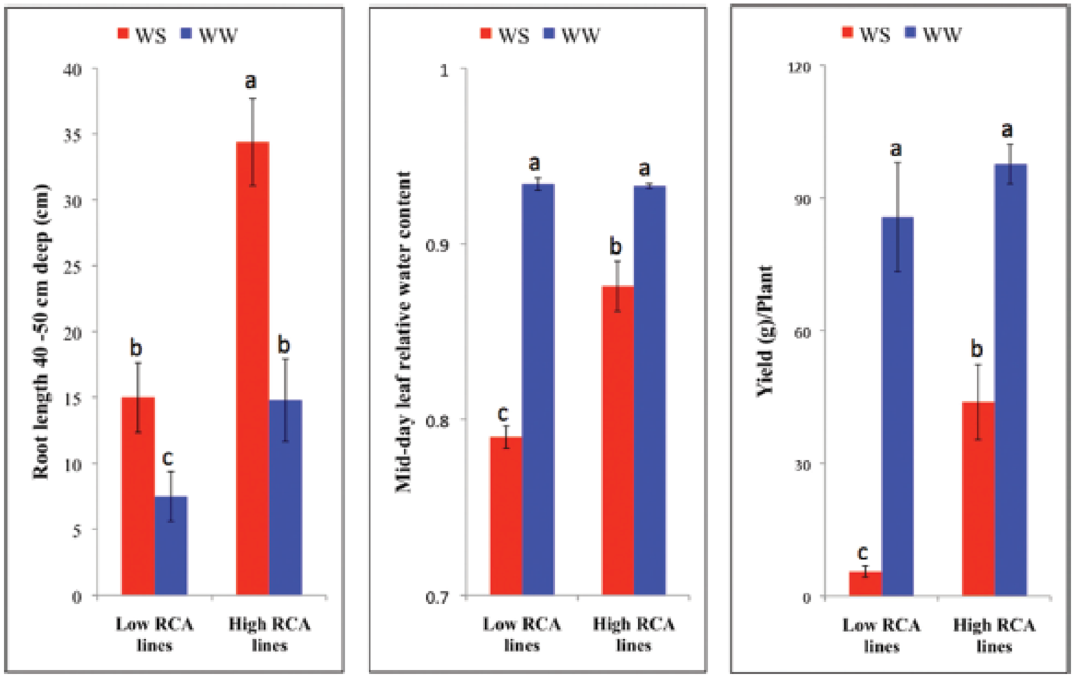


Fig. 4. Root length at a depth of 40–50 cm, mid-day leaf relative water content, and seed yield of maize plants with high or low root cortical aerenchyma (RCA) formation under well-watered (WW) or water-stressed (WS) conditions in the field. Bars having different letters within a panel are different at $P \leq 0.05$. From Zhu JM, Brown KM, Lynch Jp. 2010. Root cortical aerenchyma improves the drought tolerance of maize (*Zea mays* L.). *Plant, Cell and Environment* **33,** 740–749. (This figure is available in colour at *JXB* online.)

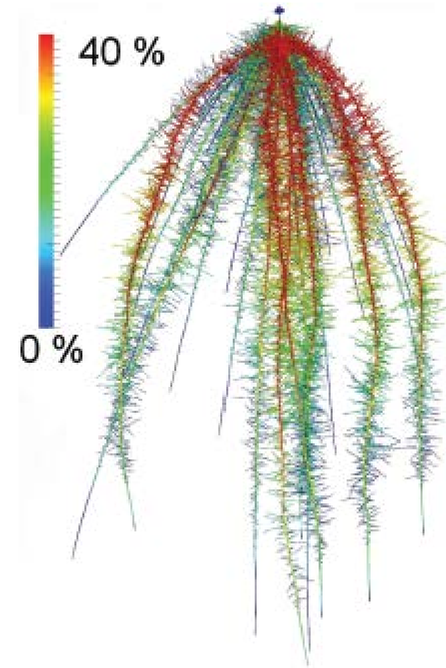


Fig. 5. Spatial distribution of root cortical aerenchyma in simulated maize plant 40 d after planting, with hotter colours representing more aerenchyma. From Postma JA, Lynch JP. 2011. Root cortical aerenchyma enhances the growth of maize on soils with suboptimal availability of nitrogen, phosphorus, and potassium. Plant Physiology 156, 1190–1201. www.plantphysiol.org. Copyright American Society of Plant Biologists.

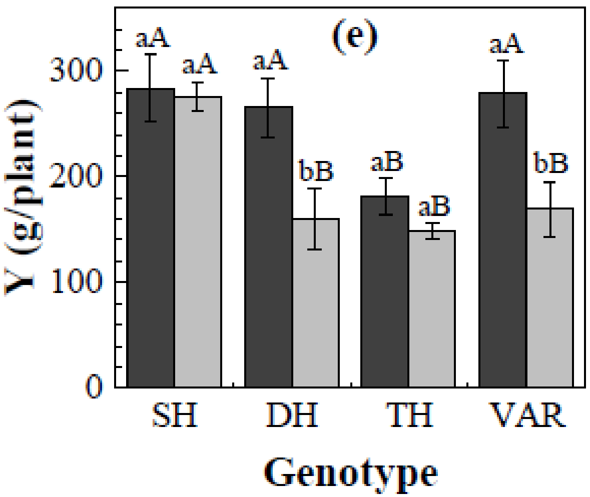
source: Lynch et al. 2014

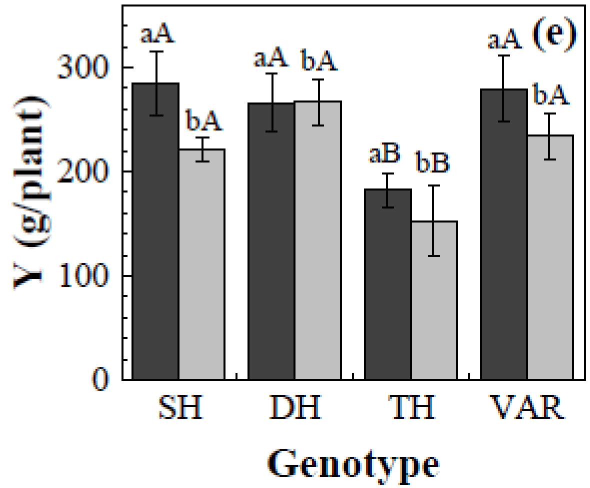
Irrigation effect in maize

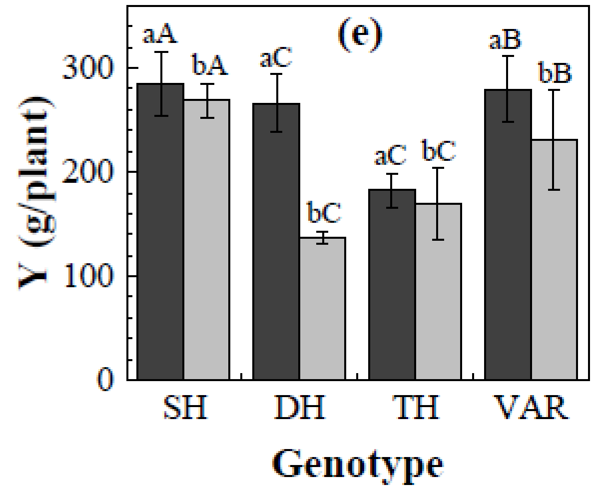
water regime	crop	yield [t DM ha^{-1}]	ET [mm]	WUE [kg ha^{-1} mm^{-1}]	TUE [kg ha^{-1} mm^{-1}]
mean					
rainfed	Cup plant	10.8f	309e	36c	54c
	Maize	**17.7b**	**320d**	**55a**	**127a**
	lucerne-grass	12.2e	373c	33d	-
irrigated	Cup plant	16.1c	542a	30e	39d
	Maize	**21.7a**	**481b**	**45b**	**91b**
	lucerne-grass	14.2d	489b	29e	-

source: Schoo et al. 2017

Reaction towards drought at vegetative growth – effects of Genotypes (grain yield, 13% H_2O)







