


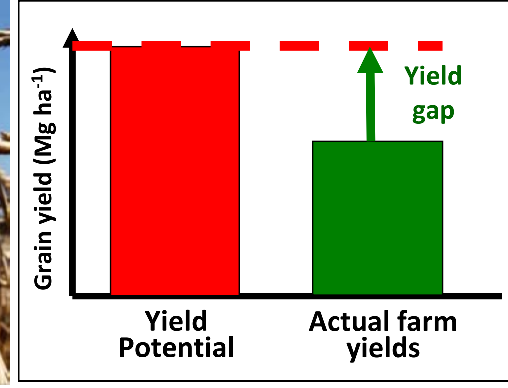

Food security and the challenge to increase crop yield potential

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*** with contributions from Ken Cassman (UNL) & A. Hall (Univ. of Buenos Aires)**

University of Nebraska Lincoln

International Workshop on Engineered Crops
April 28-29, 2014, Des Moines IA

Water for Food
ROBERT B. DAUGHERTY INSTITUTE
University of Nebraska

Trivia: How many NEW hectares (or acres) were brought into crop production globally every year during these time periods?

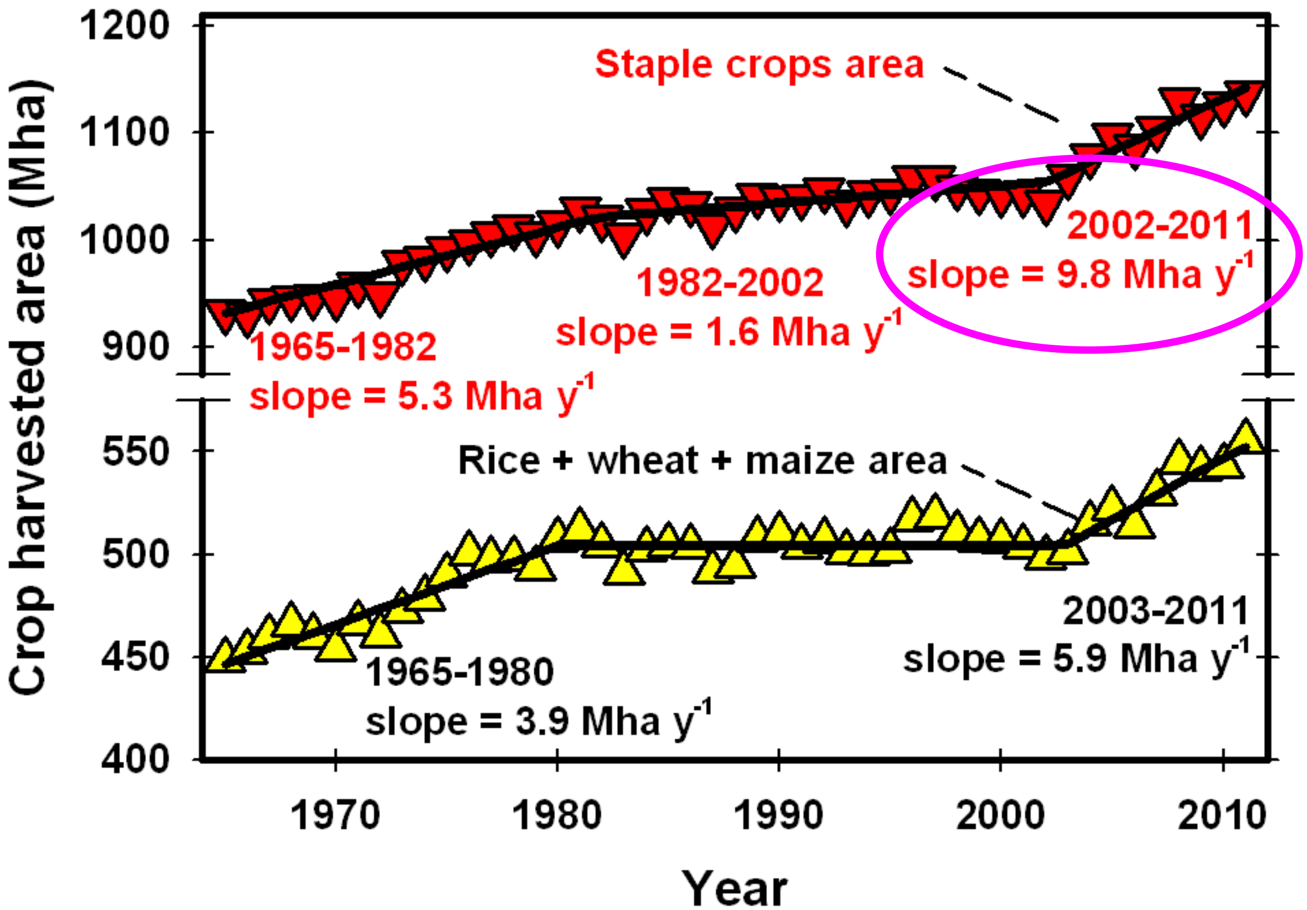
1965-1980? 5 million ha (12 million acres) per year

