Water stress on plants :

from molecular responses to yield formation in the field

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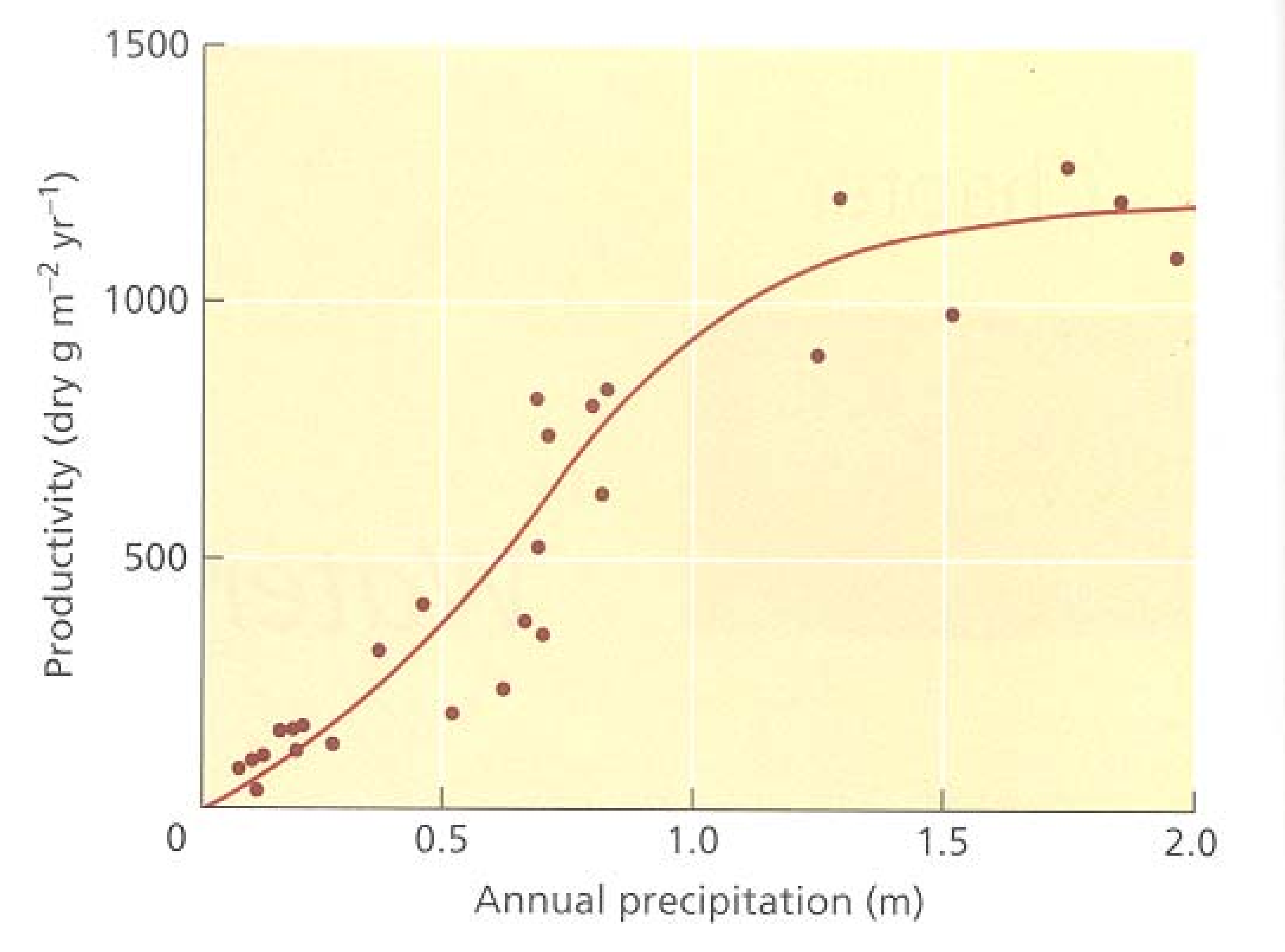
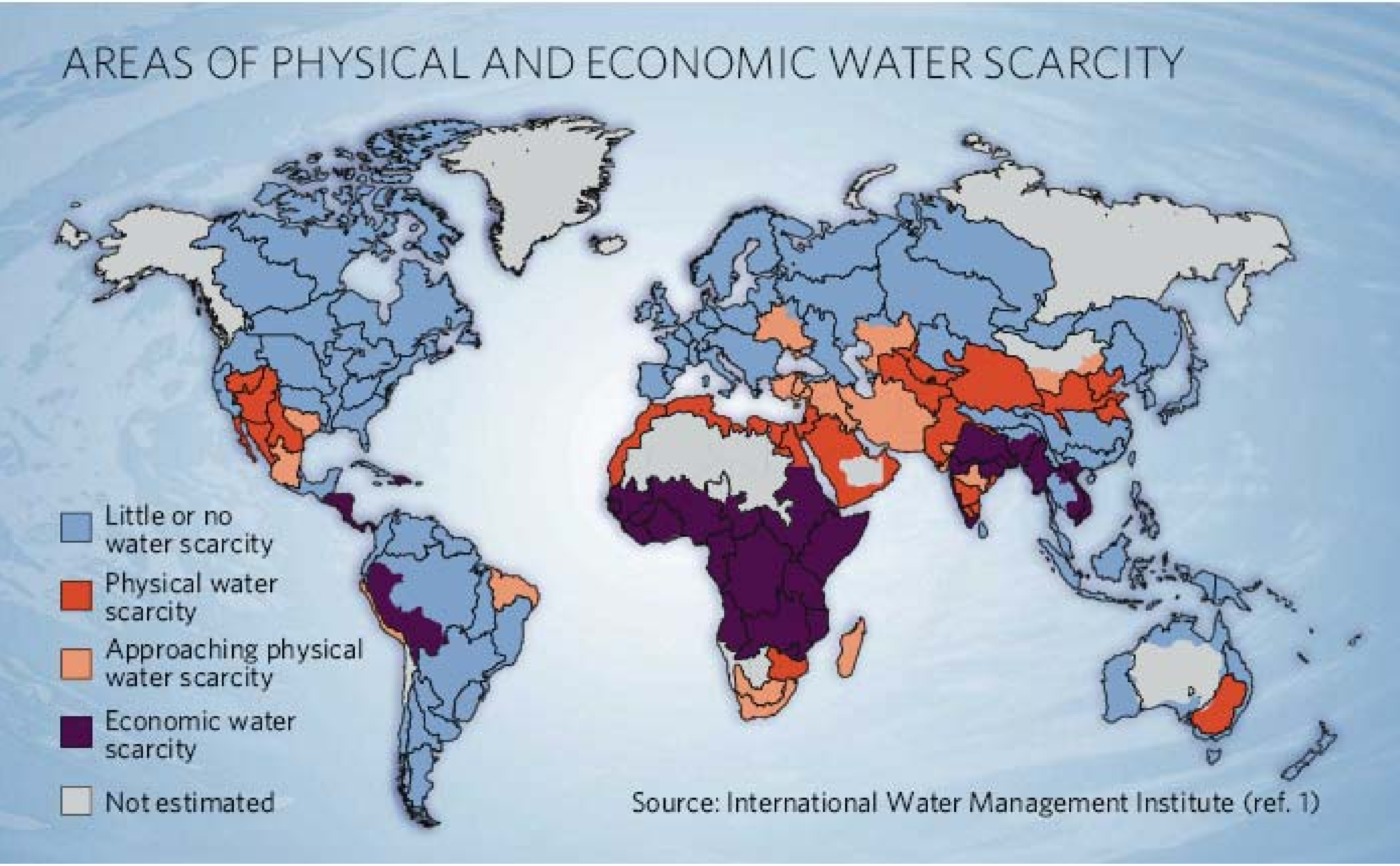
Water, the life line for plant productivity.

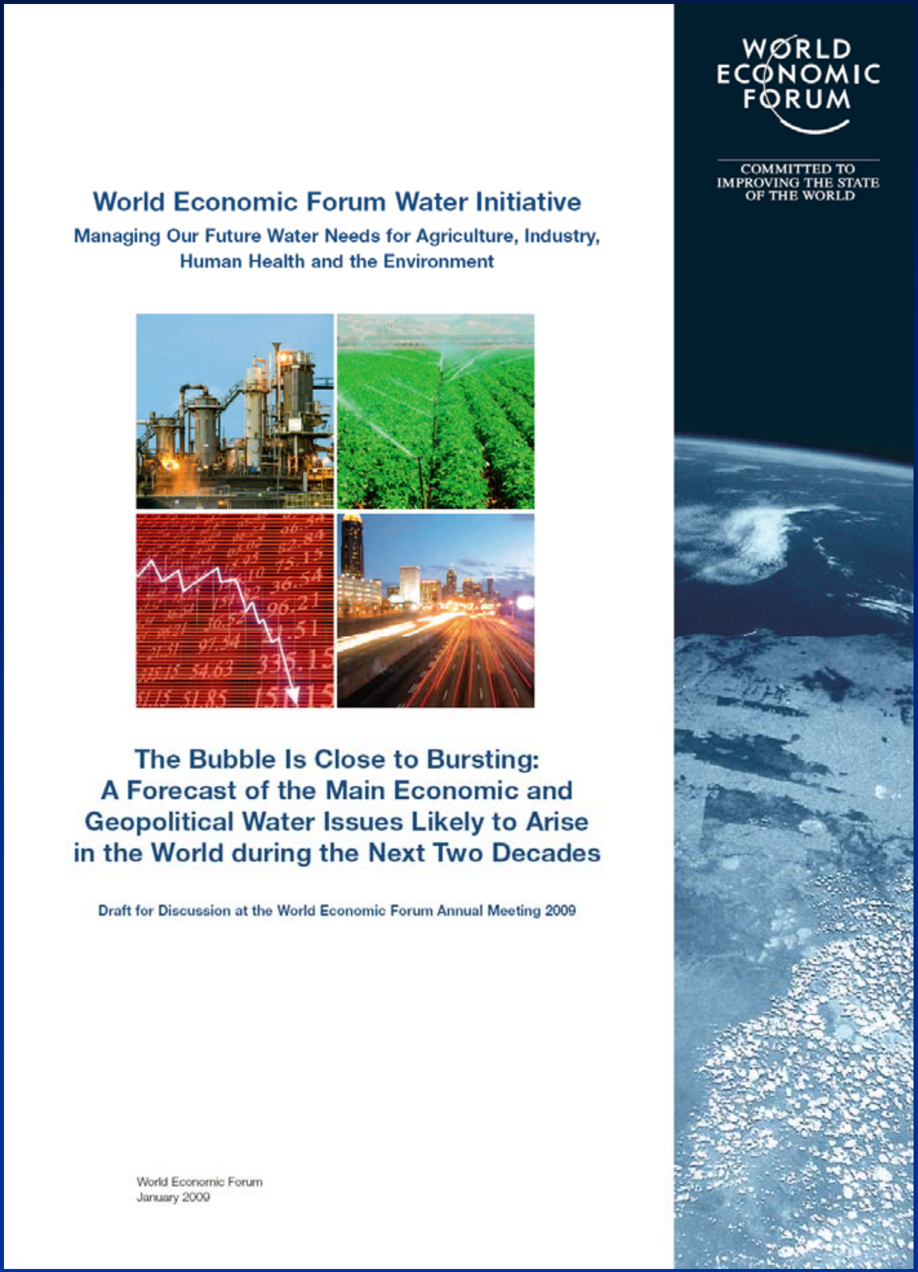
The more water, the lusher the vegetation



Whittaker 1970

1.2 billion people live in areas without enough water for everyone's needs





From 1900 to 2000, global water use increased by **9** folds, population by **4** folds.

70% is used for agriculture,
but only **50%** is used by the crops.

2.8 billion in areas of high water stress,
3.9 billion by 2030 if business-as-usual.

If business-as-usual, global crop yield loss will be **30%** of current yield by 2025, **55%** population will rely on food imports.

World Economic Forum, Davos
January 2009

Water shortage in agriculture:

Rapid expansion of cropped land and over-irrigation for high yield

'Blue Revolution – more crop for every drop'

Norman E. Borlaug
Nobel Peace Prize Laureate 1970

Water shortage in China:

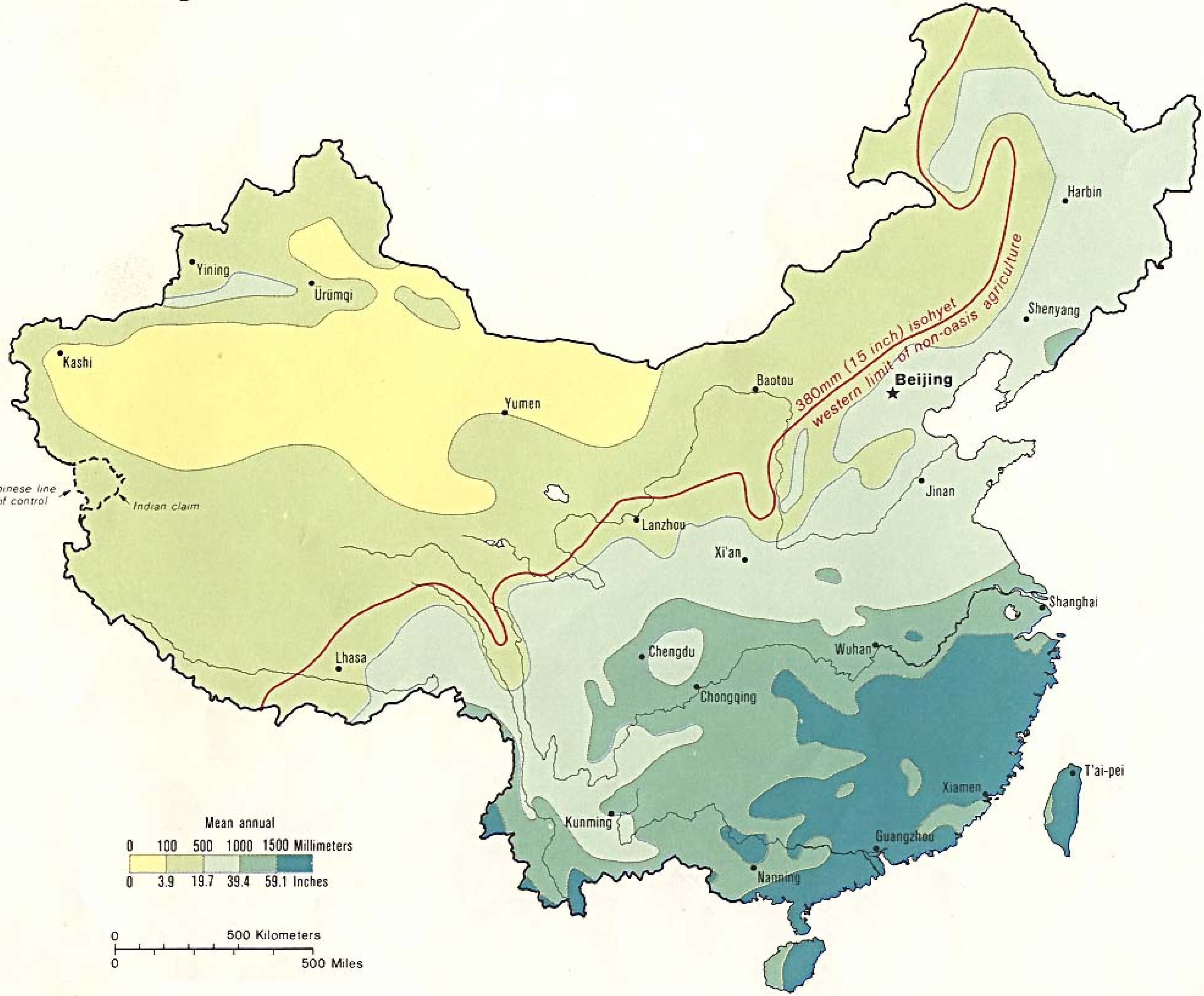
China's water resource per capita is only 1/4 of the world average,

Northern China is only 1/24 ,

Northwest China: 1/3 the nation's land, 8.3% the water resources, <400 mm per year.