1-10 | 11-20 | 21-30

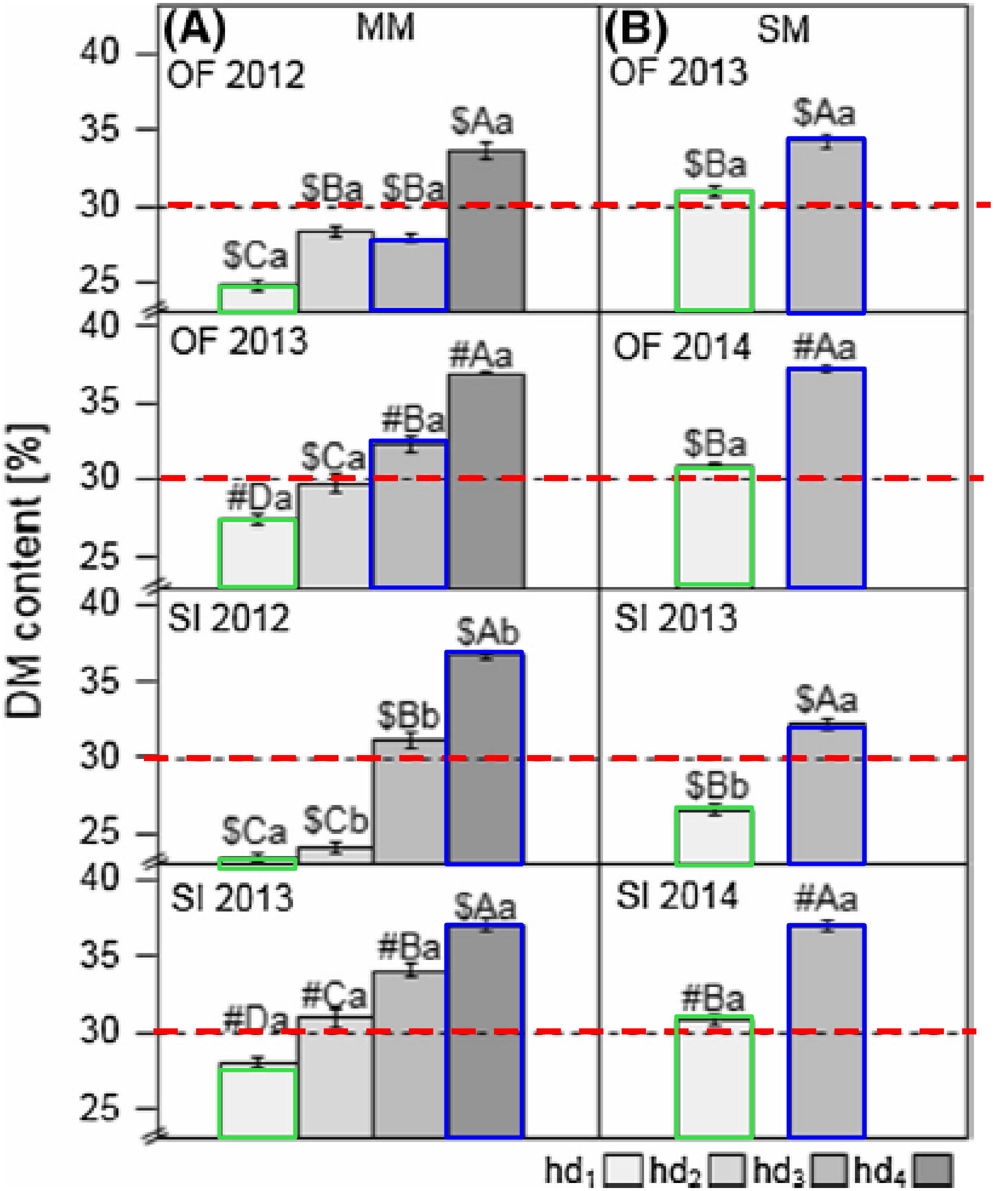
stage V4 | V6 | V8

DAE

dark bars: no drought
light bars: drought
Uppercase letters: Genotypes
Lowercase: water regimes

source: Rufino et al. 2018

decreasing precipitation and increasing temperatures



Four harvest dates (hd) during three successive years at two sites (OF and SI).

precipitation declined and temperatures increased from 1063, 1125, 1209 °Cd from 2012 to 2014

→ inflexible harvest dates should be avoided

source: Komainda et al. 2017

Alternatives besides

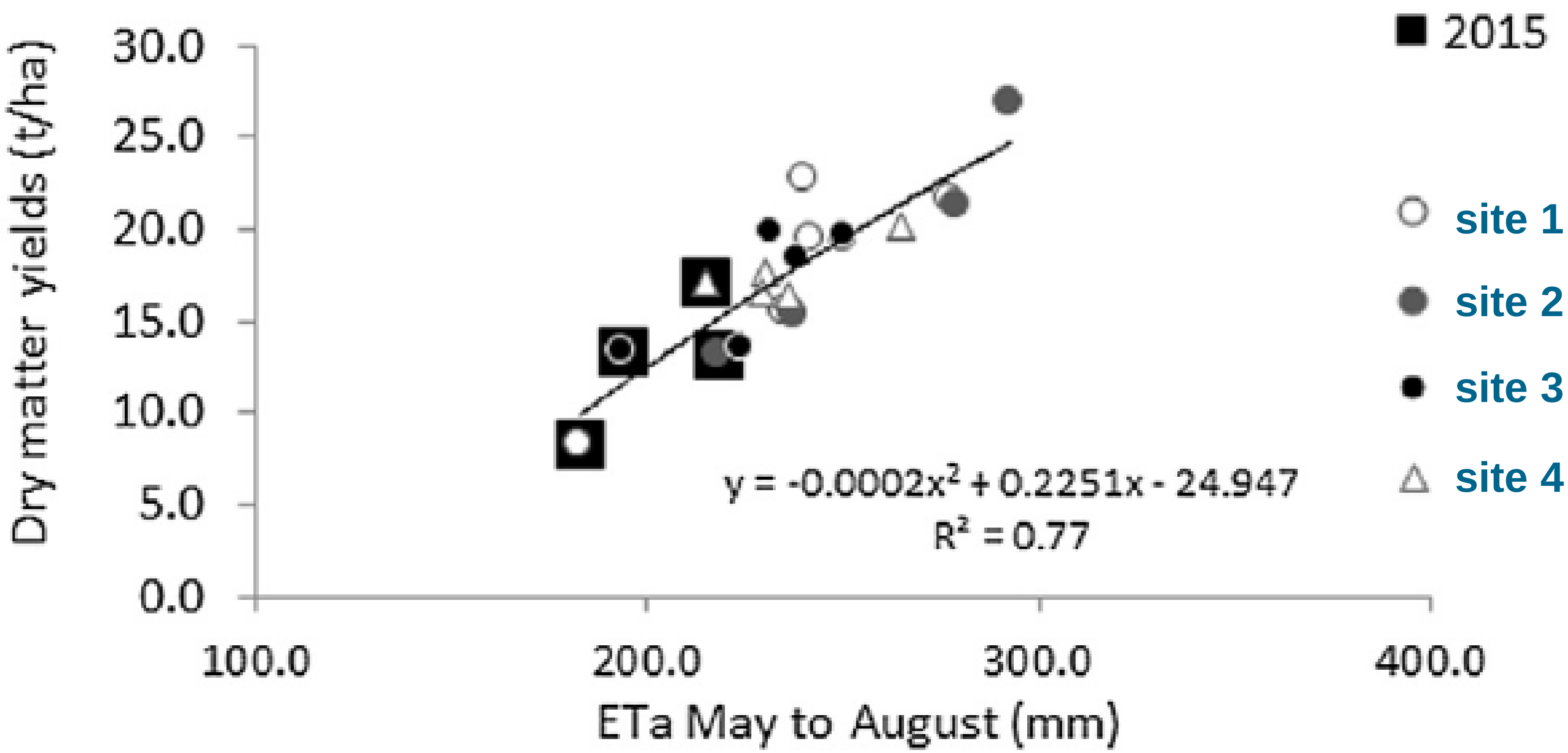
- sowing density (plants ha^{-1})

variety type	silage maize		grain maize	
	water supply			
	adequate	low	adequate	low
compact	110.000 - 120.000	100.000	100.000	90.000
mid-high	80.000 - 90.000	80.000	80.000	70.000
big	90.000 - 100.000	70.000	70.000	60.000

- plastic mulch
- straw mulch
- drip irrigation
- partial-root-drought/alternate root irrigation…

https://www.lto.de/recht/hintergruende/h/internetrecht-2017-big-five-usa-trump-eu-kommission-leistungsschutz-hate-speech-fake-news/

essential component: water



Relationship between actual evapotranspiration totals (ETa) for May-August and maize silage yields (average of several hybrids) during 2011 until 2015. 2015 was very dry.

source: Zdeněk et al. 2017 Agric.Water.Manag.

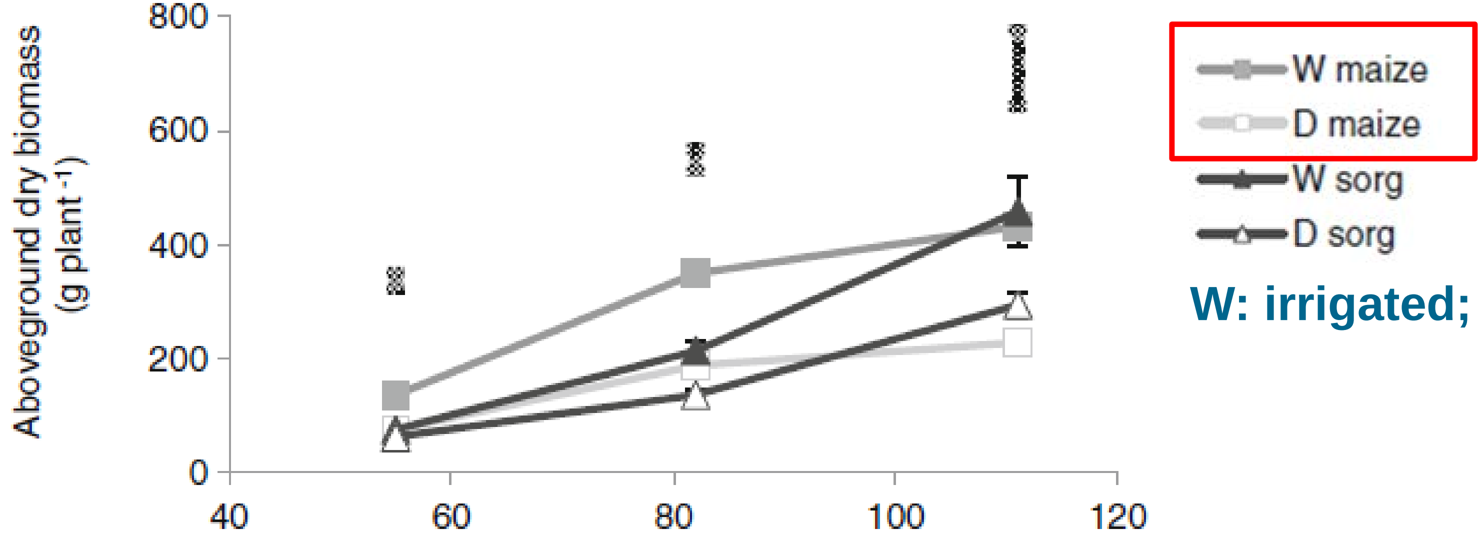
relevant phases of maize development

developmental stage	days after emergence (DAE)	development	implication
V3	9 - 12	installation seminal root system	resistance of emerging seedling
> V3	14 - 21	installation of cobs	determination of number of kernel rows per cob
V6	21 - 25	nodal root system developed	capacity of water and nutrient uptake
V12 to V14	42 - 49	number of ovules determined	number kernels per row
R1 (anthesis)	63 - 68	start of pollination, root mass near max	fertilization of ovules