1980-2000? 1½ million ha (4 million acres) per year

2000-2010? 10 million ha (24 million acres) per year

Global Cropland Trends

Staple-crop area includes cereals, oilseed, pulses, sugar, root, fiber, and tuber crops.

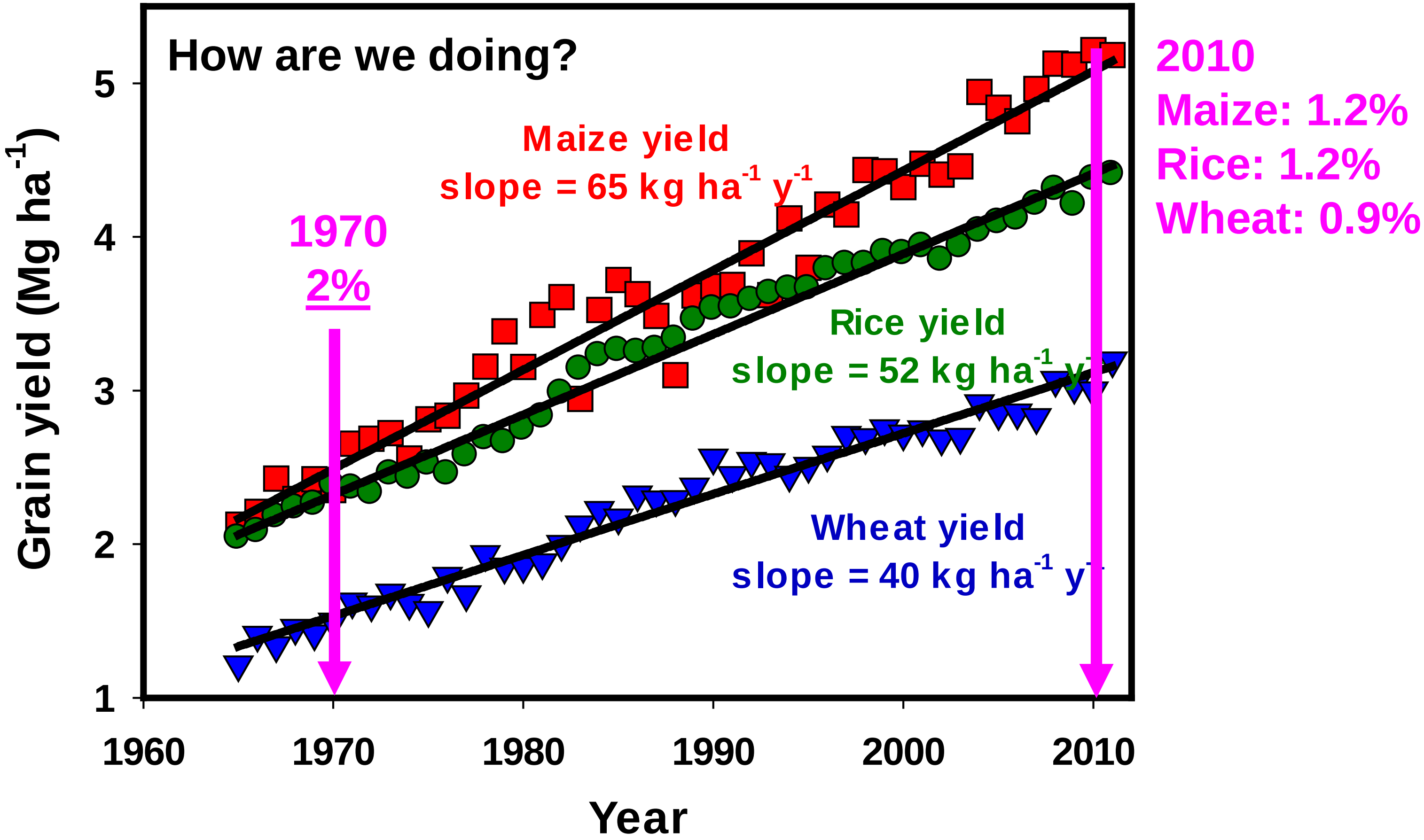


Nearly all of the increase in crop area since 2002 has occurred in South America, Asia, and Sub-Saharan Africa

Grassini et al, *Nature Comms* (2014)