Irrigation uses 70% of the total water resources and is the only way for stable agriculture.

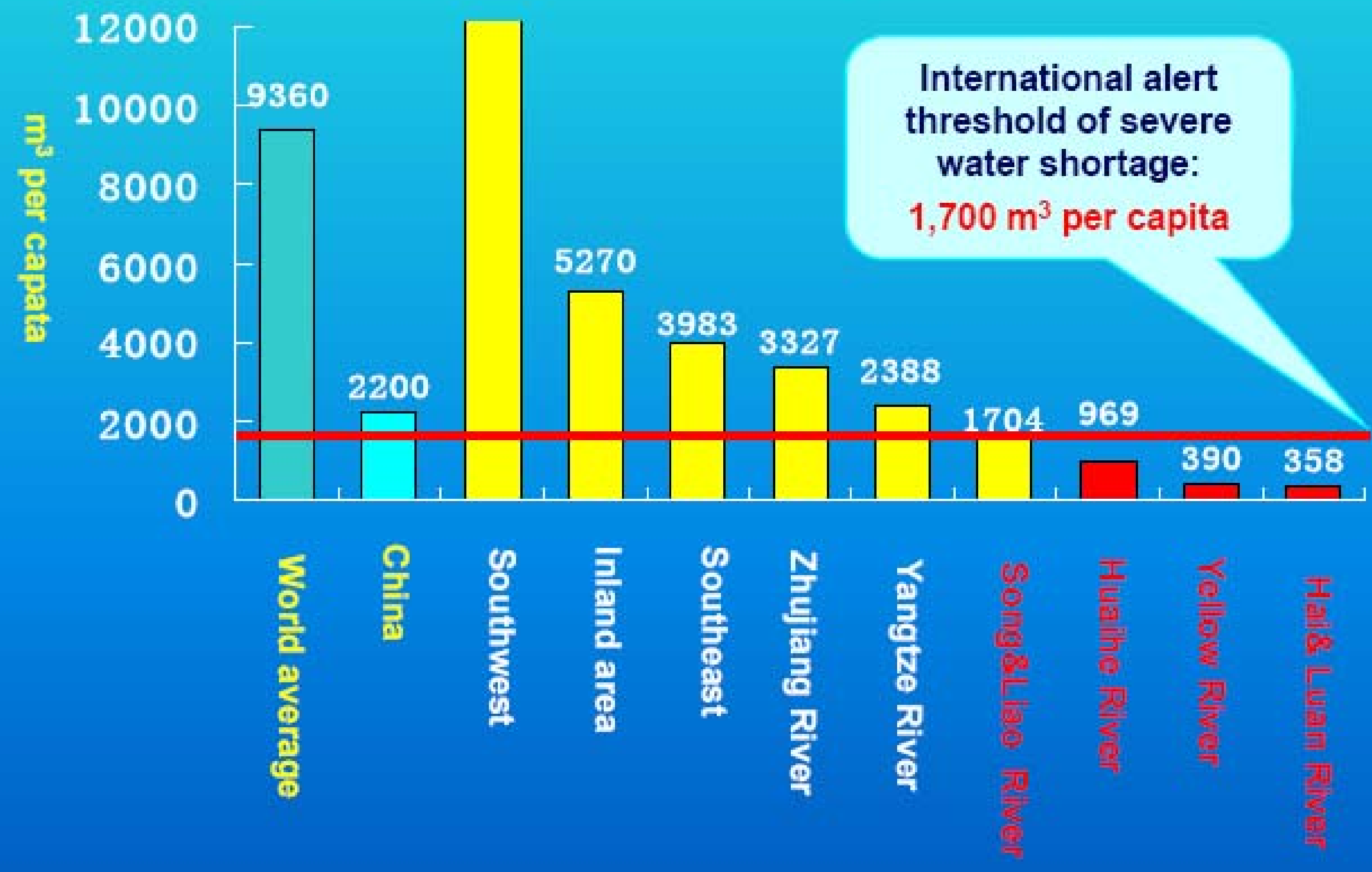
China: Precipitation



Boundary representation is not necessarily authoritative.

1. Water shortage in China

- Total water resources amount: 2,810 billion m^3
- Water resources per capita <2200 m^3, only 1/4 of the world average
- Irrigation is the only way for sustainable agriculture in North China



1. Water shortage in China

Competition for the limited water resource between agriculture and ecosystem is increasingly becoming a serious problem in North China Plain.

Yongding River in Beijing

Reservoirs Dried up

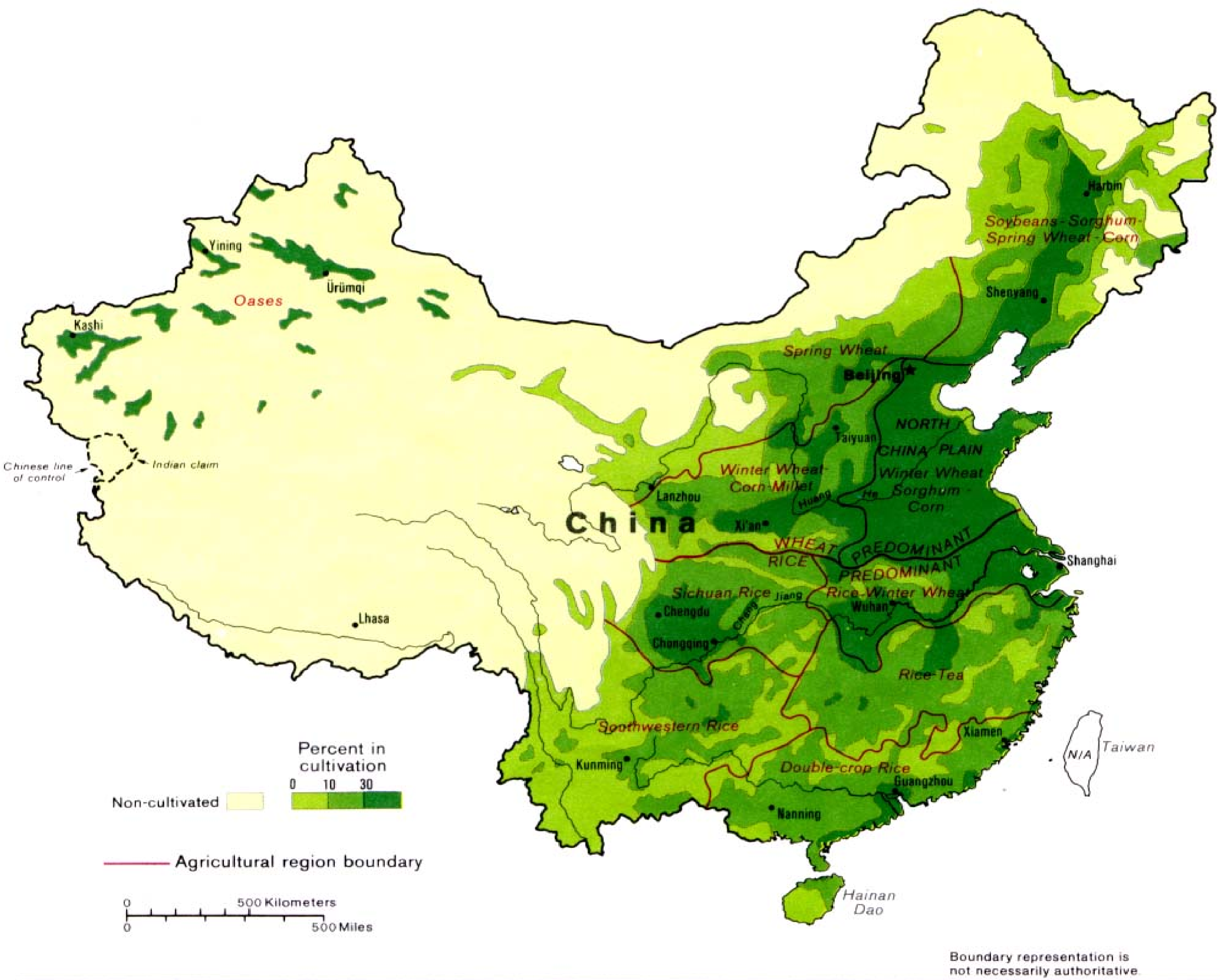
Deep groundwater pumping

Winter wheat drought

Summer maize drought

Ground subsidence

Agricultural Regions



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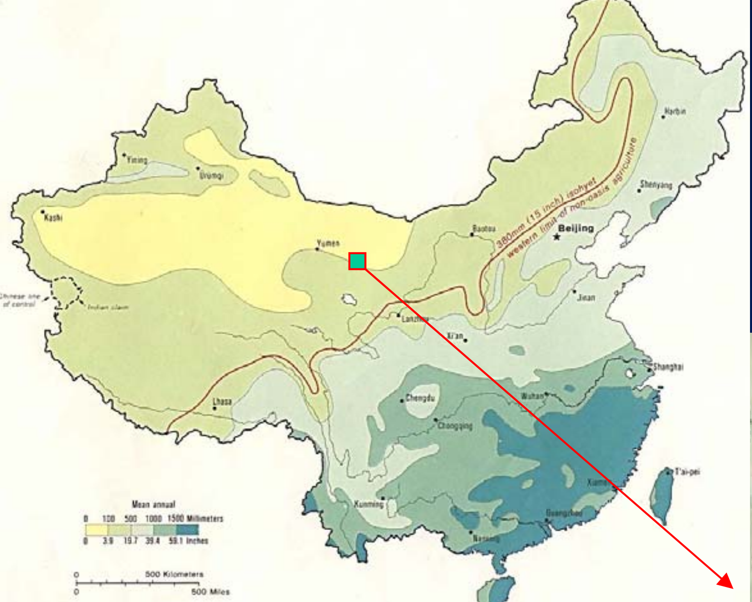
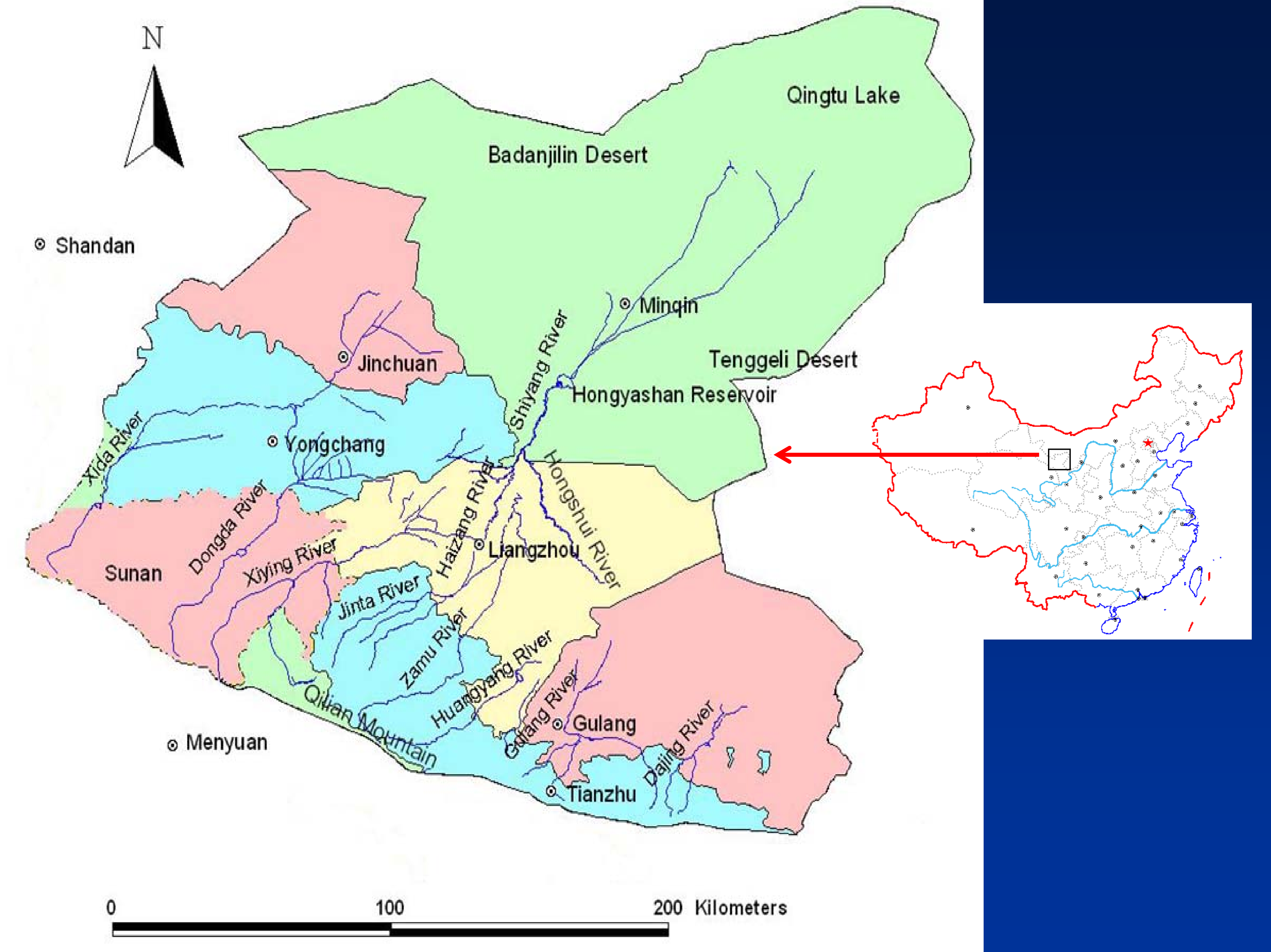
Min Qin,
a disappearing oasis?