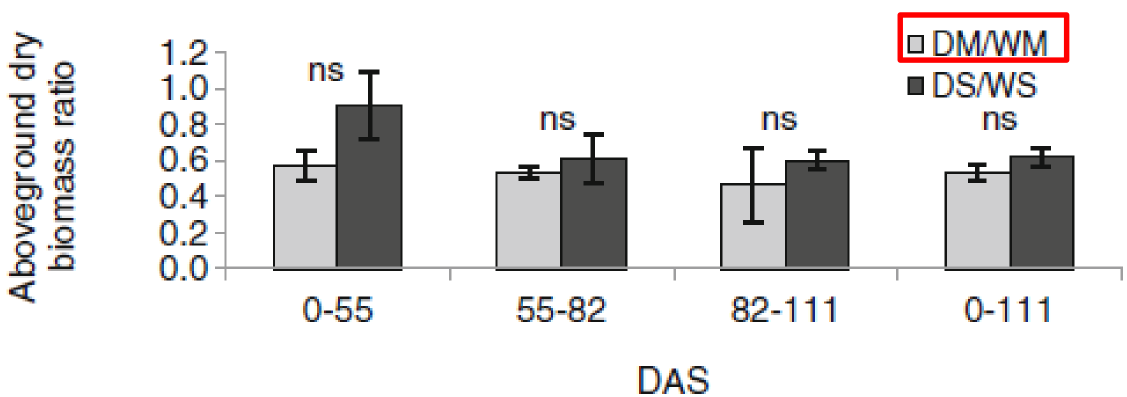
Drought beginning during vegetative growth: effects on biomass

Drought initiated 21 DAS

tassel blister dough stage



W: irrigated; D: drought

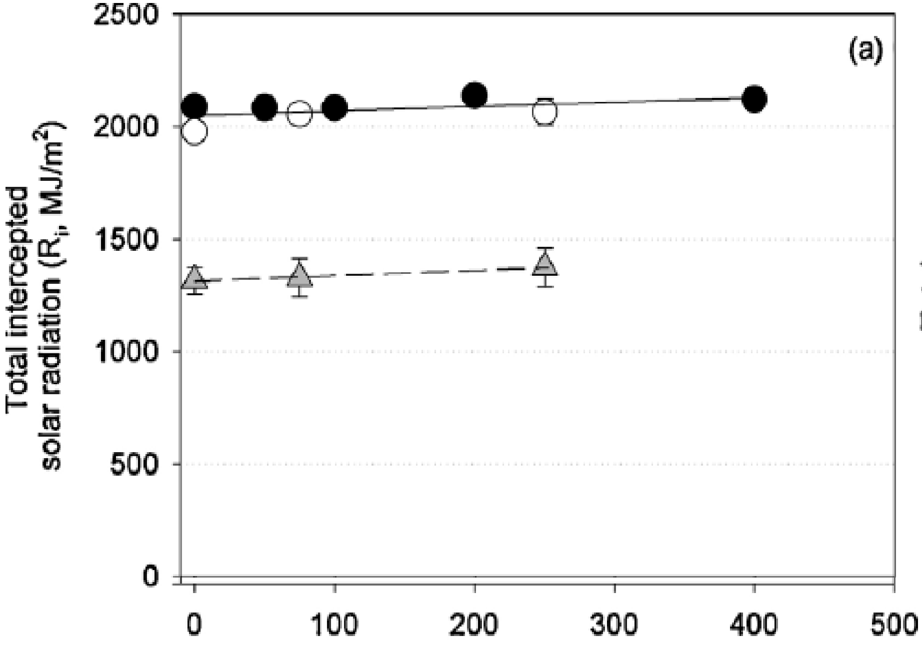


ratio of drought/no drought

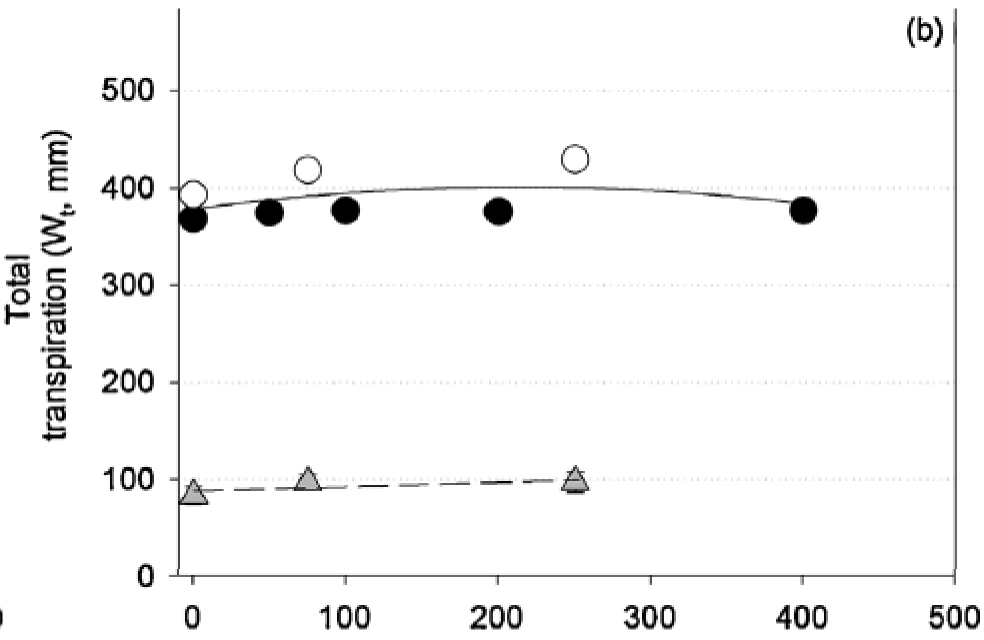
source: Zegada-Lizarazu et al. (2011) Plant and Soil

No additional water from sowing onwards: causes of yield losses

Intercepted radiation reduced by 34%



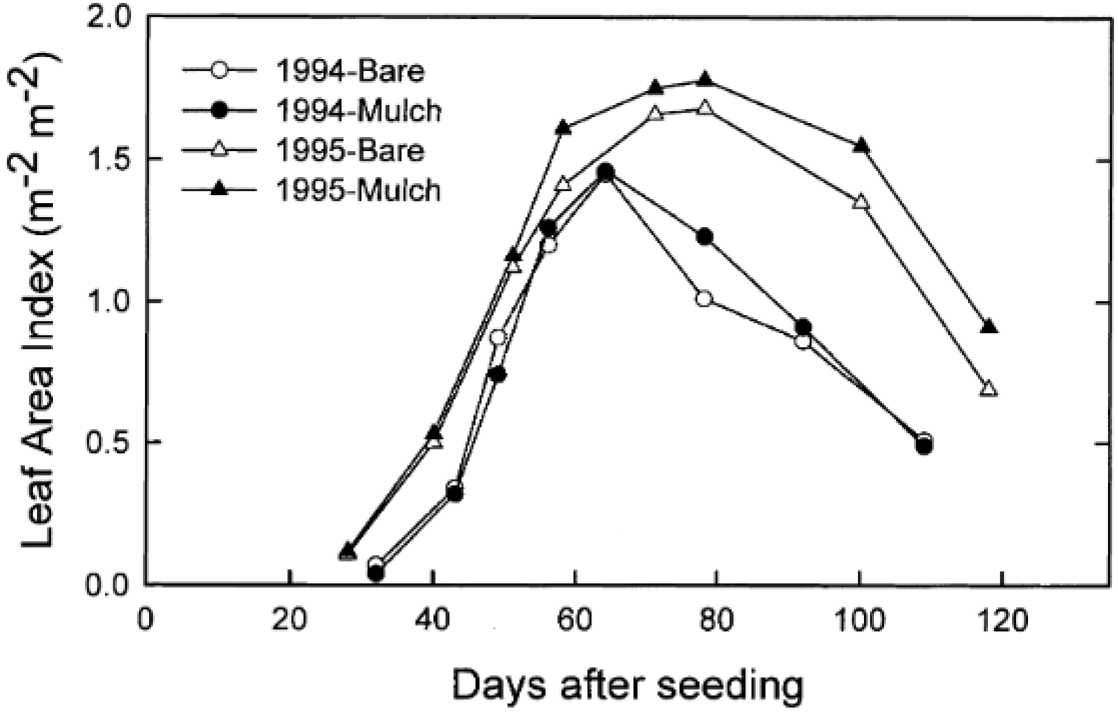
transpiration reduced by 79%



source: Teixeira et al. (2014) Field Crops Res.