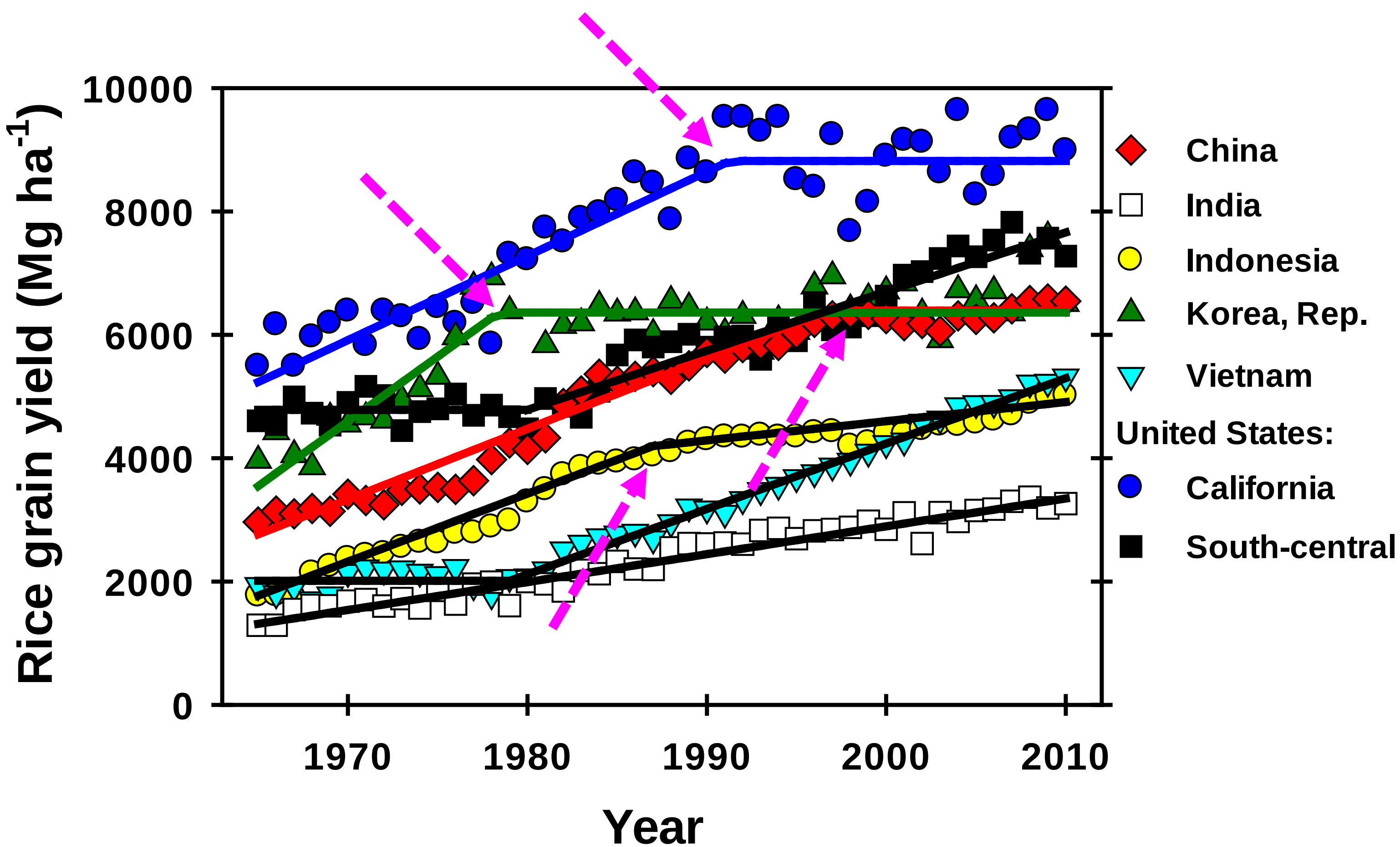
Global trends in cereal crop yields

Global crop yields have to increase 1.2-1.3% annually from NOW until 2050 (Bruinsma, 2009; Fischer, 2009)



Source: FAOSTAT

RICE yield trends



Grassini et al., *Nature Comms* (2014)