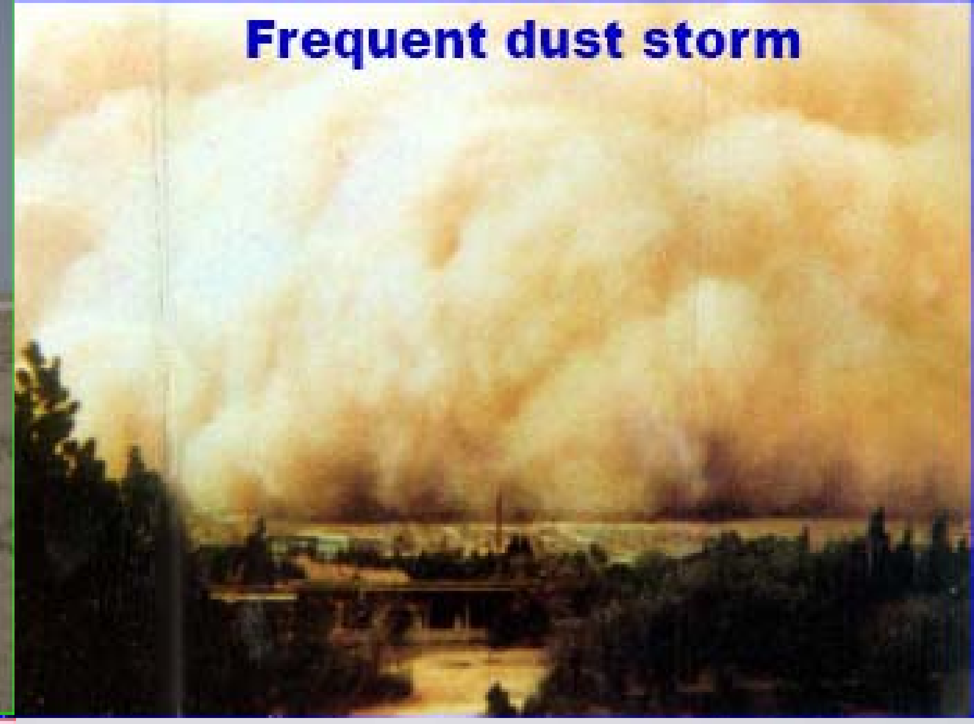

N
Qingtu Lake
Badanjilin Desert
Shandan
Minqin
Tenggeli Desert
Jinchuan
Shiyang River
Hongyashan Reservoir
Xida River
Yongchang
Hongshui River
Haizang River
Dongda River
Liangzhou
Sunan
Xiying River
Jinta River
Zamu River
Huangyang River
Gulang River
Gulang
Qilian Mountain
Menyuan
Dajing River
Tianzhu
0
100
200 Kilometers


In the old days

Qingtu Lake in Min Qin, from lake to desert in 40 years

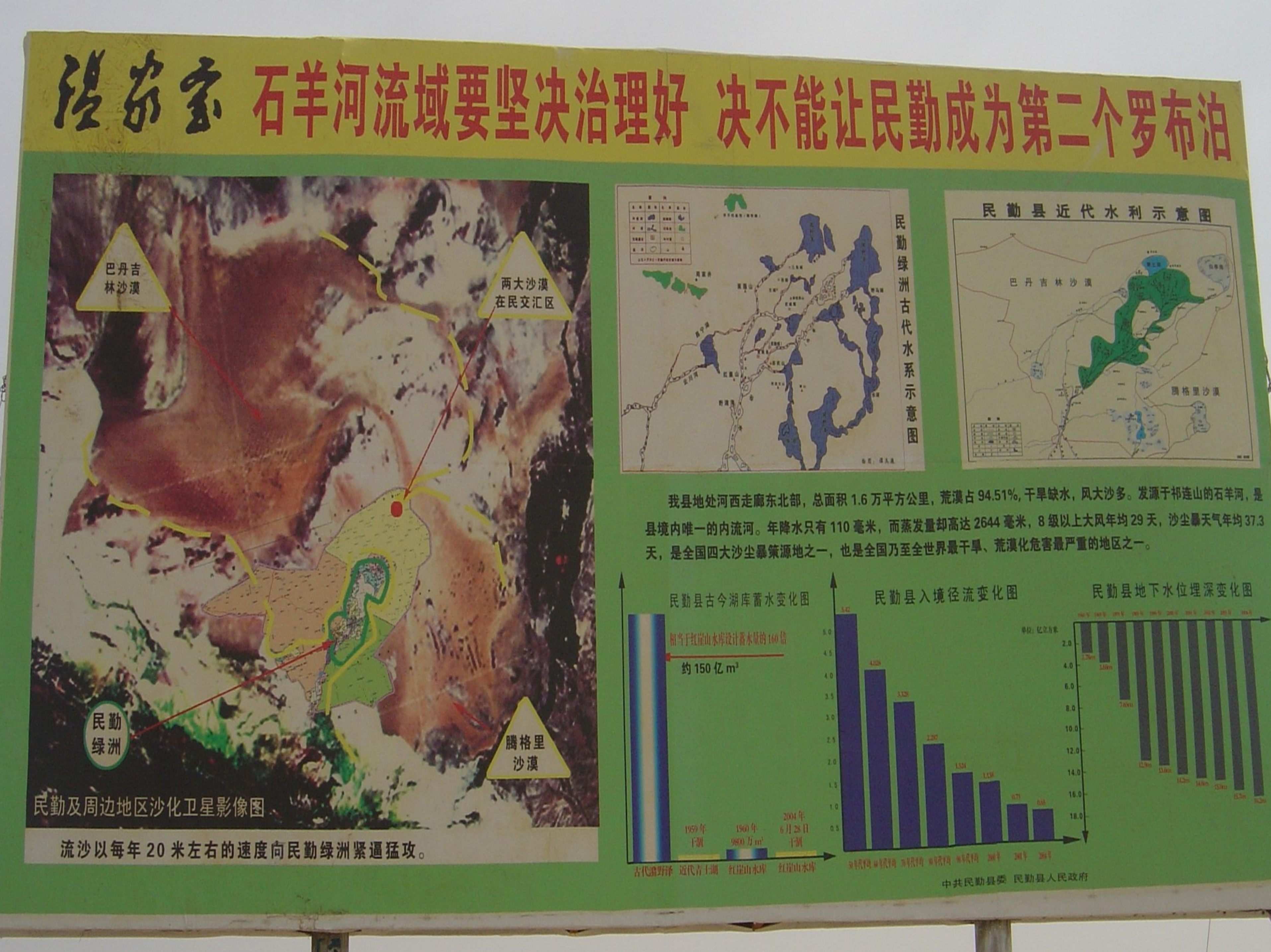
Reeds and remaining shells


Soil salinization&desertification


Frequent dust storm

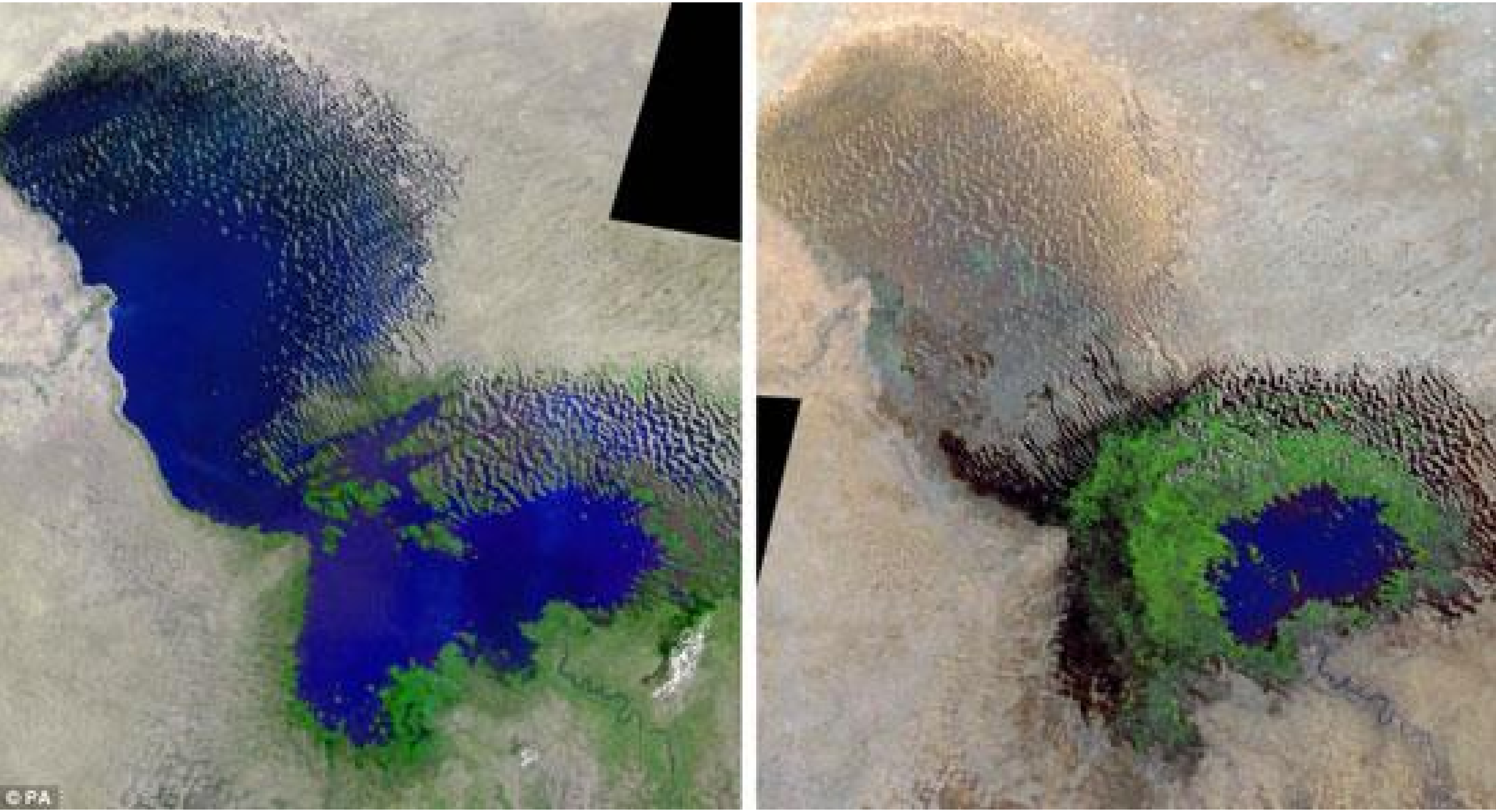

Long way for drink water


Abandoned village

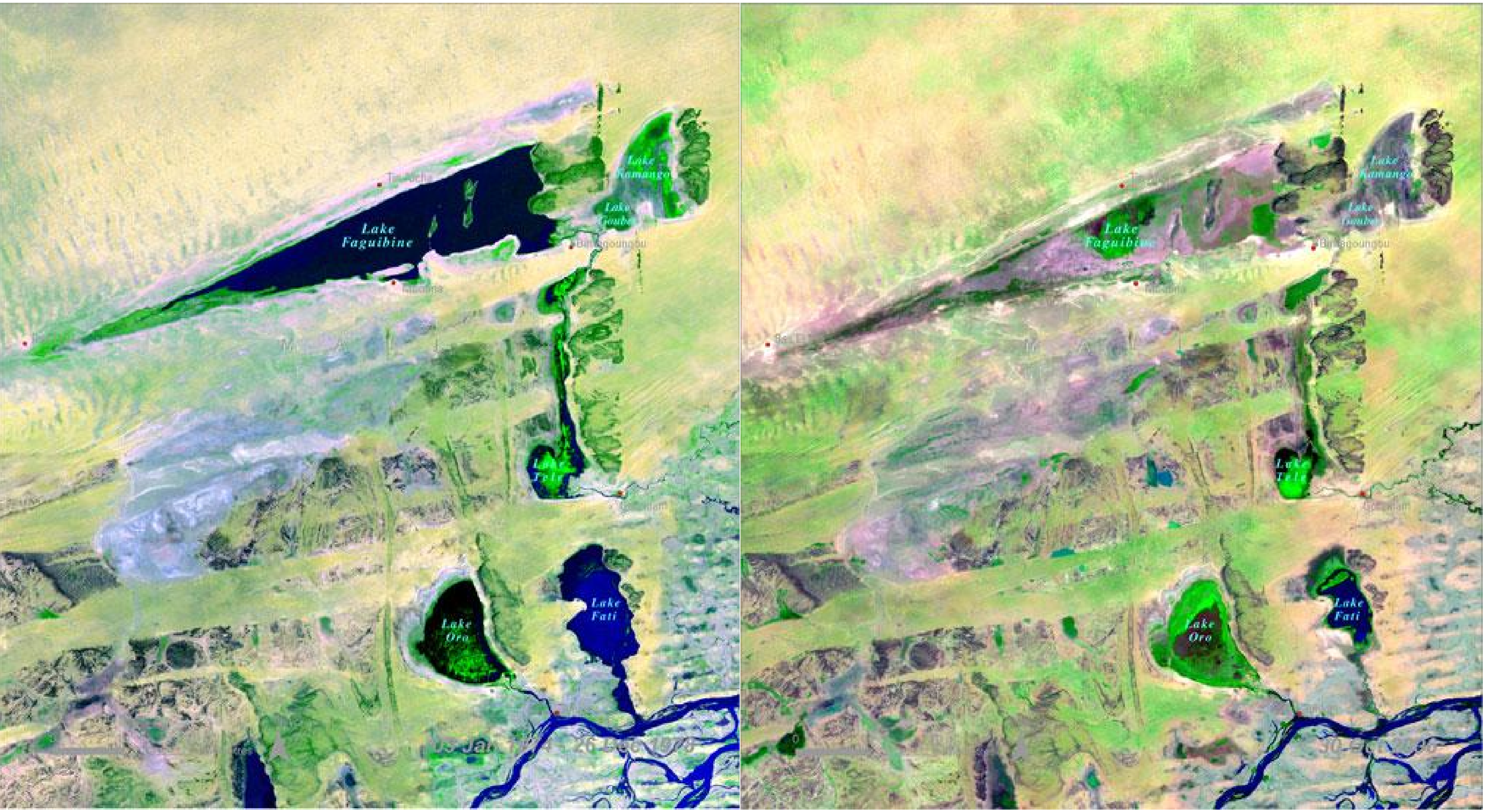


張家秦
石羊河流域要坚决治理好 决不能让民勤成为第二个罗布泊
巴丹吉林沙漠
两大沙漠在民交汇区
民勤绿洲
腾格里沙漠
民勤及周边地区沙化卫星影像图
流沙以每年 20 米左右的速度向民勤绿洲紧逼猛攻。
民勤绿洲古代水系示意图
民勤县近代水利示意图
巴丹吉林沙漠
腾格里沙漠
我县地处河西走廊东北部，总面积 1.6 万平方公里，荒漠占 94.51%，干旱缺水，风大沙多。发源于祁连山的石羊河，是县境内唯一的内流河。年降水只有 110 毫米，而蒸发量却高达 2644 毫米，8 级以上大风年均 29 天，沙尘暴天气年均 37.3 天，是全国四大沙尘暴策源地之一，也是全国乃至全世界最干旱、荒漠化危害最严重的地区之一。
民勤县古今湖库蓄水变化图
相当于红崖山水库设计蓄水量的160倍
约 150 亿 m³
1959年 干涸
1960年 9800万m³
2004年 6月28日 干涸
古代潴野泽
近代青土湖
红崖山水库
红崖山水库
民勤县入境径流变化图
民勤县地下水位埋深变化图
中共民勤县委 民勤县人民政府