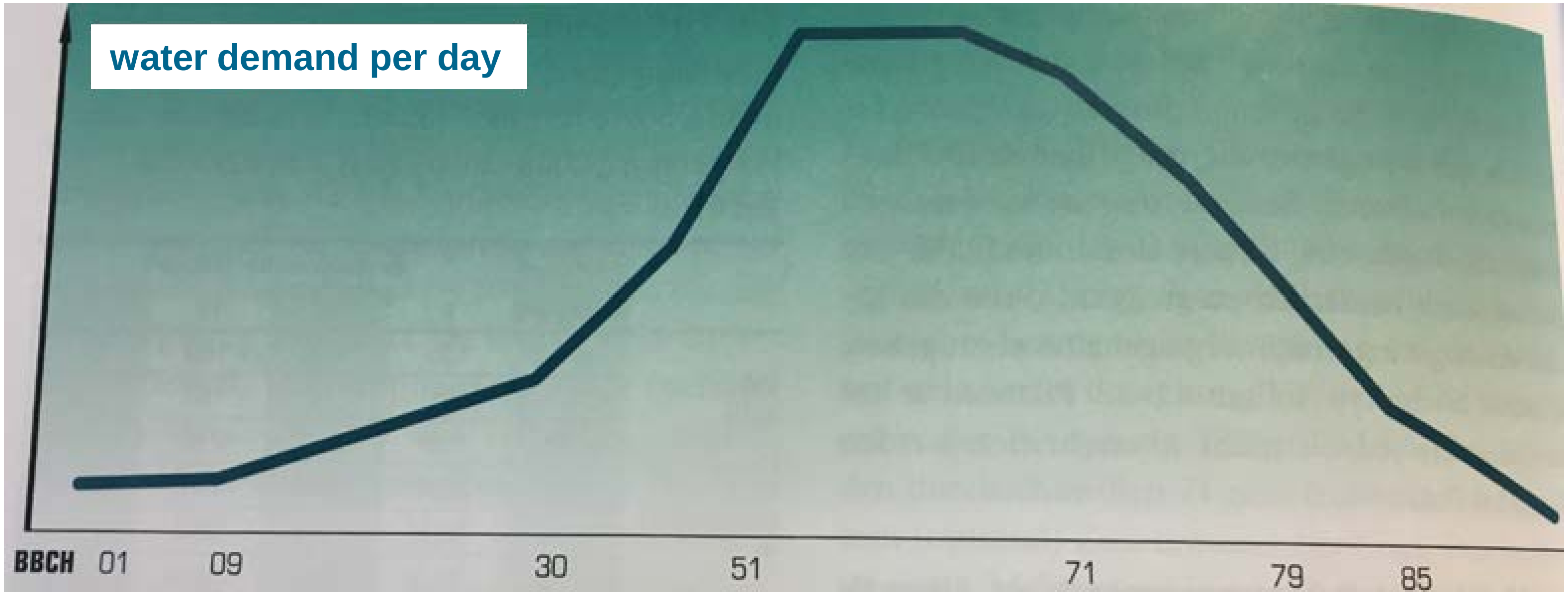
Alternatives besides

- Mulch cover



source: Tolk et al. 1999

water demand of maize in relation to development

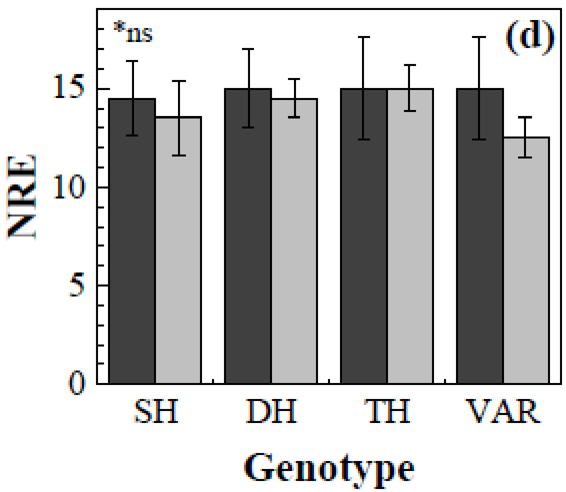


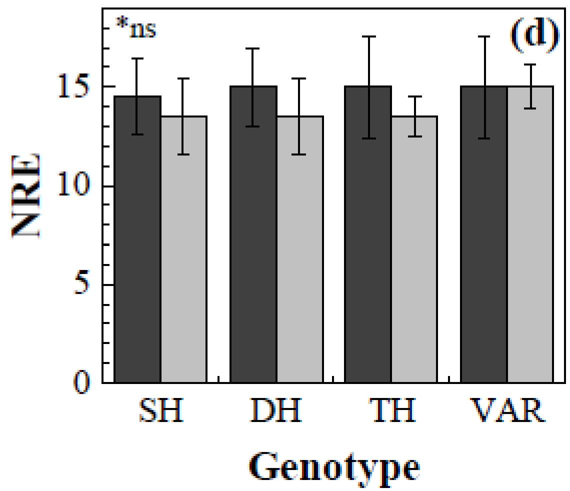
germination | leave dev. | booting | tasseling + anthesis | grain filling | ripening

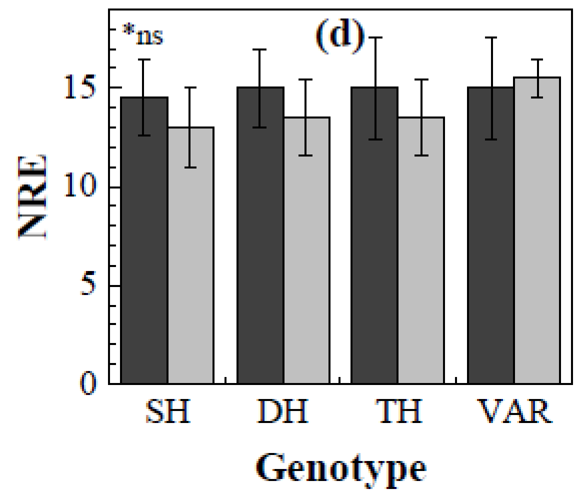
water demand 170 – 220 Liter water for 1 kg DM production

source: Handbuch Mais, 2013

Reaction towards drought at vegetative growth – effects of Genotypes (numbers rows per ear)







1-10 | **11-20** | **21-30**

stage **V4** | **V6** | **V8**

DAE

dark bars: no drought
light bars: drought
Uppercase letters: <u>Genotypes</u>
Lowercase: water regimes

source: Rufino et al. 2018

Effects of contrasting roots

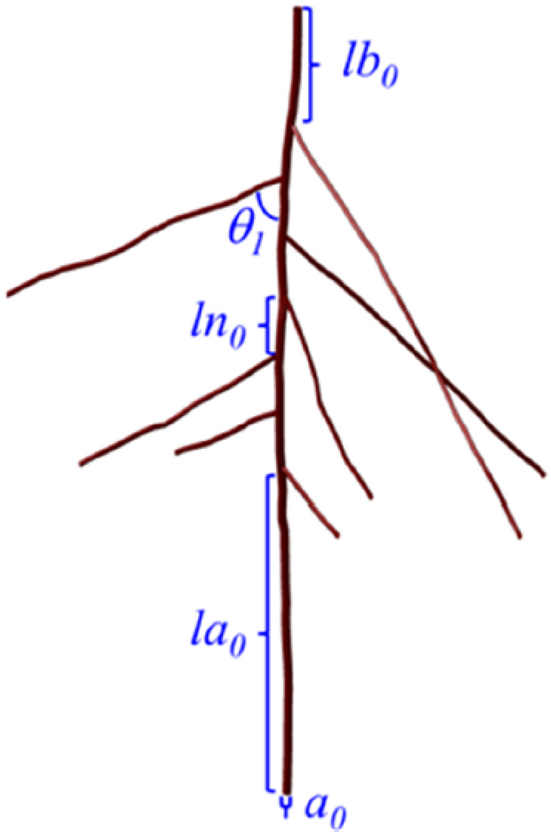


Fig. 1. Root growth parameters of the RootBox model. Each root order or root type is described by the length of the apical zone l_a, basal zone l_b, inter-root distance l_n, branching angle θ, root radius a, and (not visualized) the maximal number of branches *nob*, and root elongation rate *r*.

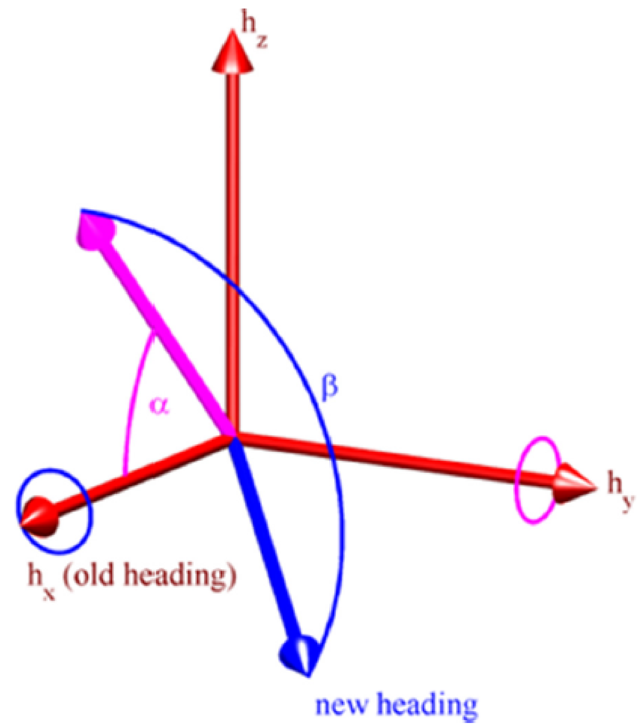


Fig. 2. Change of root tip heading due to two random angles α and β. h_x, h_y and h_z are the axes of the local coordinate system of a root segment, where h_x points into the direction of the old heading.

source: Leitner et al. 2014

root morphology of maize

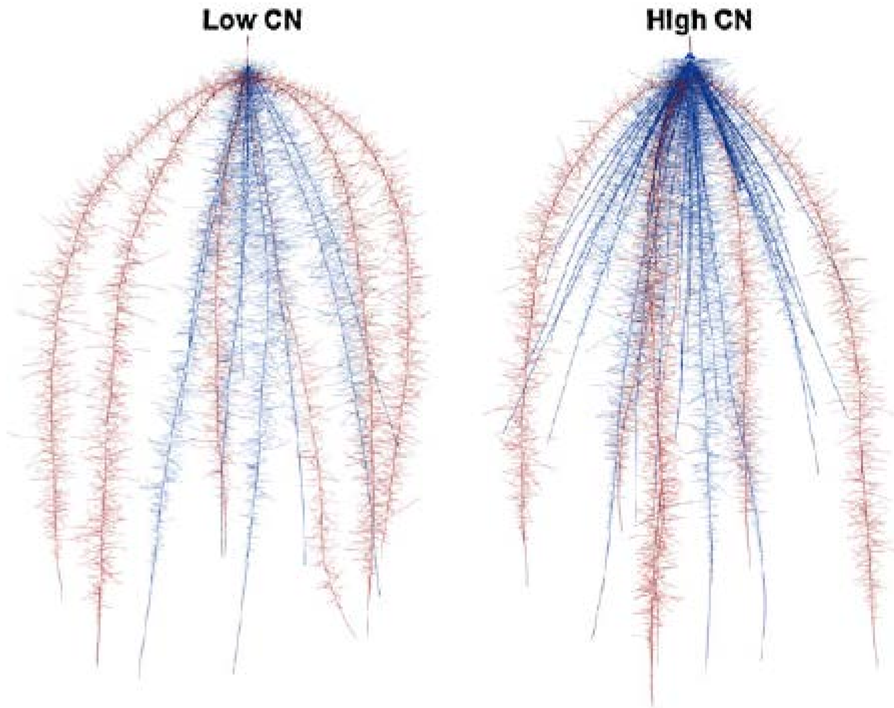


Figure 1. Visualization of maize root phenotypes varying in the number of crown roots (CN) at 40 d after germination. Crown roots are blue and seminal roots are red. The CN is 8 in the low CN phenotype and 46 in the high CN phenotype (image courtesy of Larry M. York).