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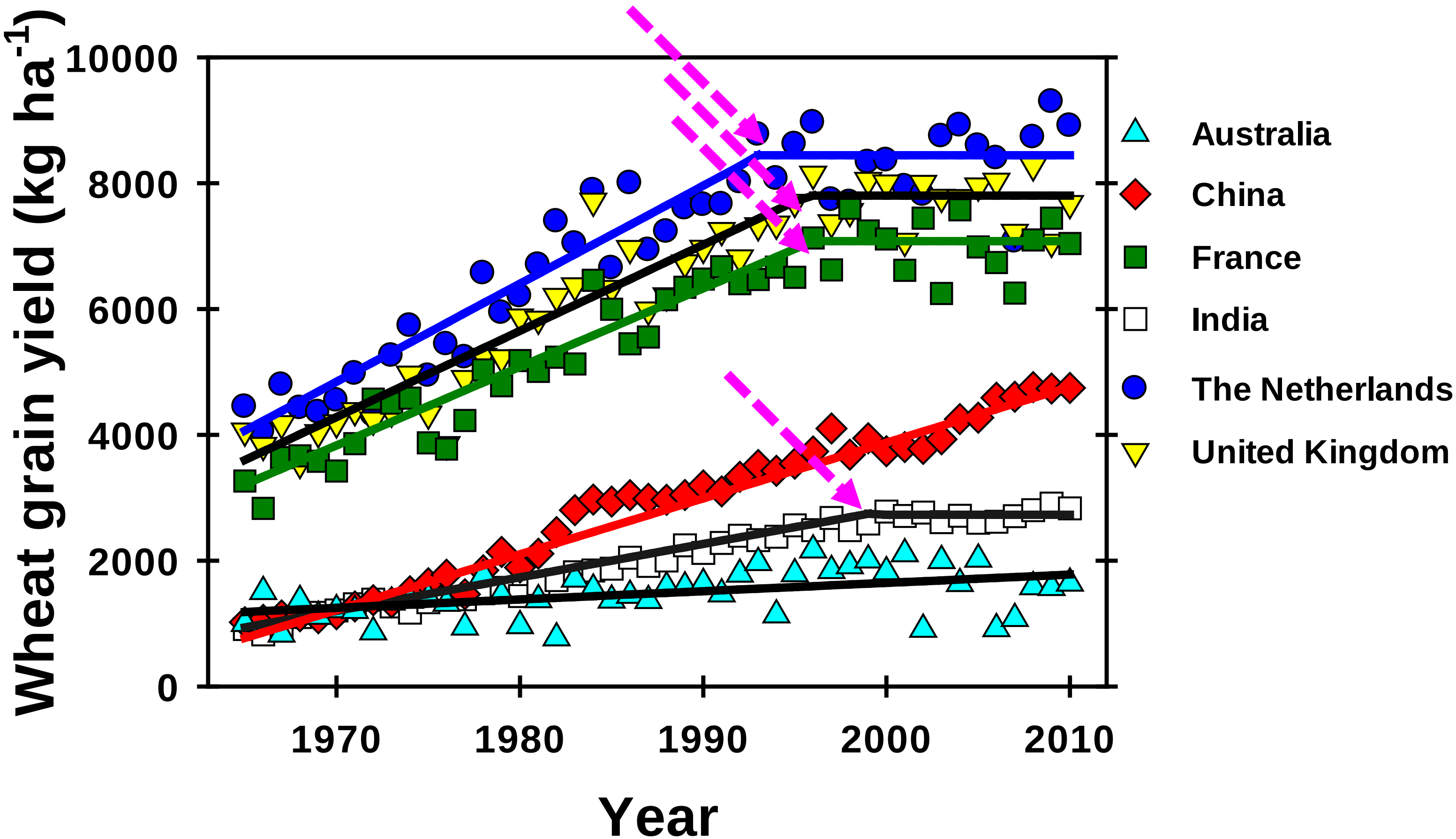