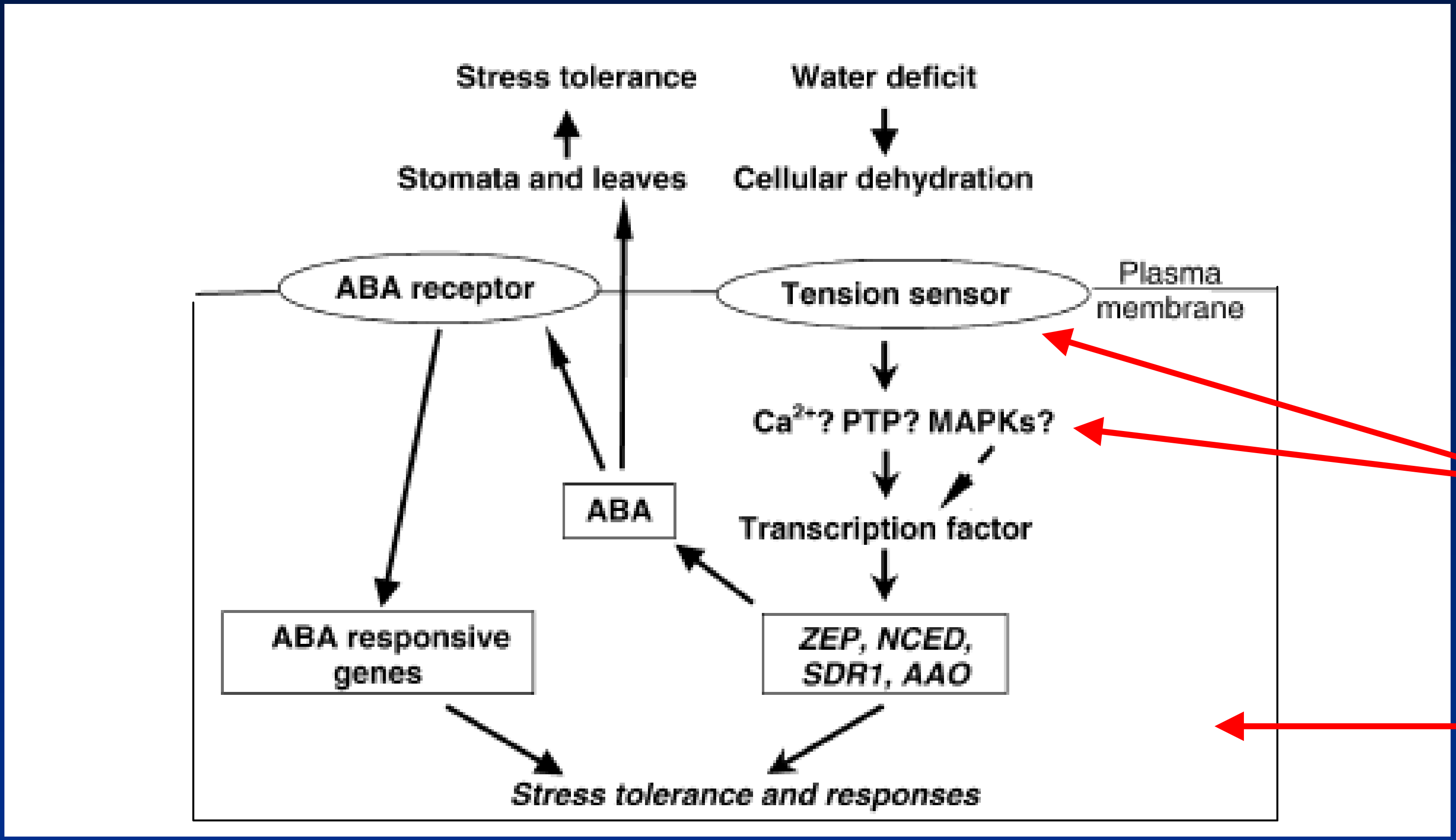
The Chad Lake, once the 6th largest lake in the world, 90% reduction in size from 1972 to 2006



Lake Faguibine in Mali, change from 1974 to 2006



Our molecular work about the perception of water stress



ABA in the whole signaling cascades in response to water deficit.

Invited review: Zhang et al. 2006 *Field Crops Research* **97**, 111-9.

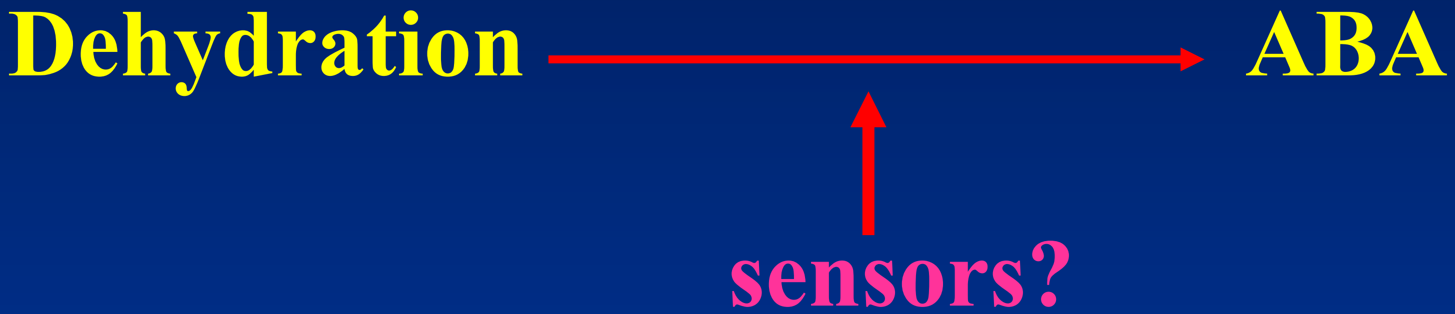
Our earlier results about ABA:

1. ABA as a root signal works in its concentration, rather than its flux into leaves

2. ABA catabolism in leaves is proportional to ABA flux

3. ABA production in roots is also triggered by osmosensors

4. Water deficit-induced ABA accumulation in maize plants could be blocked by reducing agents and sulfhydryl modifiers


Dehydration
ABA
sensors?

MAPK cascades in *Arabidopsis*

Analysis from *Arabidopsis* genome:

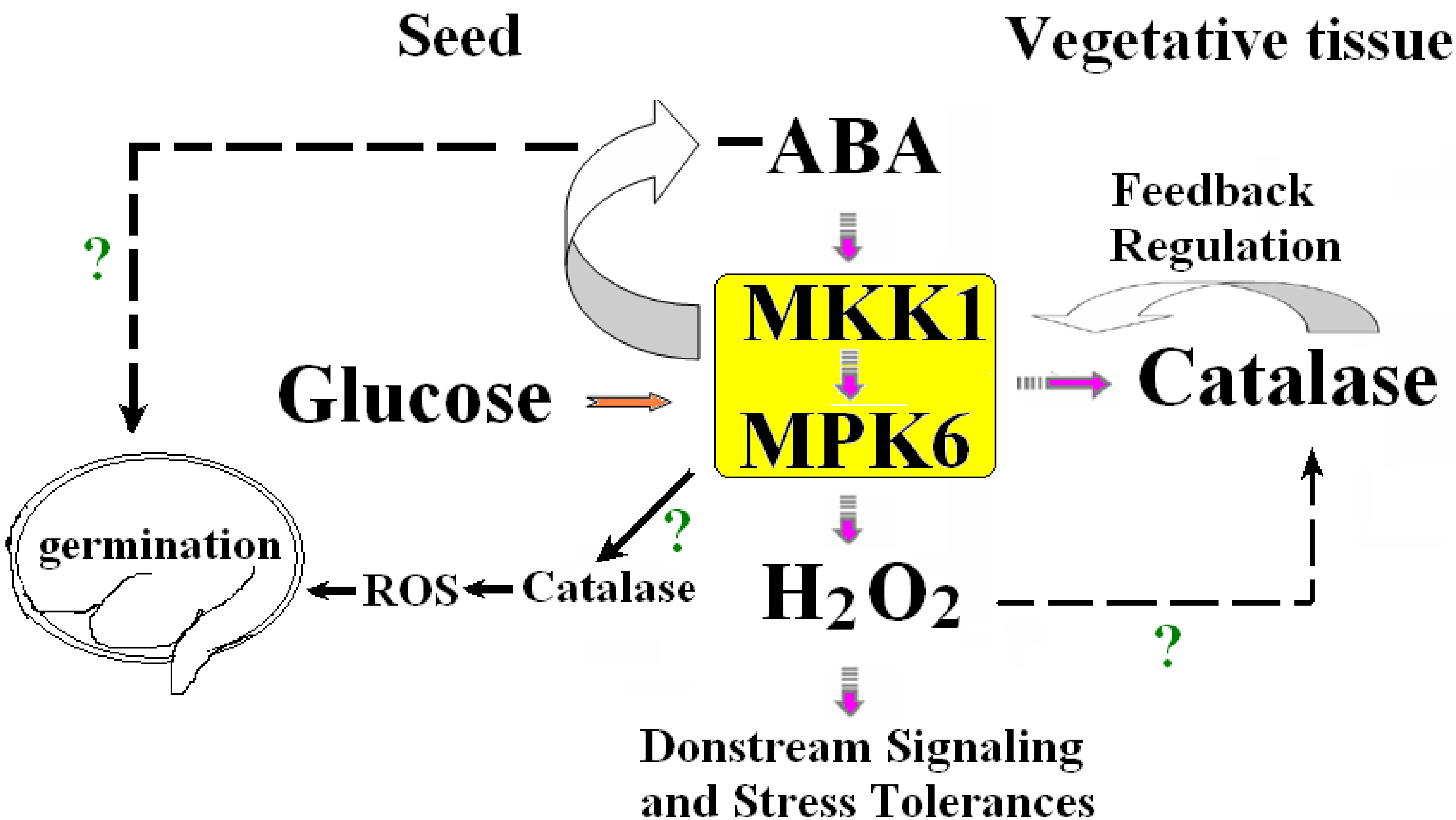
At least 20 MAP kinases

10 MAP kinase kinases

Over 60 MAPK kinase kinase kinases

We are interested in:

How MAPK cascades mediate the abiotic stress-induced plant responses, particularly the responses to oxidative stress.



Xing et al. 2008 Plant J

- We have built up the platform for more MAPK works :
  - *A complete set of MAPK mutants of Arabidopsis (20),*
  - *A complete set of MAPK over-expressing lines with a special tag (20)*
  - *A LC-MS system to track phosphorylated proteins*

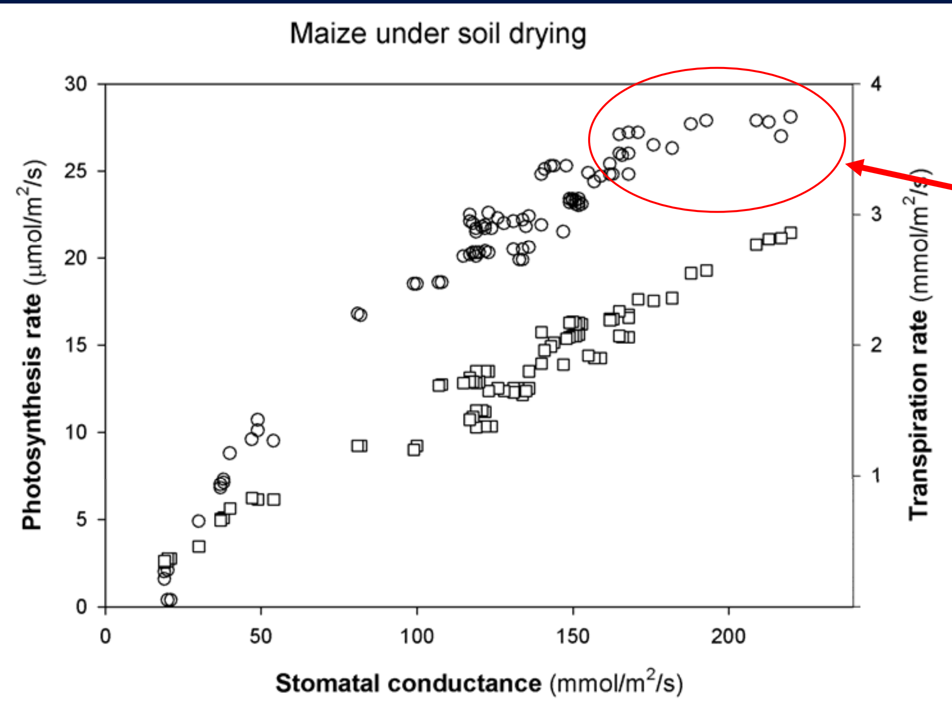
Yield responses to water stress

Physiologically, WUE means transpiration efficiency

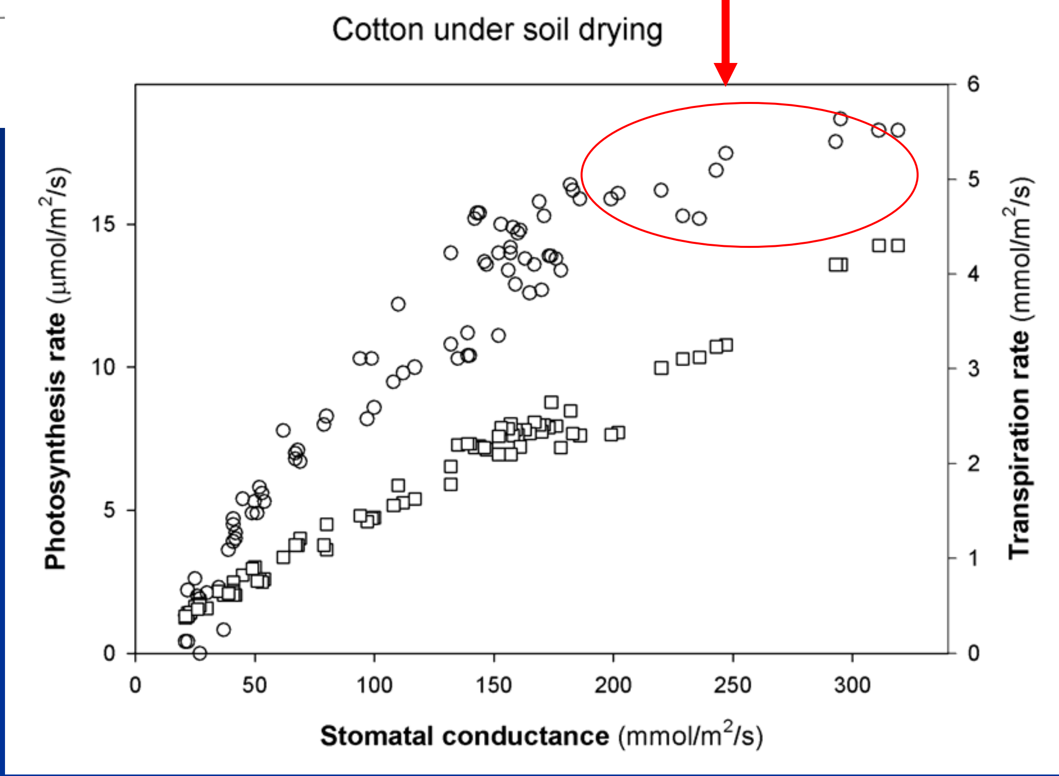
$$\text{WUE} = \frac{\text{A (CO}_2\text{ fixed)}}{\text{E (H}_2\text{O lost)}}$$

$$\text{Or} = \frac{g_a \ \Delta[CO_2]}{g_t \ \Delta[H_2O]_{vapor}}$$

($\Delta[CO_2]$ is very much a function of stomatal opening. Less opening may enlarge CO_2 gradient.)