source: Lynch, 2015

Future aspects drougth and increased CO_2

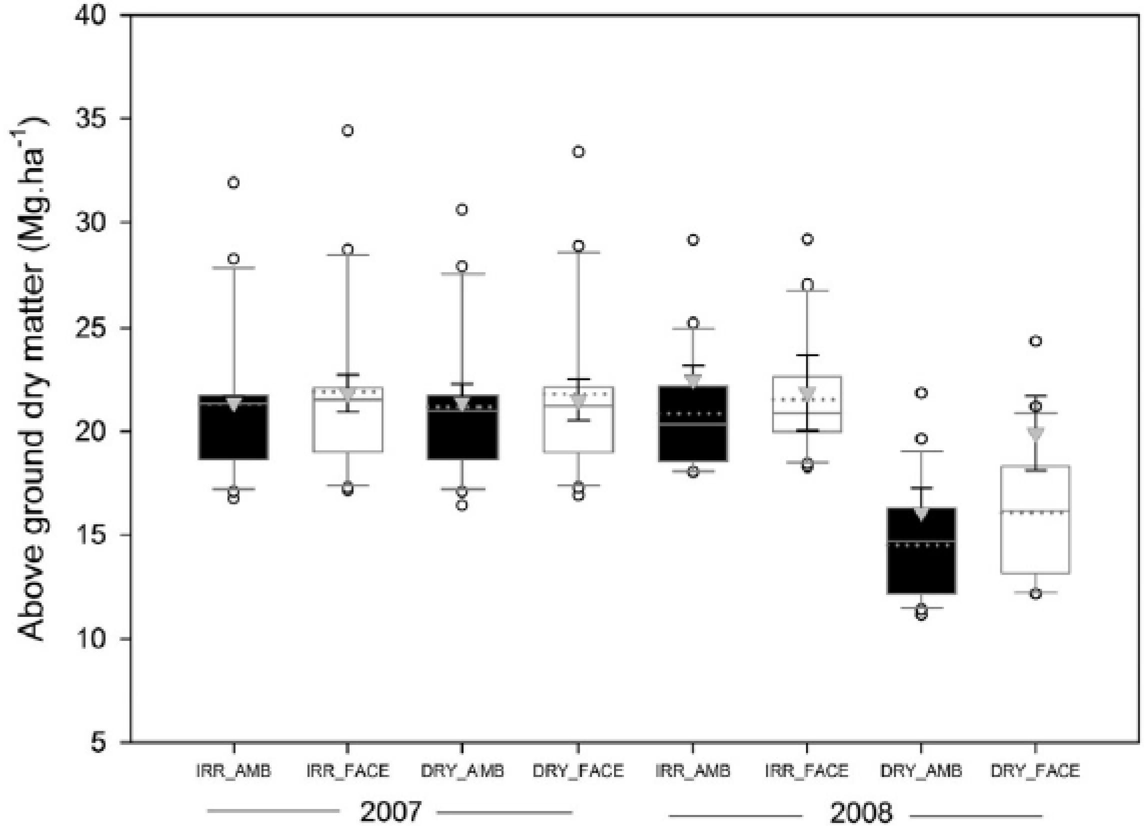


Fig. 3. Inter model variability for above ground biomass (AGB) in 2007 (4 boxes on the left) and 2008 (4 boxes on the right) under dry or wet conditions, at ambient or elevated [CO_2]. The box includes 50% of models, the error bars include 90% of models. The plain horizontal line in the boxes indicates the median and the dotted line indicates the means. The triangles indicate the experimental means. Dots show outliers.

source: Durand et al. (2017) E.Journal.Agron

Effects of contrasting roots

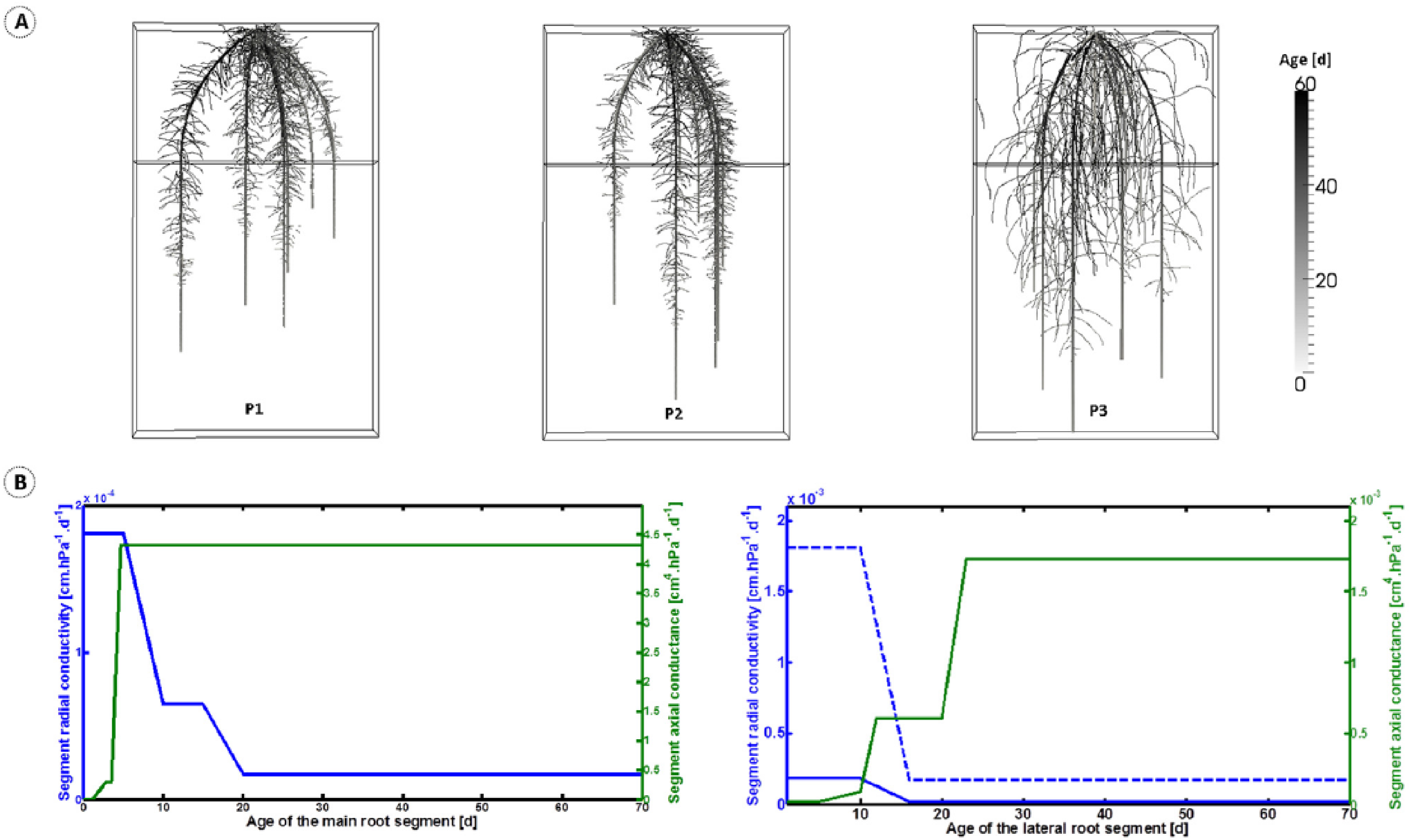


Fig. 3. (A) Architecture and age distribution of the root segments for a realization of each phenotype (P1, P2 and P3, respectively) and the separation line for the initial water content. (B) Age dependent root radial conductivity and axial conductance of primary (left) and lateral roots (right). In subplot B, solid and dashed lines stand for reference and increased conductivities, respectively.