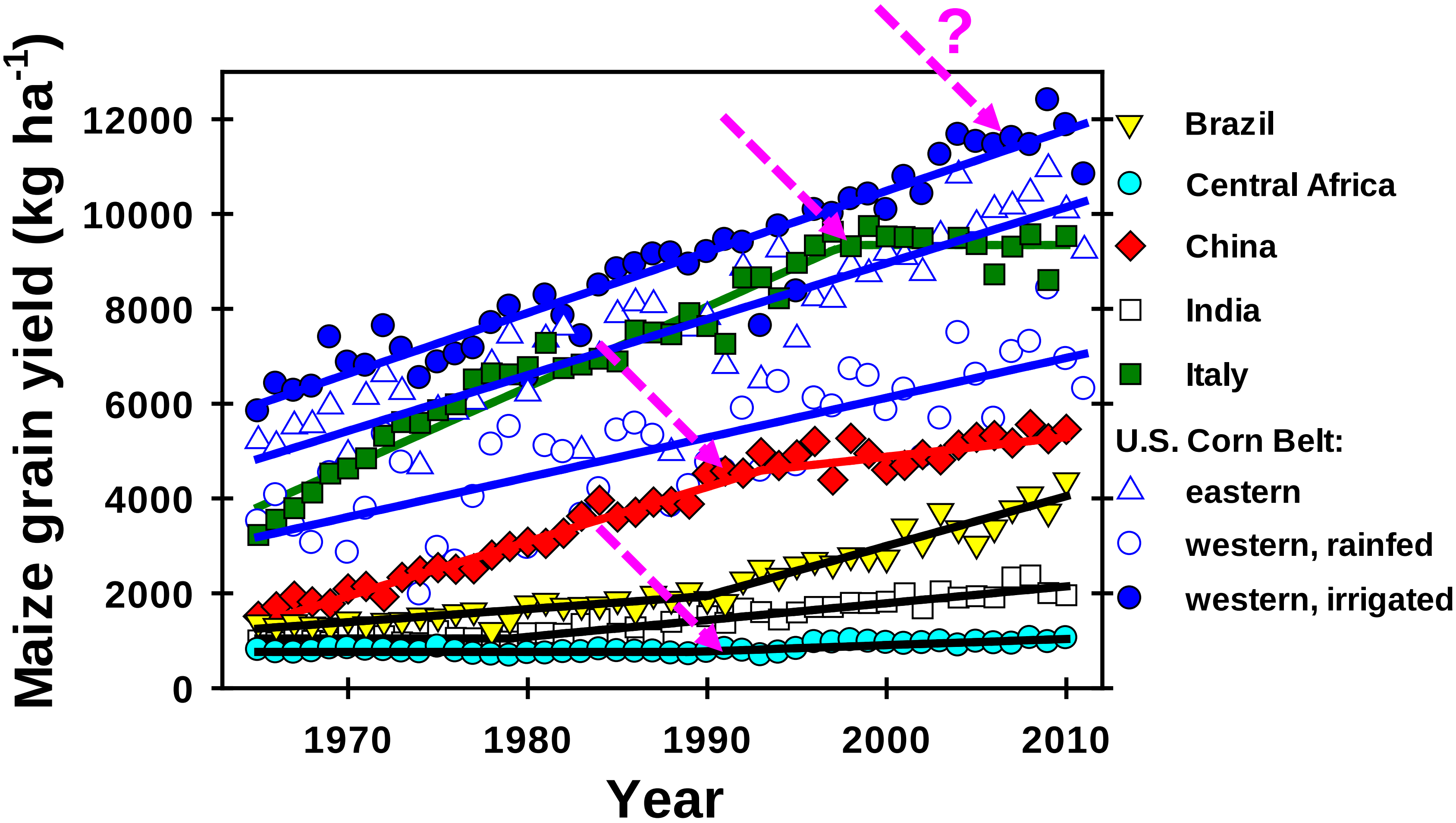
WHEAT yield trends