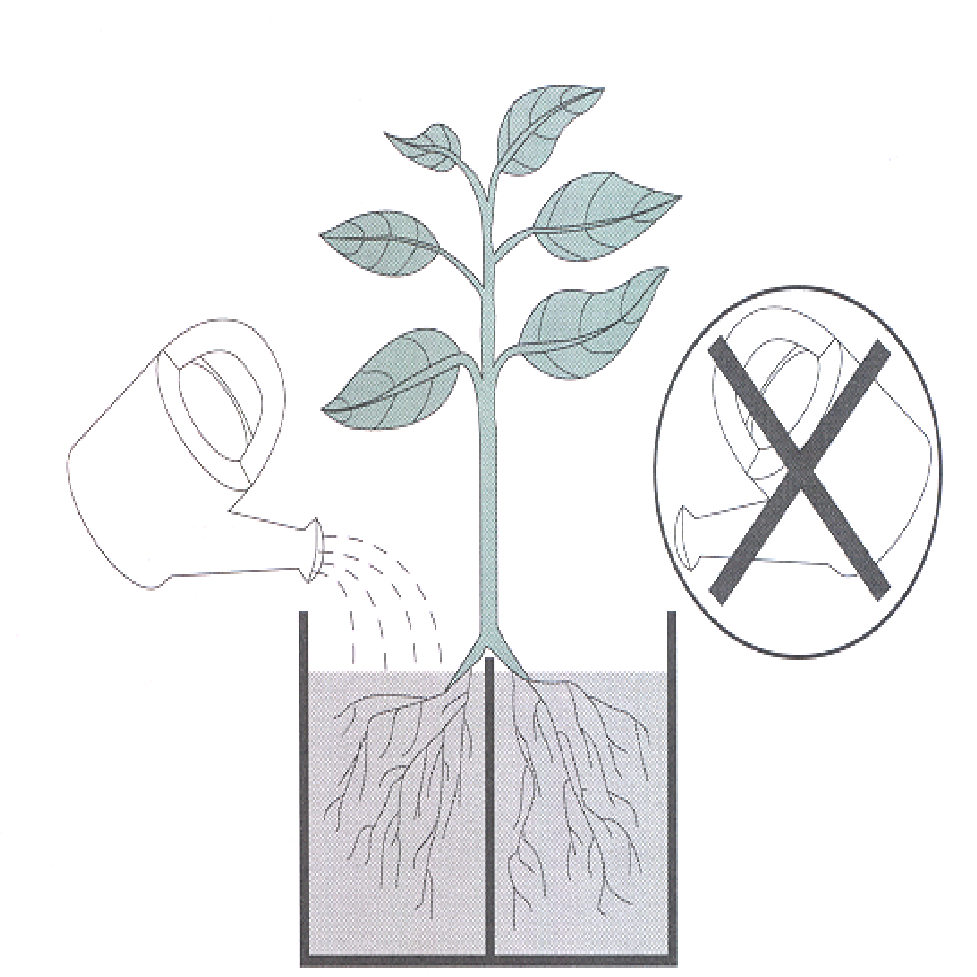


Luxury stomatal opening?



Split-root watering

Our early work in Bill Davies Lab (80s-90s) has been cited in all the major textbooks of *Plant Physiology*



Shoot stomata

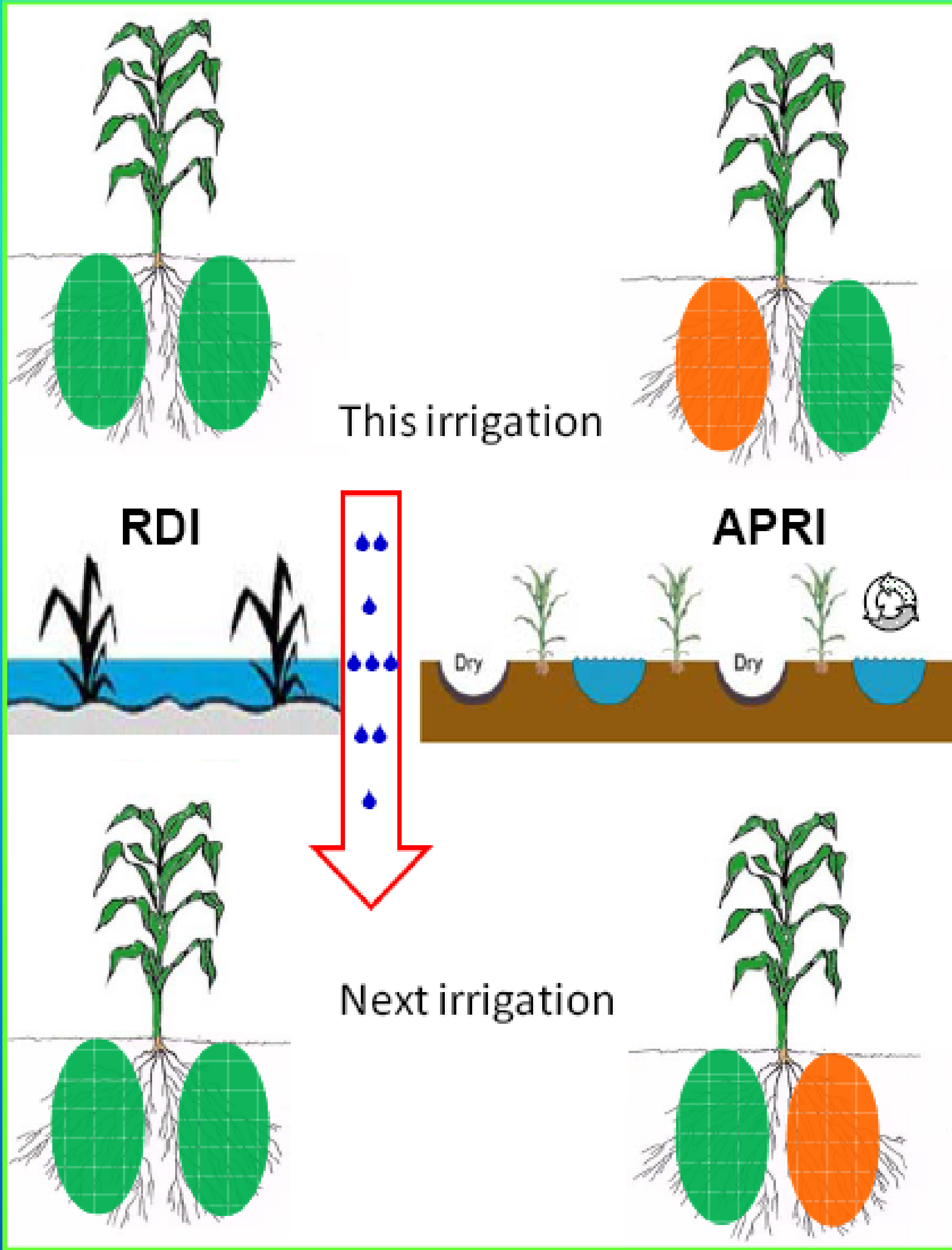
ABA

drying roots

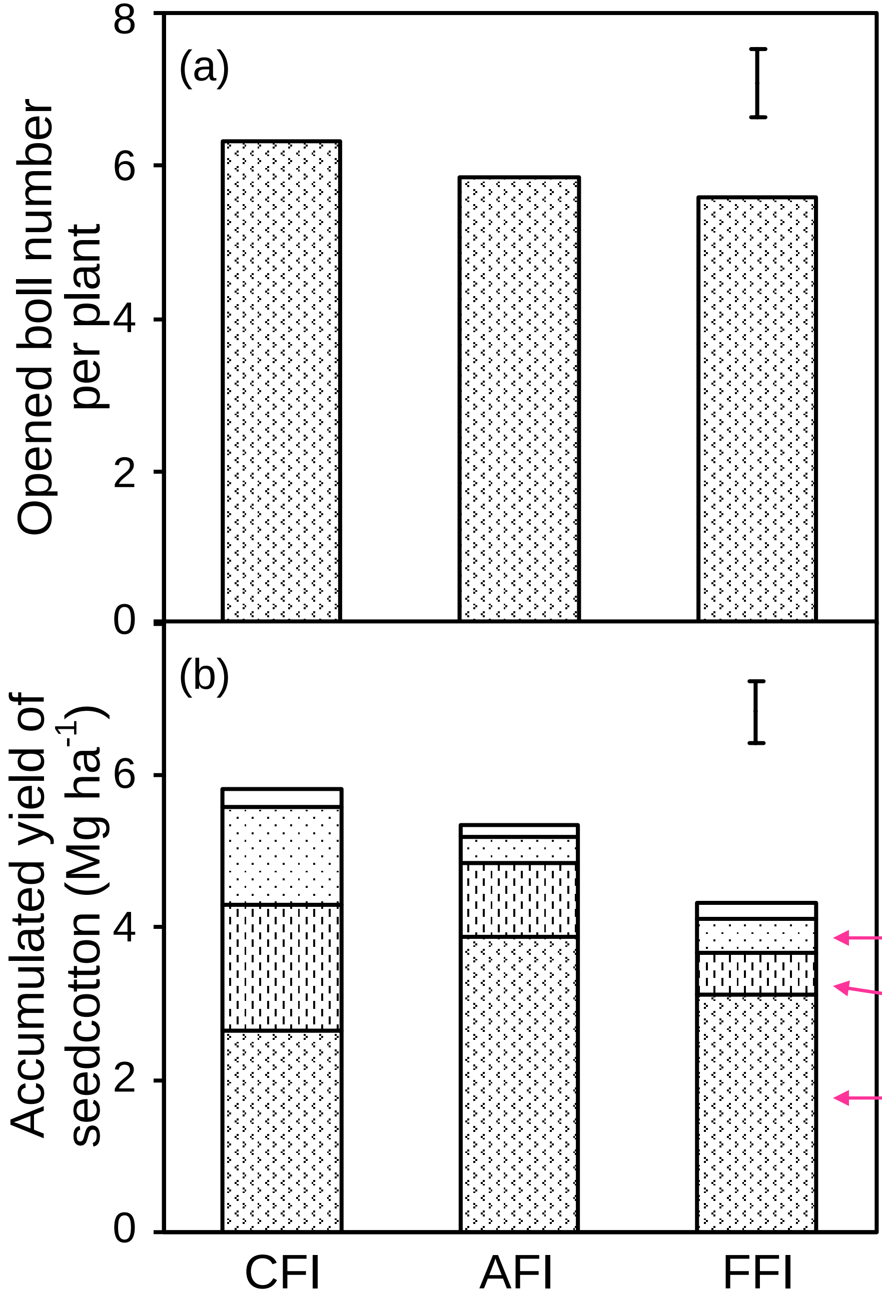
3. RDI & APRI: Temporal and spatial deficit irrigation strategy

RDI: Water stress on crops is manipulated over different growth season, but watering in the whole root zone to control reproductive and vegetative growth.

APRI: The plant growth was modified by keeping part of the root zone dry and the rest of the root zone well watered alternately, which was derived from the split-root research



Species	*Irrigation saved(%)*	*Yield reduced (%)*	*References*
Maize	50	11	Kang et al. 2000 *Agricultural Water Management*, 45, 267-274. Kang et al. 2002 *Field Crops Research* 77, 31-41.
Pear	10-18	No	Kang et al. 2003 *Journal of Hydrology* 280, 192-206.
Peach	35-40	No	Gong et al. 2005 *Hydrological Processes* 19, 2575-2590.
Grapevine	30	No	Loveys et al. 1998 *The Australian Grapegrower and Winemaker* 404a, 108-113.
Grapevine	30	No	Gu et al. 2000 *Research Notes*, #000702, California Agricultural Technology Institute
Tomato	30	No	Zegbe et al. 2004 *Agricultural Water Management* 68, 195–206 Wagdy et al. 2004 *Journal of Experimental Botany*, 55(407): 2353-2363.
Cotton	30	<5	Tang et al. 2005 *Field Crops Research* 94, 214-223. Du et al. 2006 *Agricultural Water Management* 84, 41-52.



CFI: 600 mm irrigation

AFI: 420 mm irrigation

FFI: 420 mm irrigation

30% reduction!

3rd harvest

2nd harvest

1st harvest

Tang, Li, Zhang 2005,
Field Crops Research 94, 214-223.