source: Leitner et al. 2014

Future aspects drougth and increased CO_2

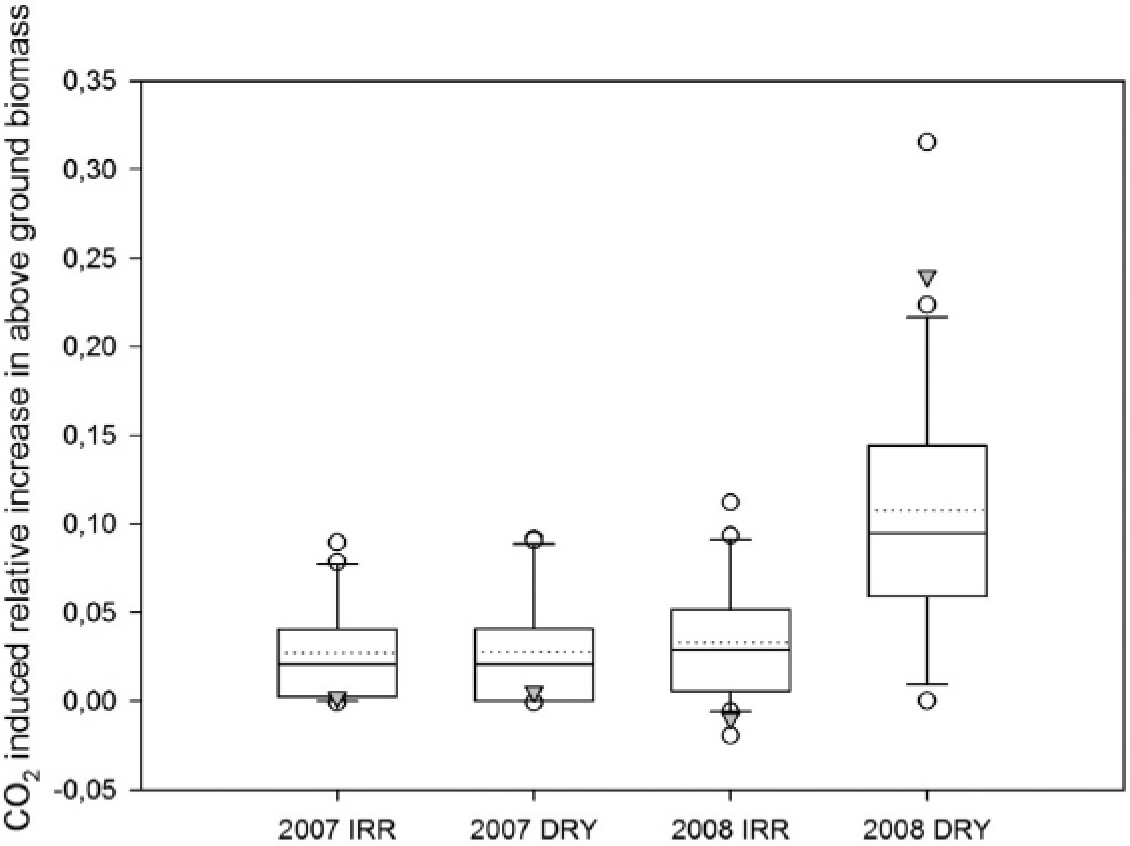


Fig. 6. Simulated relative increase of maize Above Ground Biomass at 550 ppm *versus* the ambient air [CO_2] in 2007 and 2008 for irrigated and dry plots: ((FACE-AMBIENT)/AMBIENT).

source: Durand et al. (2017) E.Journal.Agron

Future aspects drougth and increased CO_2

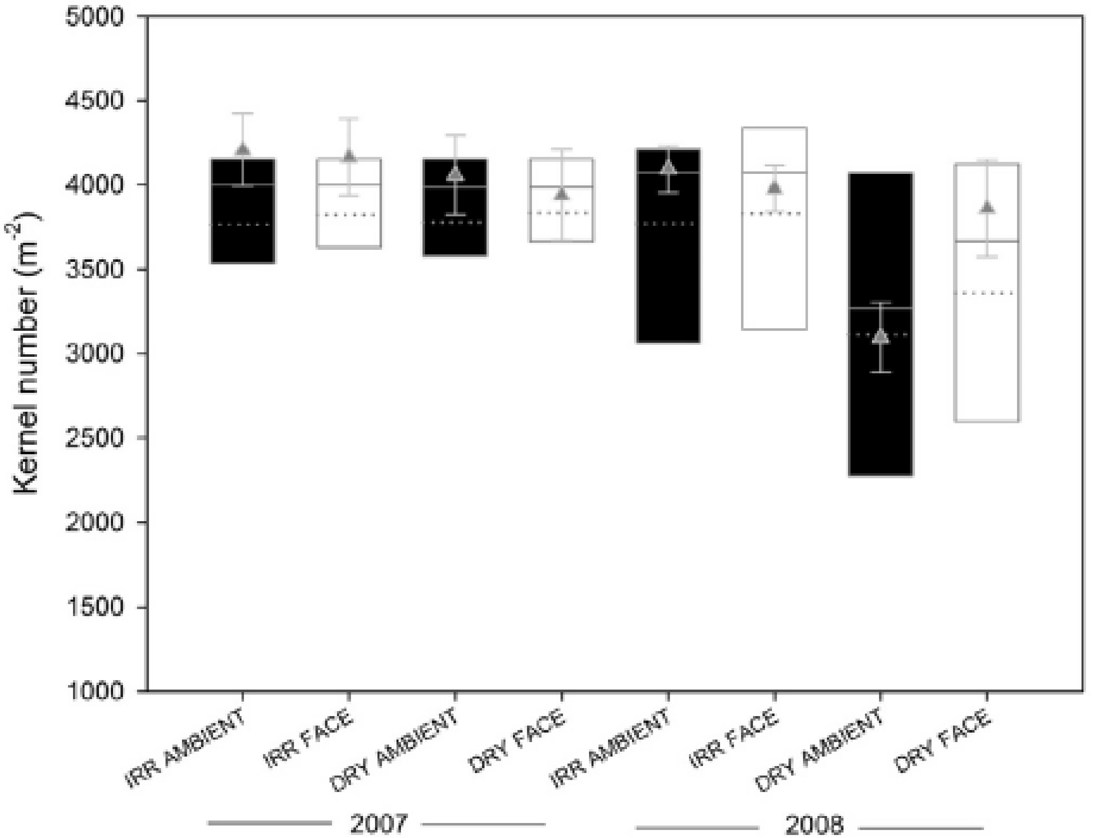


Fig. 2. Inter model variability for kernel number in 2007 (4 boxes on the left) and 2008 (4 boxes on the right) under dry or wet conditions, at ambient or elevated [CO_2]. The box includes 50% of models, the error bars include 90% of models. The plain horizontal line in the boxes indicates the median and the dotted line indicates the means. The triangles indicate the experimental means. Dots show outliers.

source: Durand et al. (2017) E.Journal.Agron

Effects of contrasting roots

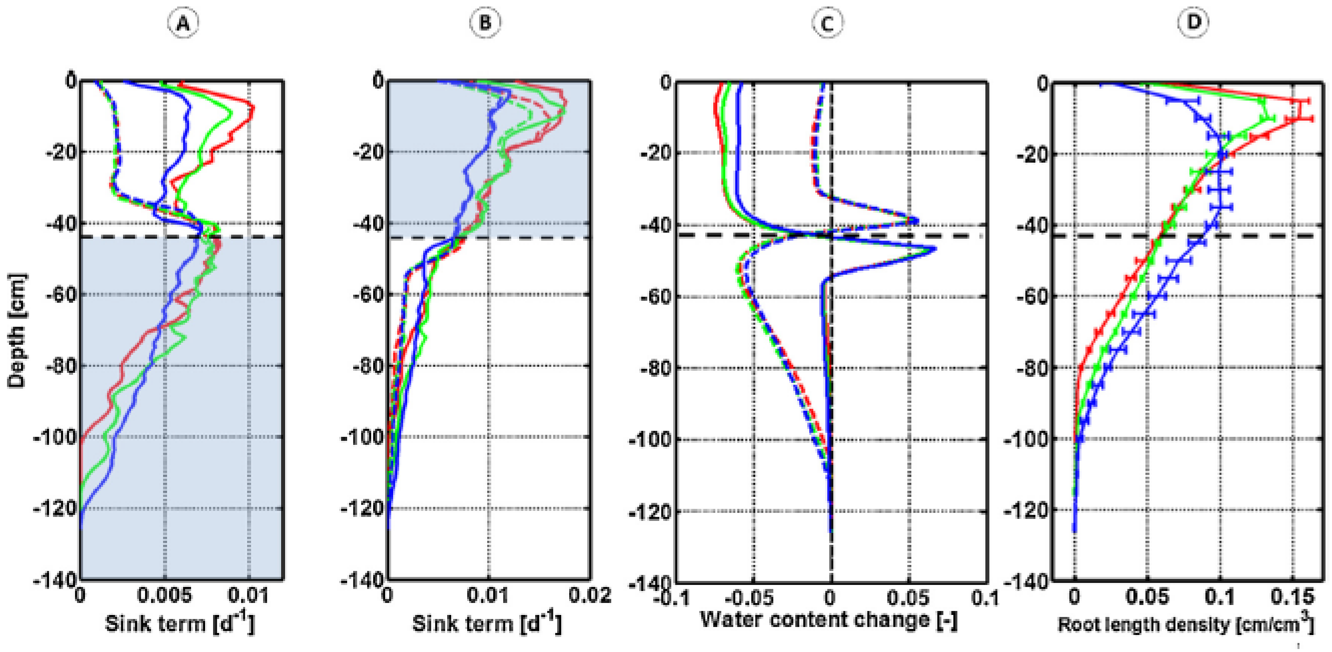


Fig. 8. 1-D sink term profile under scenario SWbot (A) and SWtop (B) after 0.5 (solid lines) and 6.5 (dashed lines) days and corresponding water changes (C) and root length densities (D). Red: P1, green: P2 and blue: P3. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

source: Leitner et al. 2014

Effect of irrigation

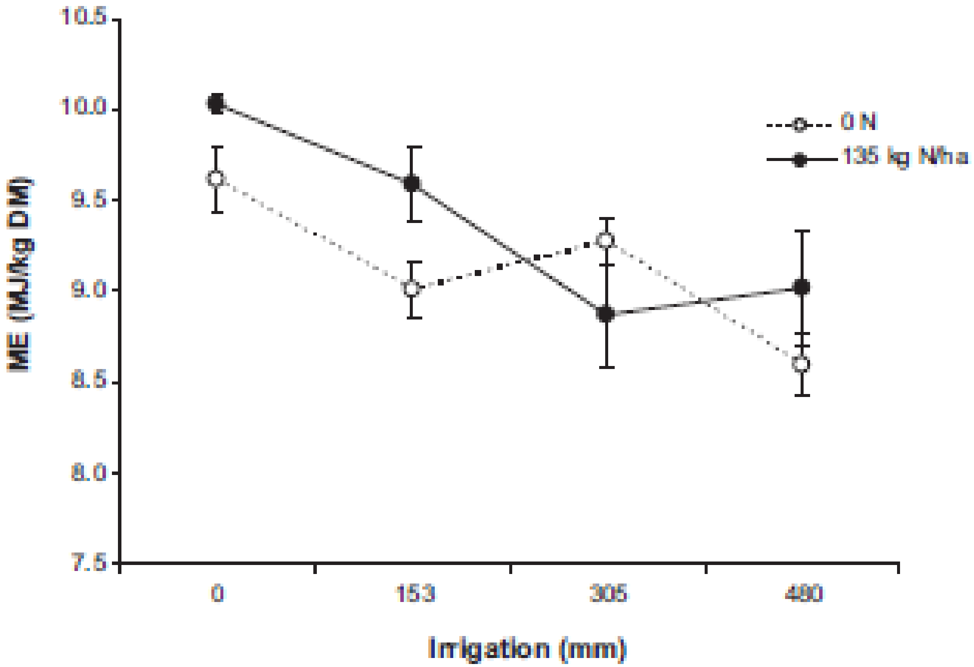
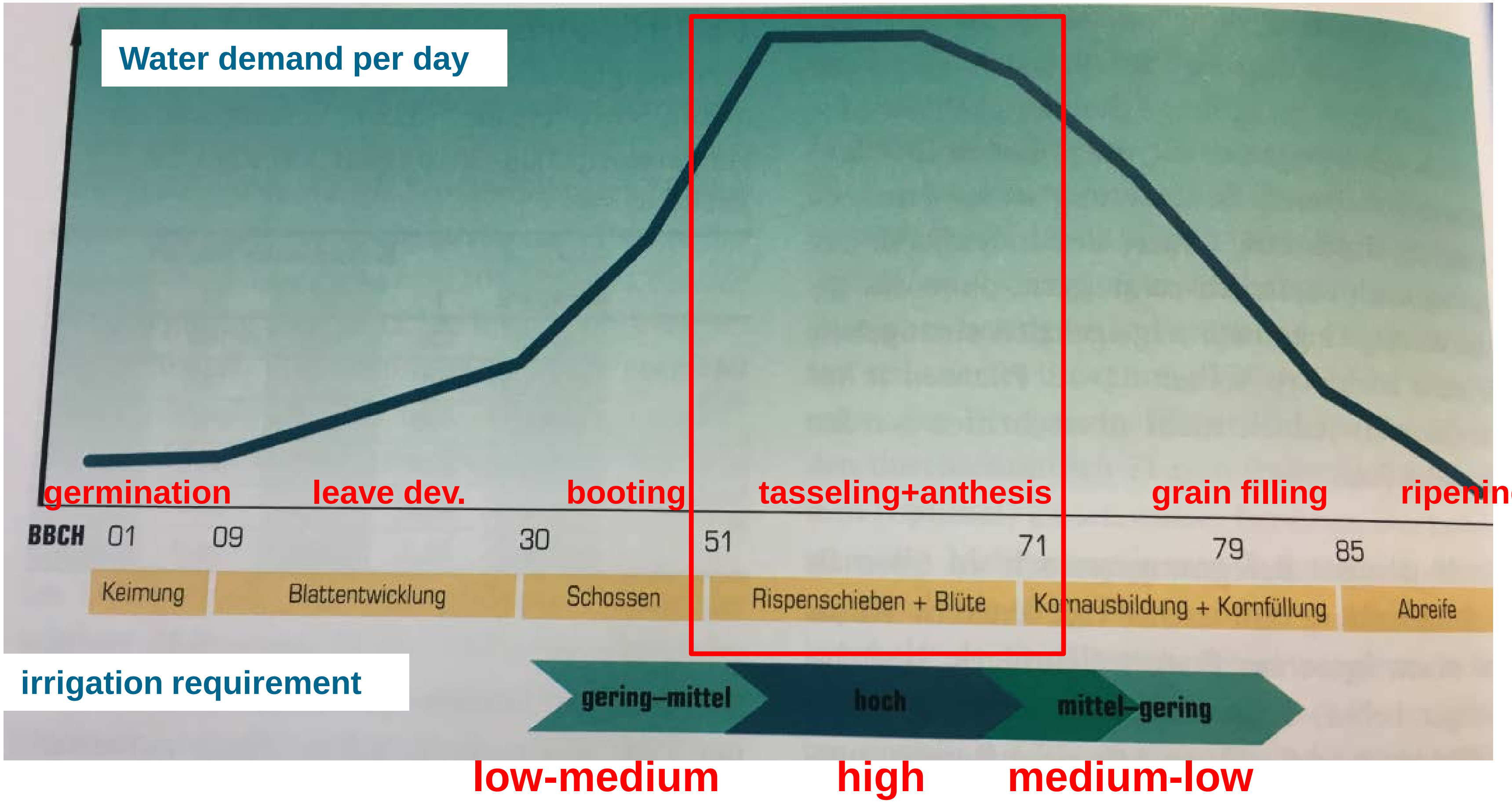


Fig. 1. Interaction between of irrigation water × pre-sown N fertilizer (0, 135 kg N/ha) on metabolizable energy (ME) content of maize silage (bar indicates ± SEM).

source: Islam et al., 2012

water demand of maize in relation to the development



source: Handbuch Mais, 2013

water demand for yield formation

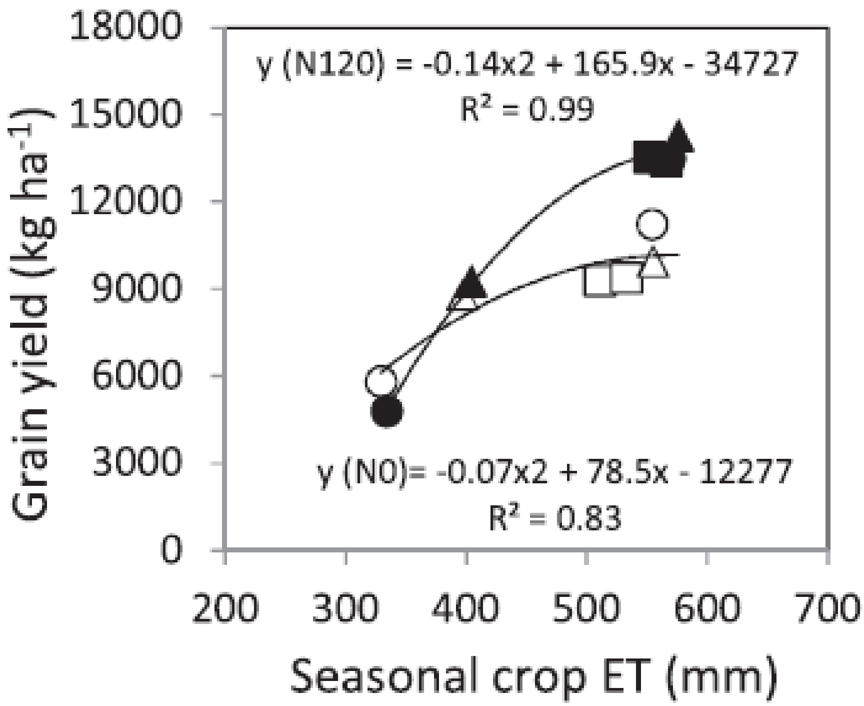
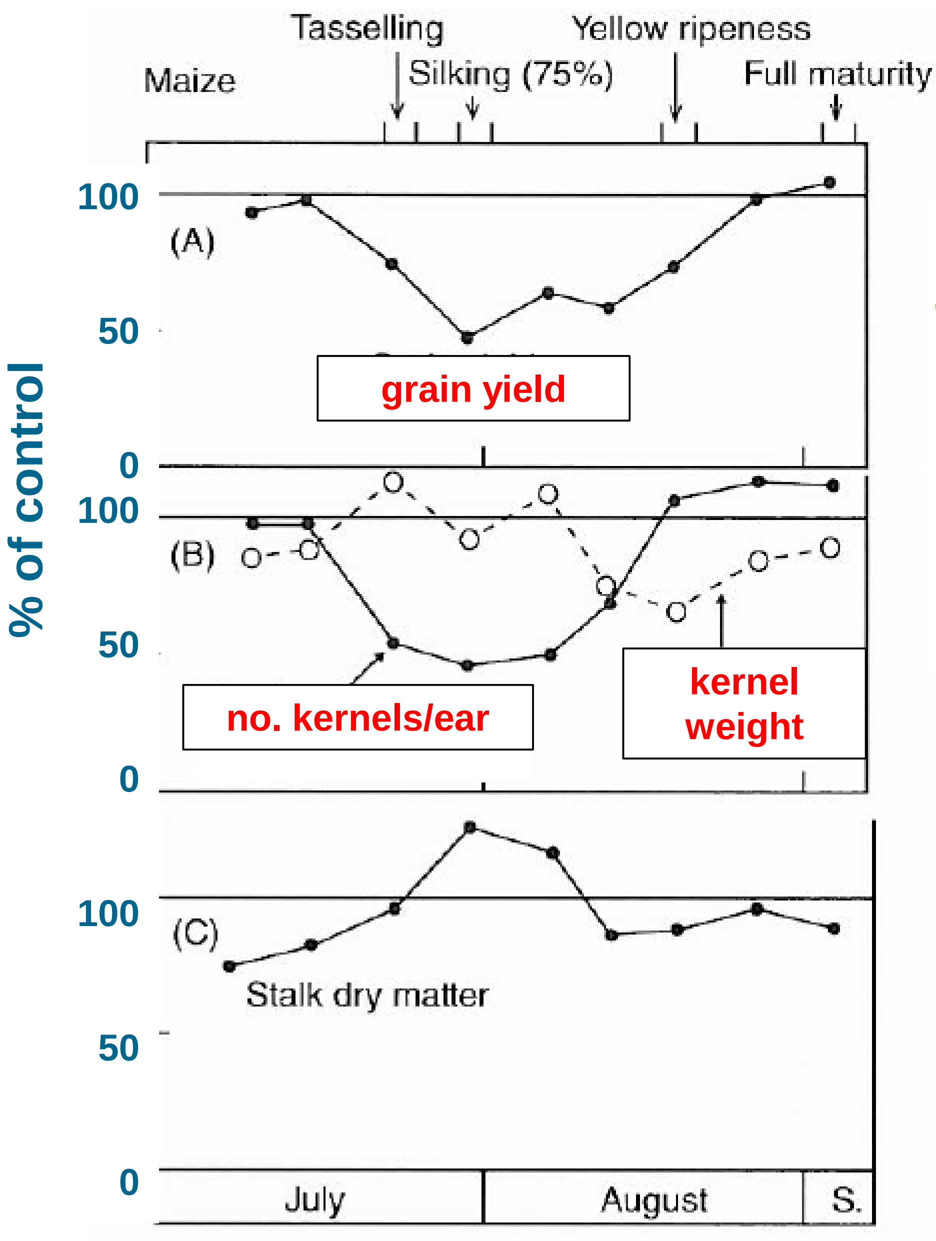
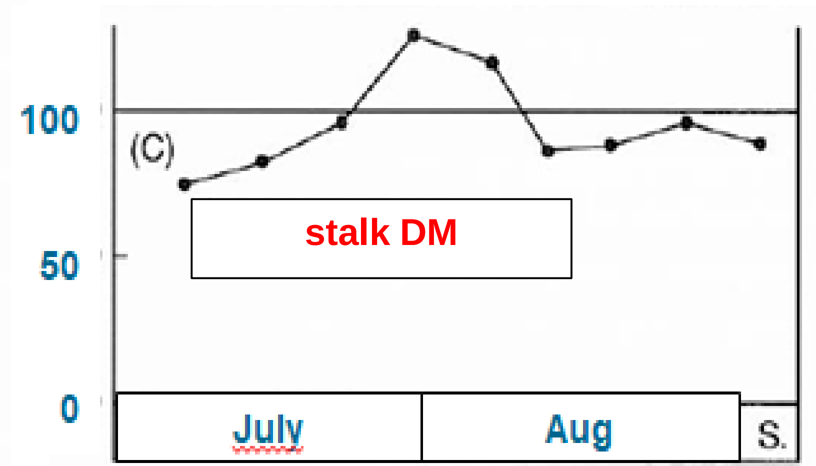