Case Study-1

Improved WUE by spatial deficit irrigation on maize in arid Northwest China

Case Study-2

Improved WUE by temporal deficit irrigation on wheat in semi-arid North China Plain

Case Study-3

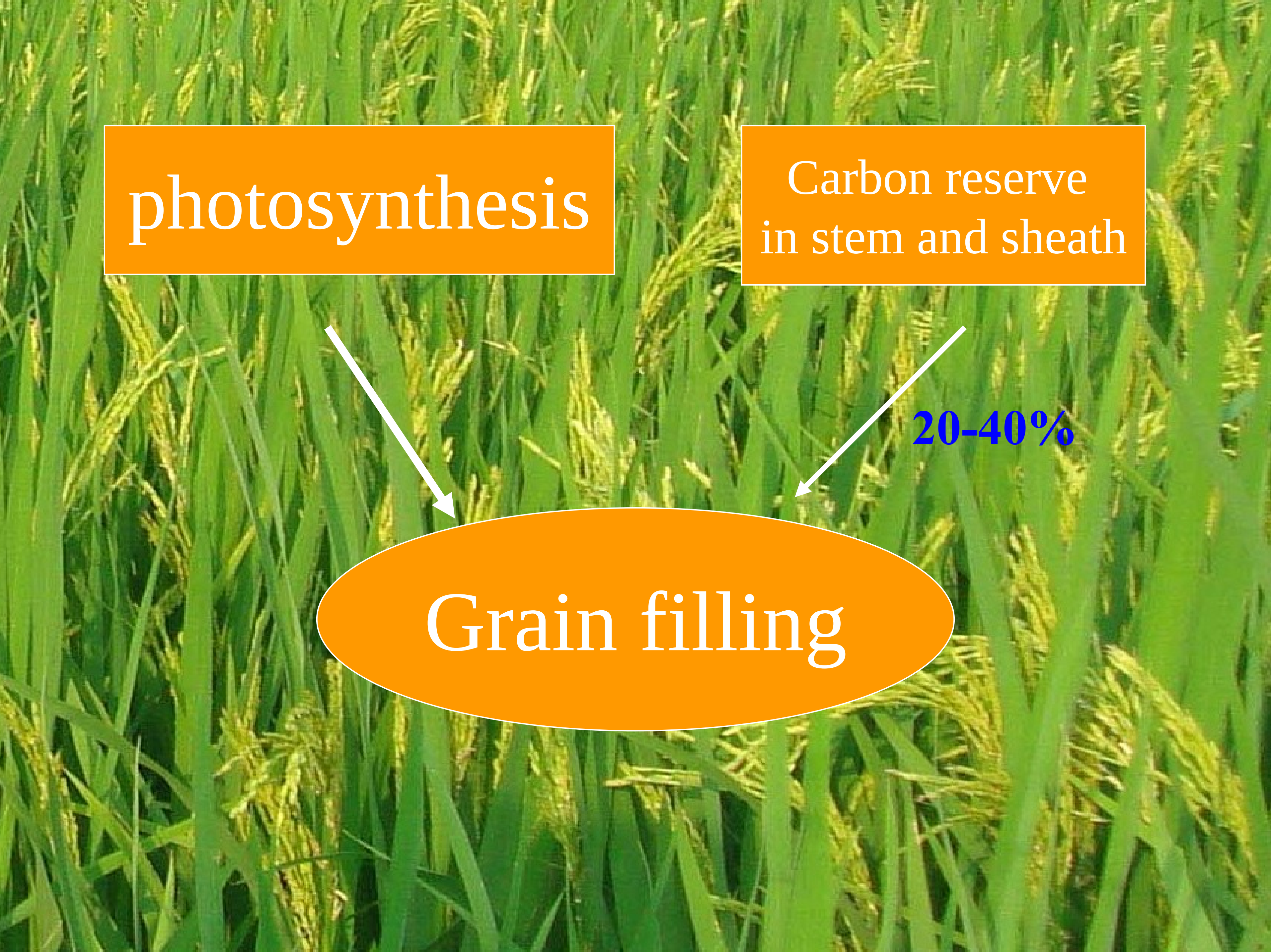
Improved WUE by temporal deficit irrigation on winter wheat and summer maize in semi-arid Central China

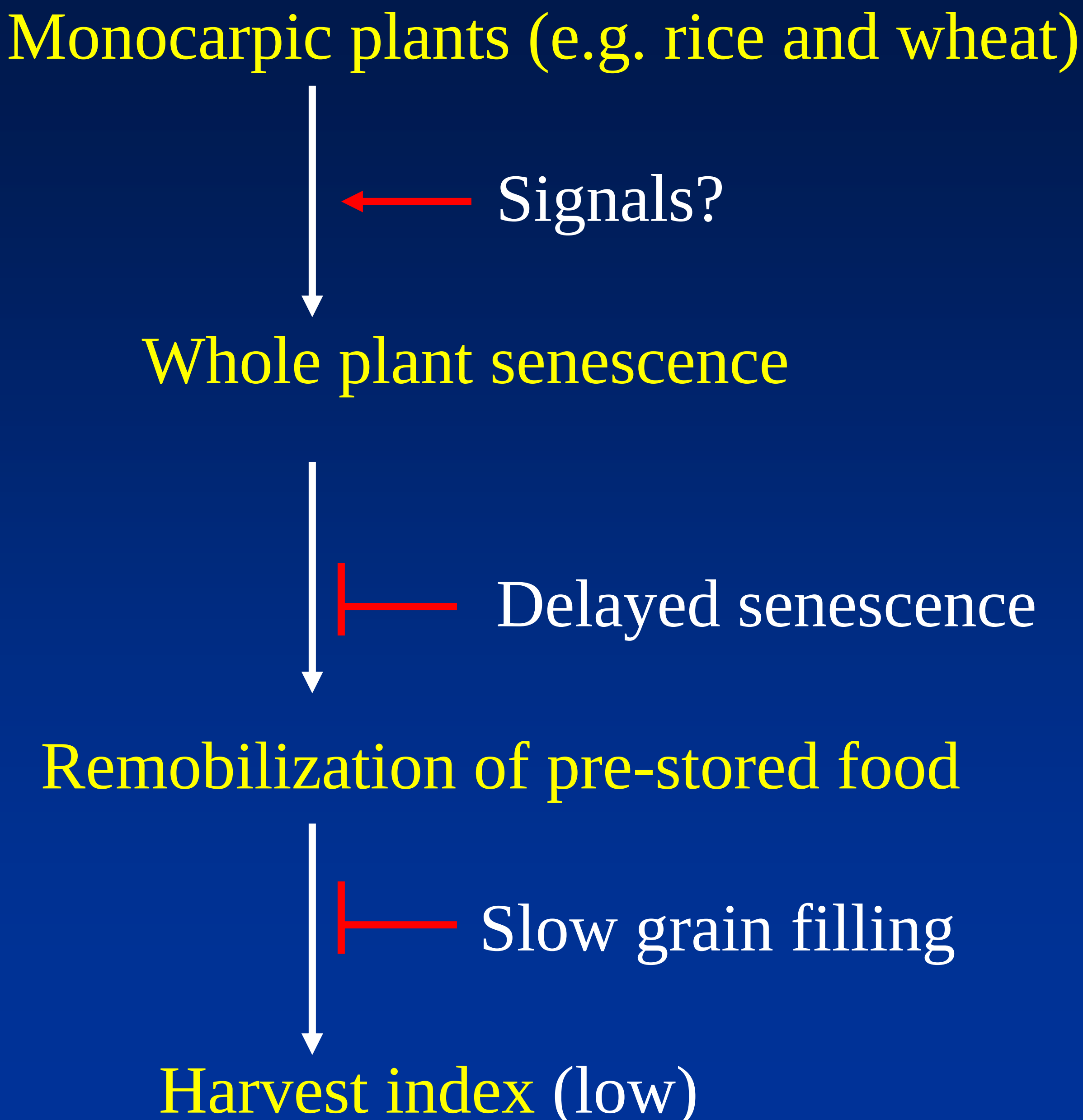
In agronomy, WUE means water productivity:

$$\text{WUE} = \frac{\text{biomass} \times \text{HI}}{\text{water used}}$$

High WUE, a trade off for less biomass?
Usually, WUE is high with drought.

Improving Harvest Index should be an effective way to enhance WUE.


photosynthesis
Carbon reserve
in stem and sheath
20-40%
Grain filling


Monocarpic plants (e.g. rice and wheat)
Signals?
Whole plant senescence
Delayed senescence
Remobilization of pre-stored food
Slow grain filling
Harvest index (low)

The problems:

Senescence is unfavorably delayed by

1. Heavy-use of N-fertilizers,

2. Introduction of lodging-resistant cultivars, (stay ‘green’ for too long at maturity)

3. Utilization of heterosis (e.g. hybrid rice).

In all the cases, slow grain filling and unused food are the two problems.

		Yield	NSC in straw mg g^{-1} DW	Harvest index	References
Wheat Yangmai 158	**Normal N**	**55 g pot^{-1}**	**188**	**0.39**	**Yang et al. 2000, *Crop Sci* 40, 1645-55**
	High N	**43**	**232**	**0.35**	
Rice Yangdao 6	**Normal N**	**912g m^{-2}**	**98**	**0.51**	**Yang et al. 2001, *Field Crops Res*, 71, 47-55**
	High N	**820**	**151**	**0.47**	

Wheat	**XN901 (hybrid)**	**672 g m^{-2}**	**185**	**0.39**	**Gong et al. 2005, *J Agron Crop Sci* 191, in press**
	Shaan 229	**584**	**95**	**0.48**	
Rice (hybrids)	**Shanyou 63**	**929g m^{-2}**	**87**	**0.48**	**Yang et al. 2002, *Agron J*, 94, 102-9**
	Ce03/Yangdao4	**911**	**201**	**0.41**	

Our experience in wheat field under water-saving culture:

Comparison between wheat plots that were well-watered or unwatered during grain-filling stage. Fate of fed ^{14}C was measured on day 18 from anthesis.

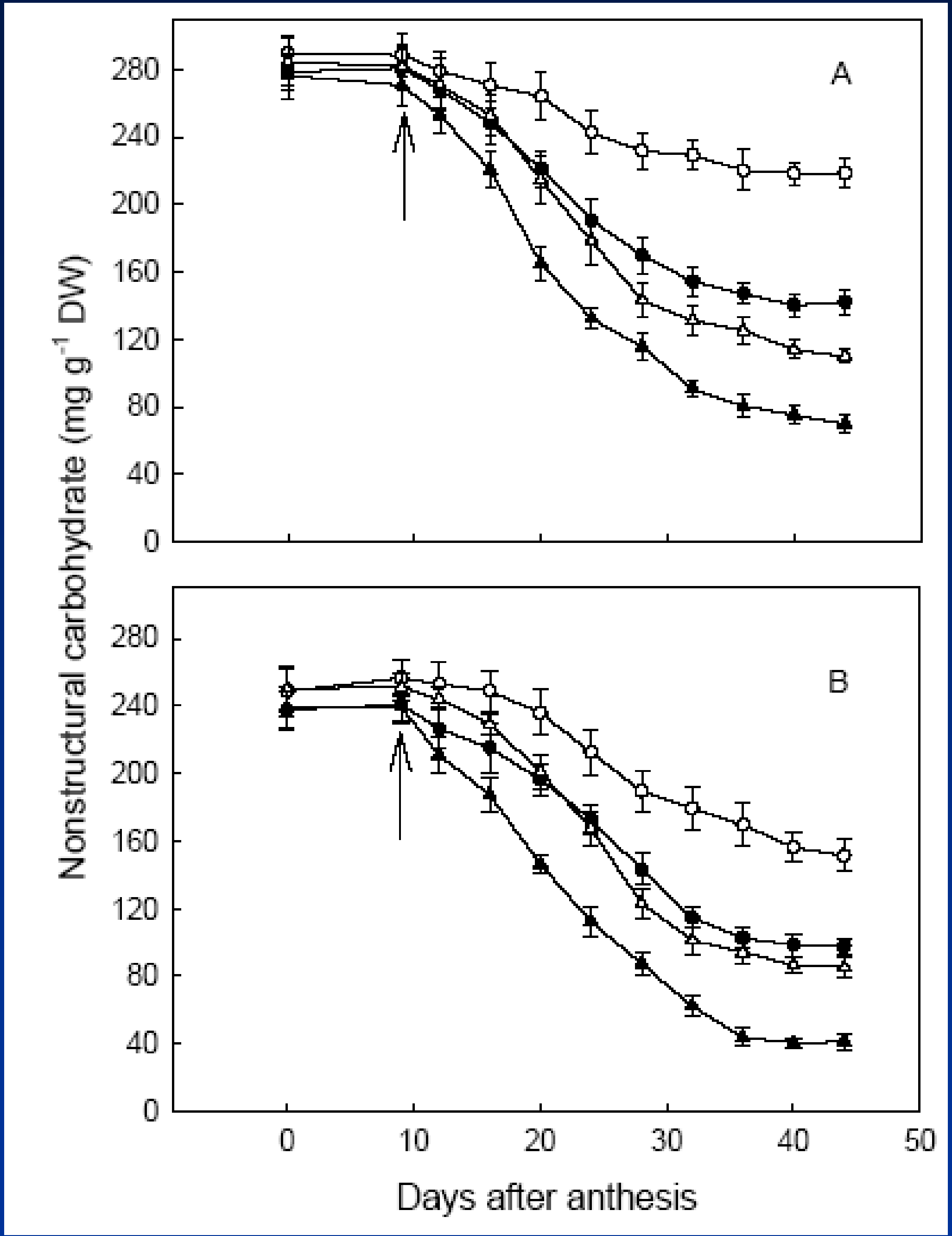
	Duration from anthesis to maturation (days)	Fate of fed ^{14}C ($^{14}CO_2$ applied 10 days early) % in kernels	% in stem	Total sugars left in stem (on day 26)
Well-watered	41	41.3	40.5	29%
Unwatered	31	81.3	9.6	8%

(Zhang et al. 1998, *Field Crops Res*., 59, 91-98)

Soil drying can greatly promotes senescence and C remobilization.

Unwatered from anthesis

Well watered



WW-HN

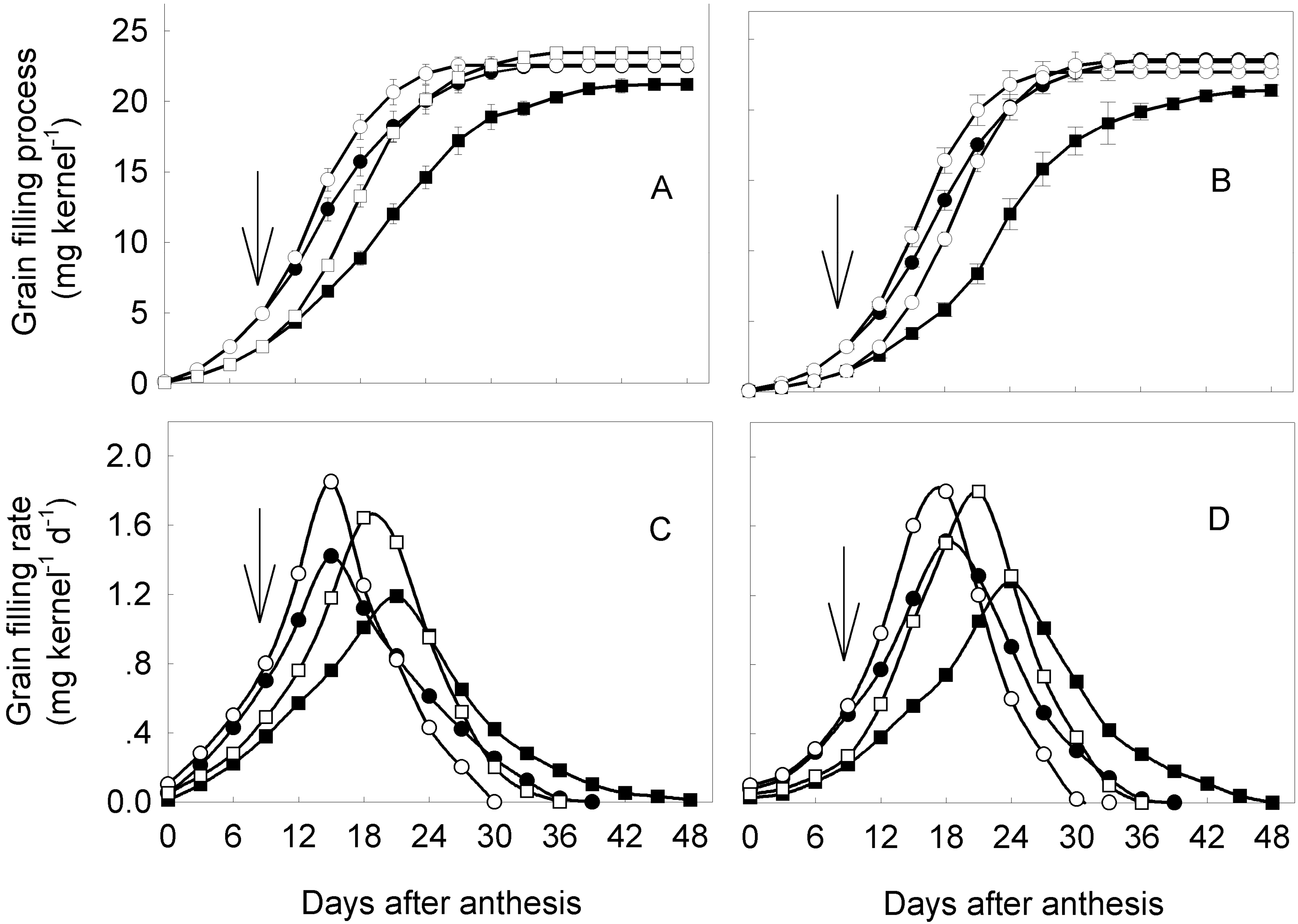
WW-NN

WS-HN

WS-NN

Lodging-resistant rice cultivars

Yang et al. 2001 *Field Crops Res.*, 71, 47-55.