Fig. 2. Mean grain yield (kg ha^{-1}) as a function of mean seasonal crop evapotranspiration (ET, mm) for two N supply treatments (0 N, white symbols; 120 kg ha^{-1} N, solid symbols) across water regimes and three seasons (Season 1, circles; Season 2, squares; Season 3, triangles). Standard errors for grain yield were 460, 280 and 465 kg ha^{-1} for Seasons 1, 2 and 3, respectively. Standard errors for seasonal crop ET were 7.2, 8.9 and 5.6 mm for Seasons 1, 2 and 3, respectively.

source: Hernandez et al. 2015 FieldCropsRes.

drought during different stages of development





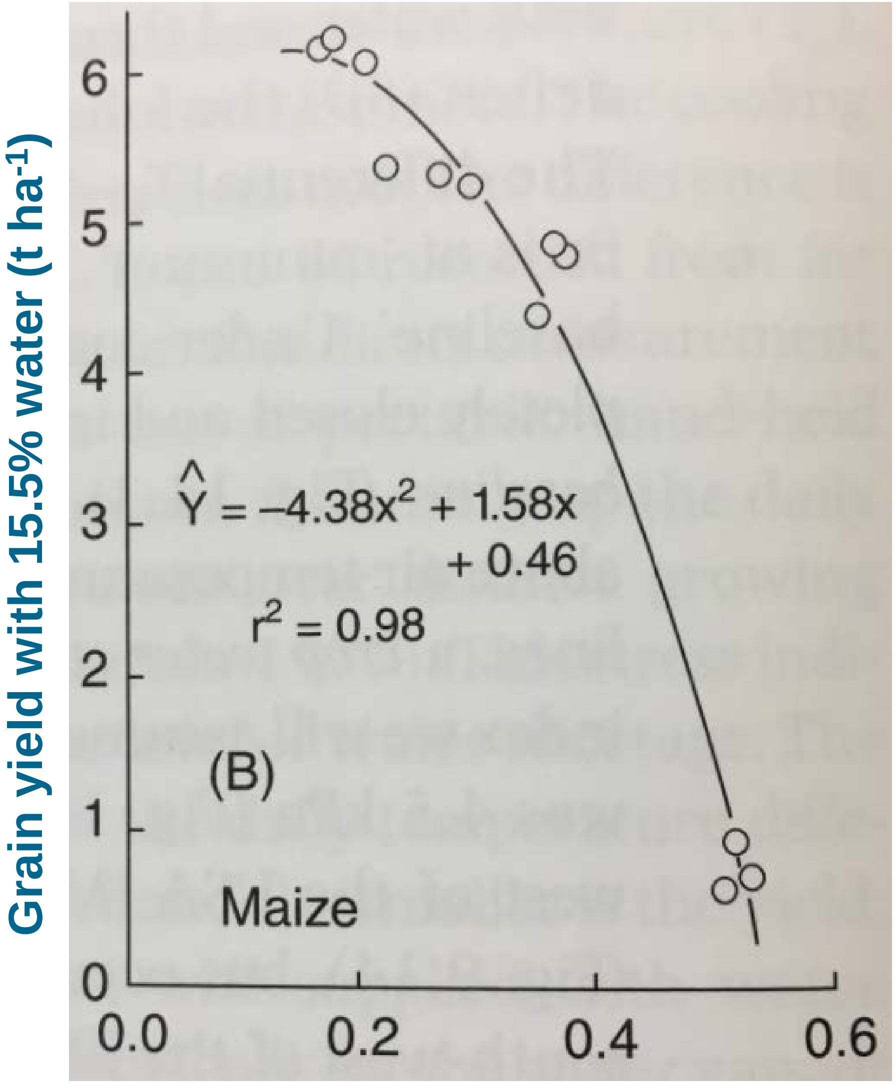
from Claassen & Shaw, 1970a,b

a problem for maize – were is maize grown?
acreage of silage maize in EU-28

	2013	2014	2015	2016	2017
Deutschland	2.003	2.093	2.100	2.138	2.096
Frankreich	1.487	1.412	1.475	1.433	1.425
Italien	327	343	337	321	327
Niederlande	230	226	224	204	205
Belgien/Lux.	191	193	188	184	186
V. Königreich	183	171	179	186	195
Dänemark	181	178	183	182	167
Spanien	107	113	108	106	105
Portugal	84	85	81	79	79
Österreich	111	83	92	85	82
Polen	462	541	555	597	560
Slowakai	93	86	89	78	80
Tscheschien	234	237	245	234	225
Ungarn	102	85	90	76	65
EU 28	**5.992**	**6.077**	**6.262**	**6.251**	**6.119**

no Sweden

measuring water stress (CSWI)



CSWI – Crop water stress Index

Maize grown in Antalya (Turkey) daily CSWI values are provided averaged from early pollination to mid-Sep

source: Abdul-Jabbar et al. 1985; Irmak et al. 2000

Reaction towards drought – absisic acid accumulation

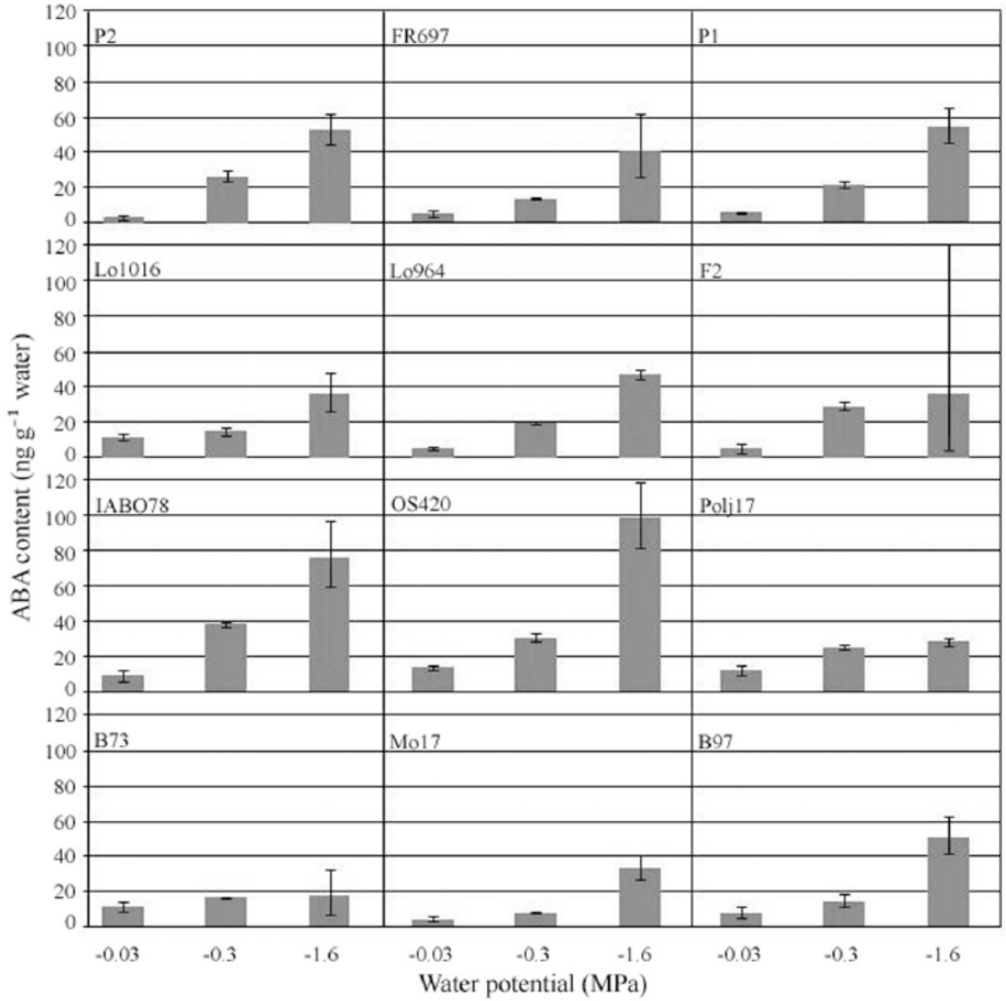


Figure 3. Histograms displaying abscisic acid (ABA) content of the primary root elongation zone expressed as ng ABA g^{-1} water for each water potential treatment where –0.03 MPa = well watered (WW), –0.3 MPa = mild stress (MS), and –1.6 MPa = severe stress (SS). Error bars represent the interpolated ABA content for one standard deviation from the median optical density. Ordered from upper left to lower right as determined by root elongation rank under SS.

source: Leach et al. (2011) Crop Science