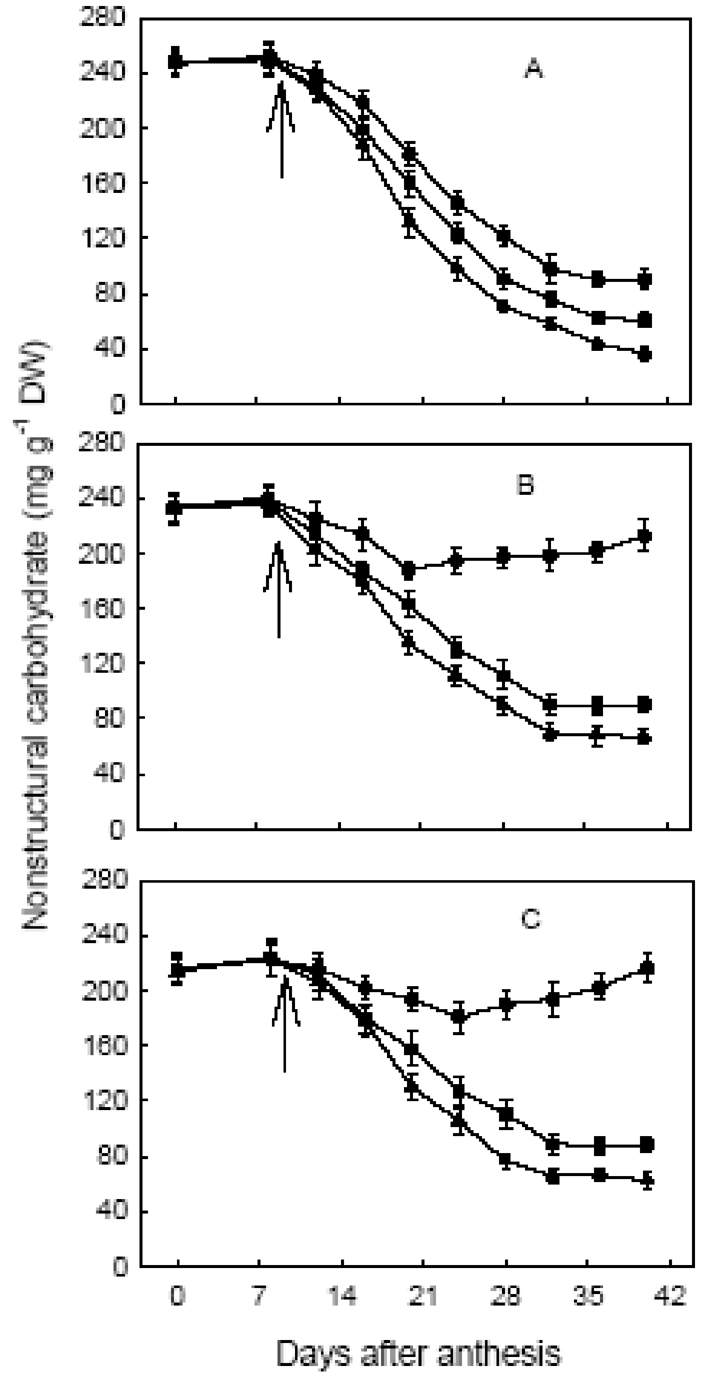
Yang et al. 2001 *Plant Physiol*, 127, 315-323.

Table 3 Grain-filling rate and grain yield of rice subjected to various N and soil moisture treatments

Cultivars	Water deficit treatment	Nitrogen applied	Active grain filling period d	Grain filling rate mg d^{-1} $grain^{-1}$	Total spikelets $\times 10^3$ m^{-2}	Ripened grains %	Grain weight mg $grain^{-1}$	Grain yield g m^{-2}
Wuyujing 3	WW	NN	19.7 b	1.21 c	33.73 a	90.8 b	26.2 b	802.4 b
	WW	HN	24.8 a	0.91 d	33.78 a	84.2 c	25.1 c	713.9 c
	WS	NN	17.0 c	1.39 a	33.71 a	90.2 b	26.3 b	799.7 b
	WS	HN	19.1 b	1.28 b	33.62 a	94.2 a	27.1 a	858.3 a
Yangdao 6	WW	NN	23.9 b	1.02 c	41.80 a	80.5 ab	27.1 a	911.9 ab
	WW	HN	28.6 a	0.82 d	42.09 a	74.6 b	26.1 b	819.5 c
	WS	NN	18.4 d	1.31 a	41.81 a	78.9 b	26.8 a	884.1 b
	WS	HN	21.2 c	1.14 b	42.23 a	82.5 a	26.9 a	937.2 a

Yang et al. 2001 *Plant Physiol*, 127, 315-323.

Hybrid rice cultivars



(indica/indica)

(japonica/indica)

(japonica/indica)

Yang et al. 2003 *Crop Sci*, 43, 2099-2108.

Table 1 Remobilization of stored assimilates in straw of rice subjected to various soil moisture treatments.

Hybrid	Water deficit treatment	Remobilized C reserve †	Contribution to grain ‡	TRA §	NSC in residue ¶	Harvest index #
		---------------------%	---------------------		mg g^{-1} DW	
Shanyou 63 (indica/indica)	Well-watered	64 c††	19 c	71 c	87 a	0.48 b
	Moderate water-deficit	76 b	26 b	86 b	57 b	0.53 a
	Severe water-deficit	89 a	38 a	92 a	33 c	0.55 a
Ce 03/Yangdao 4 (japonica-indica)	Well-watered	14 c	6 c	47 c	201 a	0.41 c
	Moderate water-deficit	61 b	24 b	80 b	92 b	0.48 b
	Severe water-deficit	74 a	32 a	88 a	61 c	0.53 a
PC311/Zaoxian-dang 18 (japonica-indica)	Well-watered	7 c	2 c	23 c	215 c	0.37 c
	Moderate water-deficit	53 b	21 b	65 b	103 b	0.46 b
	Severe water-deficit	67 a	27 a	80 a	85 a	0.51 a

Yang et al. 2003, *Agronomy J*, 94, 102-109.

Table 3 Grain-filling rate and grain yield of three rice hybrids subjected to various soil moisture treatments.

Hybrid	Water Deficit treatment	Active grain filling period	Grain filling rate	Total spikelets	Ripened grain	Grain weight	Grain yield
		d	mg d^{-1} $grain^{-1}$	$\times 10^3$ m^{-2}	%	mg $grain^{-1}$	g m^{-2}
Shanyou 63 (indica/indica)	WW	21.2 a†	1.16 c	40.7 a	83.6 a	27.3 a	929 a
	MD	18.5 b	1.30 b	41.1 a	81.9 a	26.8 a	902 a
	SD	16.7 c	1.39 a	40.4 a	74.2 b	25.9 b	776 b
Ce 03/Yangdao 4 (japonica-indica)	WW	24.2 a	0.94 c	46.9 a	76.8 b	25.3 a	911 b
	MD	20.7 b	1.11 b	46.6 a	80.1 a	25.5 a	952 a
	SD	18.4 c	1.23 a	47.1 a	77.5 b	25.1 a	916 b
PC311/Zaoxiandang 18 (japonica-indica)	WW	27.3 a	0.82 c	48.3 a	67.1 b	24.9 a	807 b
	MD	22.0 b	1.03 b	48.5 a	74.8 a	25.2 a	914 a
	SD	18.6 c	1.19 a	48.1 a	71.2 a	24.5 a	839 b

Yang et al. 2003, *Agronomy J*, 94, 102-109.

Soil drying,   a regulative tool?

Narrow stomatal opening to enhance physiological WUE?

Promote whole plant senescence and enhance C remobilization so that HI and WUE can be improved?

(HI improvement as a result of semi-dwarf breeding has also led to the WUE improvement.)

A grain filling problem in super rice:

the superior kernels:

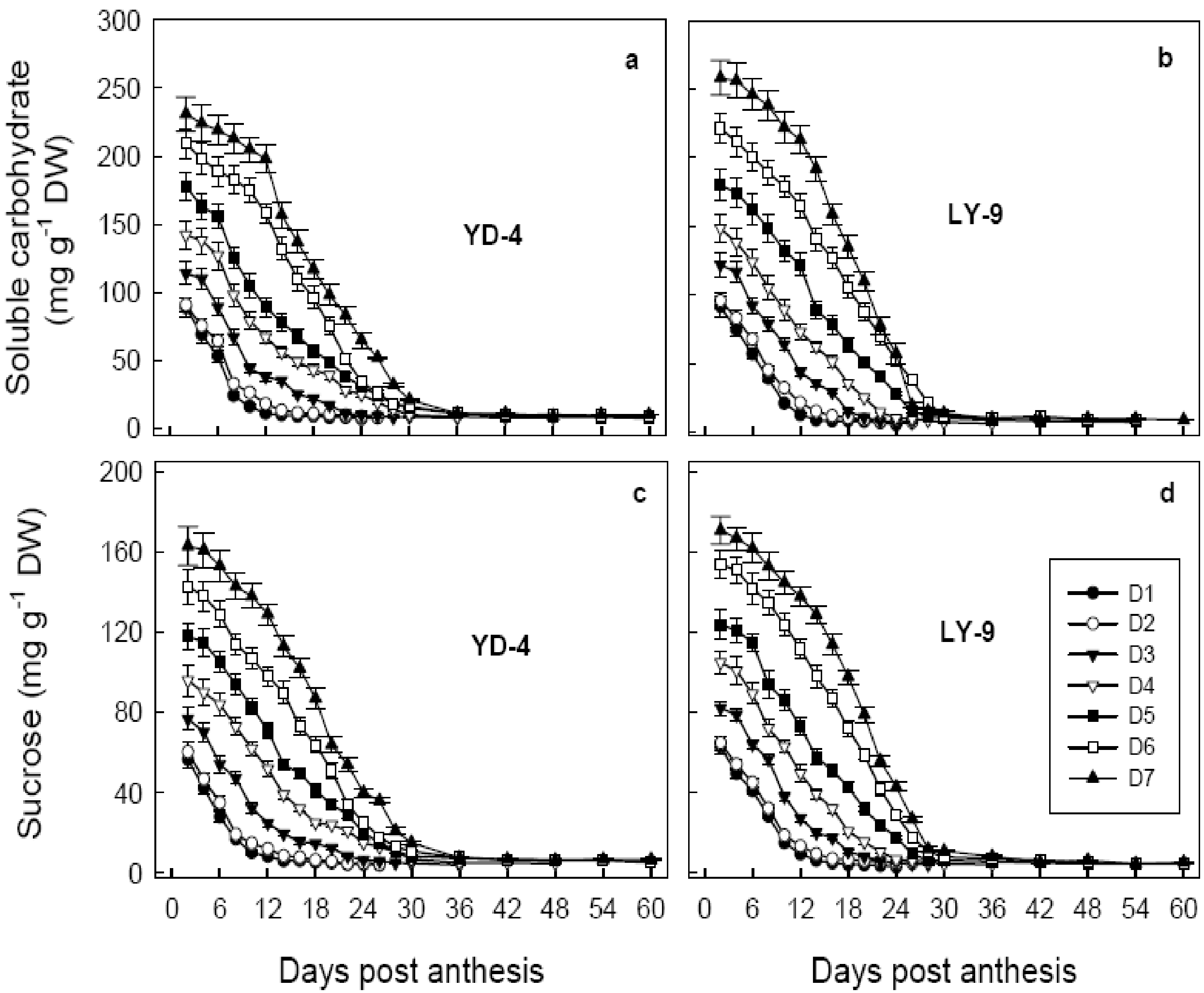
earlier flowering,
located on apical primary branches,
fill fast and produce heavier grains

the inferior kernels:

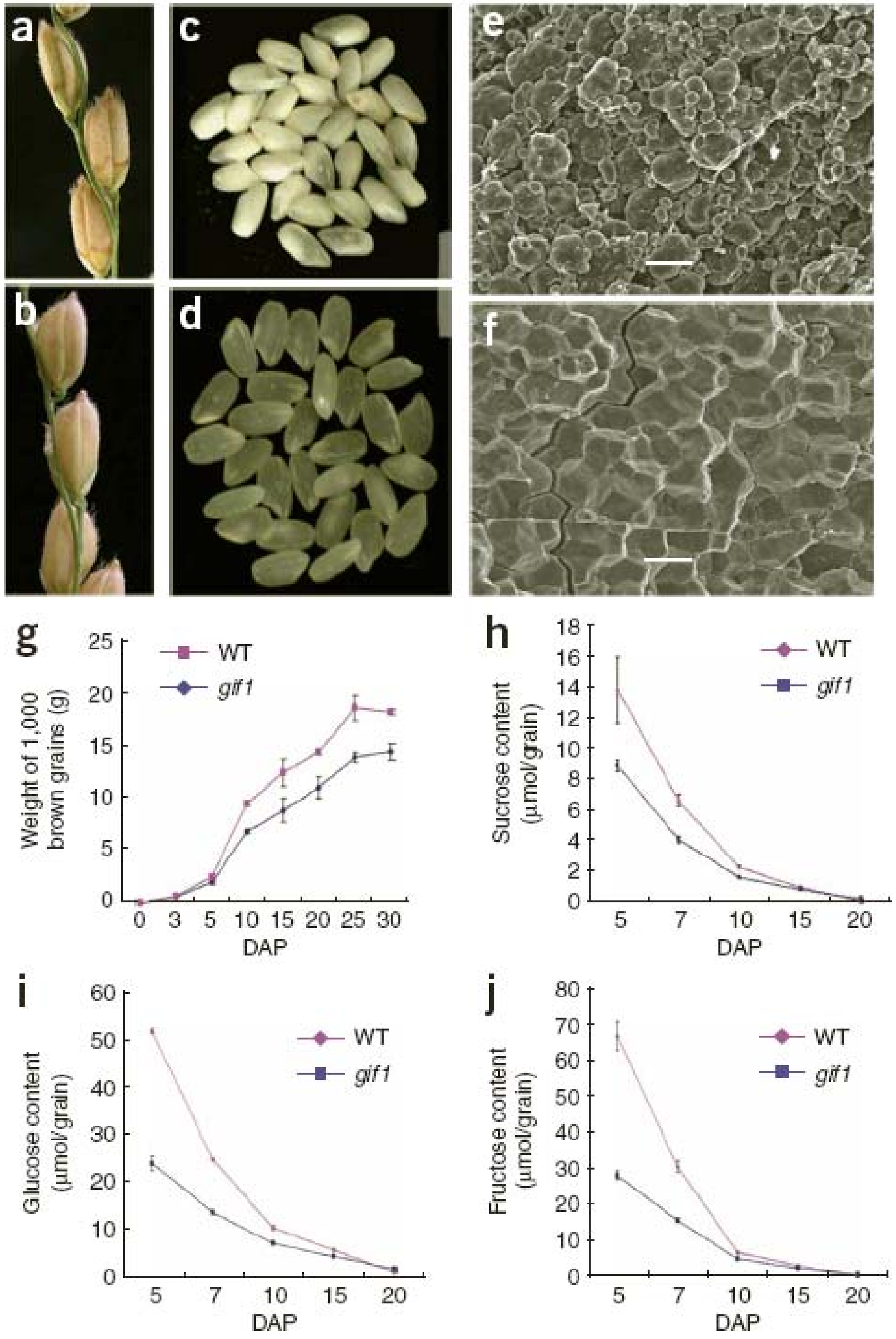
later-flowering,
located on proximal secondary branches,
either sterile or fill slowly

Cultivars	Whole panicle average (mg)	Superior spikelets (mg)	Inferior spikelets (mg)	Less than the panicle average (%)
Super rice				
两优培九	25.2	28.7	21.6	-14.3
新两优 6 号	27.5	31.2	23.5	-14.5
II 优 7954	27.4	30.9	23.6	-13.9
II 优 084	27.1	30.4	23.4	-13.7
II 优航 1 号	26.6	30.6	22.7	-14.7
II 优明 86	27.2	30.5	23.8	-12.5
III 优 98	27.0	30.3	23.5	-13.0
丰优 299	26.2	30.2	21.8	-16.8
D 优 527	28.2	31.9	24.3	-13.8
武粳 15	28.8	31.8	24.9	-13.5
宁粳 1 号	26.7	29.4	23.8	-10.9
淮稻 9 号	27.2	31.5	23.9	-12.1
Means	**27.1**	**30.6**	**23.4**	**-13.6**
Filling rate (%)	**85.3**	**97.2**	**73.0**	**-12.3**
Conventional rice				
Wuyungeng 7	26.7	28.3	25.1	-6.0
Filling rate (%)	93.6	98.3	88.9	-4.7

Inferior grains lead to unstable yield performance in super rice



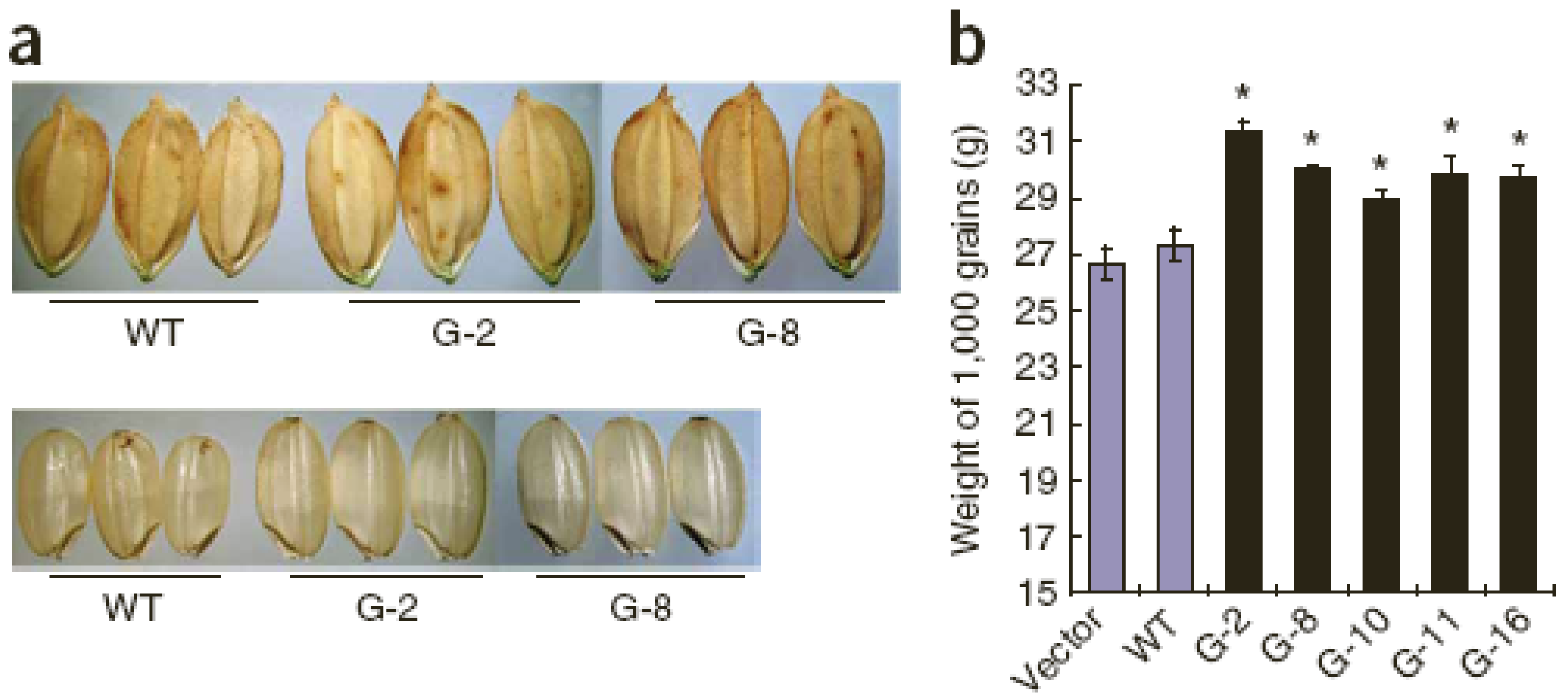
Sugar concentration in the grains is adequate



Rice *GIF1* gene (grain incomplete filling 1), encoding a cell-wall invertase, is responsible for poor grain filling and smaller grains.

Wang et al. 2008 *Nature Genetics* 40, 1370 – 1374

Rice *GIF1* gene: Over-expression leads to larger grains.



Wang et al. 2008 *Nature Genetics* 40, 1370 – 1374

Apparently *GIF1* is involved in phloem unloading.

But inferior kernels of super rice have adaquote sucrose. *GIF1* should not be limiting there.

What are involved?

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Our students: Liang Jiansheng, Jiang Mingyi, Xing Yu, Liu Yinggao, Li Ying Xuan, Chu Wingkei, Zhou Yanghong……

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College of Agricultural Biotechnology, China Agricultural University

Kang Shaozhong Lab
Center for Agricultural Water Research in China, China Agricultural University

Yang Jianchang Lab
College of Agriculture, Yangzhou University

FIVE CROP RESEARCHERS WHO COULD CHANGE THE WORLD

The current crisis in worldwide food prices reinforces the need for more productive agriculture. **Emma Marris** meets five ambitious scientists determined to stop the world from going hungry.

The thriving peasant

Zhang Jianhua

Plant physiologist at Hong Kong Baptist University

Timescale for change: now

Research on water-saving crop production

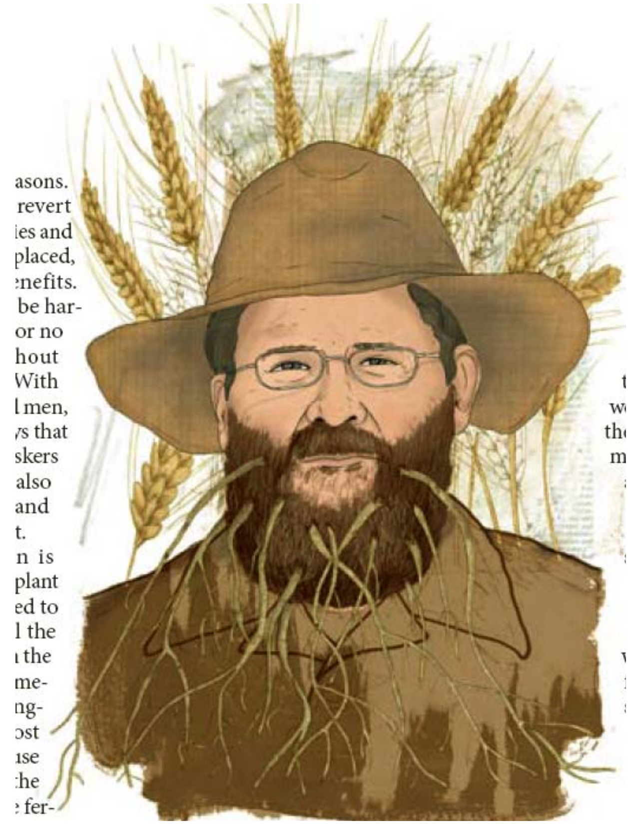
The rust hunter

Peter Dodds

Molecular biologist at the Commonwealth Scientific & Industrial Research Organization Plant Industry in Canberra, Australia

Timescale for change: 10 years

Find the gene to resist the Ug99-induced wheat rust



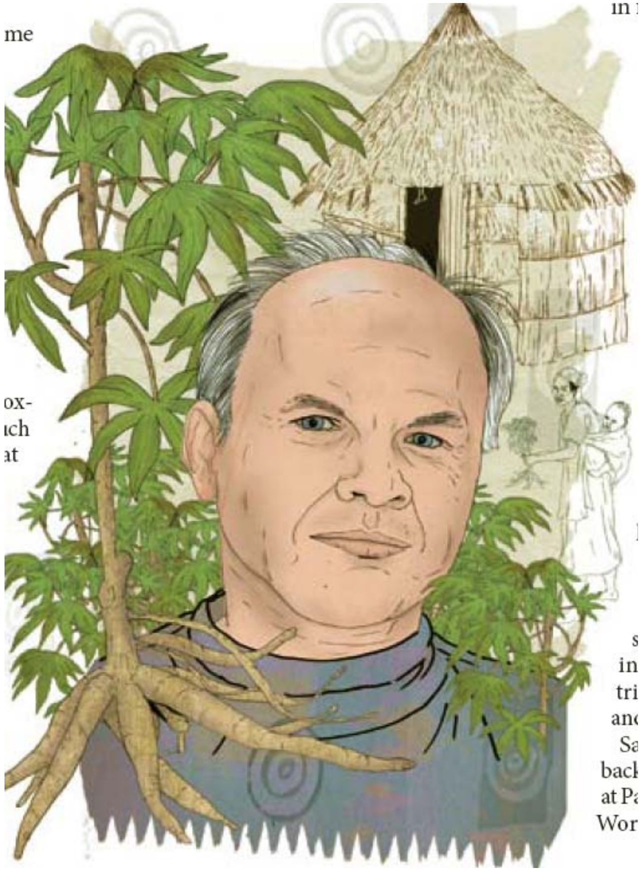
The perennial optimist

Jerry Glover

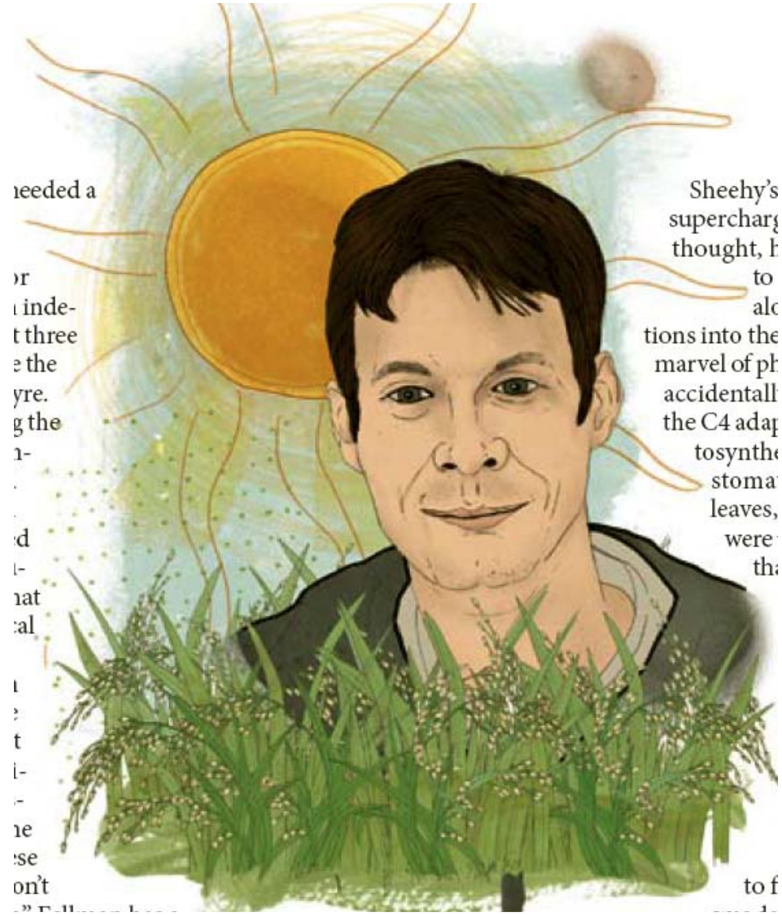
Agroecologist at the Land Institute in Salina, Kansas

Timescale for change: 30 years

Grow wheat as perennial?
No till and less N farming



The biotech humanitarian
Richard Sayre
Director of the Enterprise Rent-A-Car Institute for Renewable Fuels at the Donald Danforth Plant Science Center in St Louis, Missouri
Timescale for change: 6 years



The rice transformer
Julian Hibberd
Molecular biologist at the University of Cambridge, UK
Timescale for change: 15–20 years

BioCassava as biofuel?

The C4 rice?