Grassini et al, *Nature Comms* (2014)

MAIZE yield trends



Grassini et al., *Nature Comms* (2014)

Food security: don't worry, no problem (?)

"The commercial maize productivity simulation is driven by the estimate from private sector sources that hybrid maize yields can be expected to increase by 2.5 percent per year at least until the 2030s."

"…this productivity change would affect about 80 percent of world production in 2010. The effects on world maize prices are dramatic: prices increase only 12 percent, instead of 101 percent, between 2010 and 2050. The effect on malnourished children is also not insignificant, with a 3.2 percent decline relative to the baseline in 2050."

Nelson, Rosegrant, *et al.*, 2010. Food Security, Farming and Climate Change to 2050, IFPRI.

ROBERT E. EVENSON*

Department of Economics, Yale University, New Haven, CT 06520

ABSTRACT The development of improved technology for agricultural production and its diffusion to farmers is a process requiring investment and time. A large number of studies of this process have been undertaken. The findings of these studies have been incorporated into a quantitative policy model projecting supplies of commodities (in terms of area and crop yields), equilibrium prices, and international trade volumes to the year 2020. These projections show that a "global food crisis," as would be manifested in high commodity prices, is unlikely to occur. The same projections show, however, that in many countries, "local food crisis," as manifested in low agricultural incomes and associated low food consumption in the presence of low food prices, will occur. Simulations show that delays in the diffusion of modern biotechnology research capabilities to developing countries will exacerbate local food crises. Similarly, global climate change will also exacerbate these crises, accentuating the importance of bringing strengthened research capabilities to developing countries.

Evenson, R.E., 1999. Global and local implications of biotechnology and climate change for future food supplies. PNAS 96, 5921-5928.

food, such as hydropower production, and a stronger focus on biotechnologies that have already significantly contributed to conserving natural resources and are also important means for achieving enhanced access to food for rapidly growing developing countries.

The *Bioeconomy Scenario* as developed results in increased food security while removing pressure on water and land resources. It combines increased resource use efficiency in agriculture and water through advanced technologies and increased use of economic incentives, more rapid adoption of second-generation biofuel technologies, and higher fertilizer prices to both reflect increased energy prices and reduced fertilizer application with higher economic growth. However, as higher food

Rosegrant et al., 2013. Water and food in the bioeconomy: challenges and opportunities for development. Agric. Economics, 44, 139-150

World food trends and prospects to 2025

TIM DYSON*

Department of Social Policy, London School of Economics, London WC2A 2AE, United Kingdom

ABSTRACT This paper reviews food (especially cereal) production trends and prospects for the world and its main regions. Despite fears to the contrary, in recent years we have seen continued progress toward better methods of feeding humanity. Sub-Saharan Africa is the sole major exception. Looking to the future, this paper argues that the continuation of recent cereal yield trends should be sufficient to cope with most of the demographically driven expansion of cereal demand that will occur until the year 2025. However, because of

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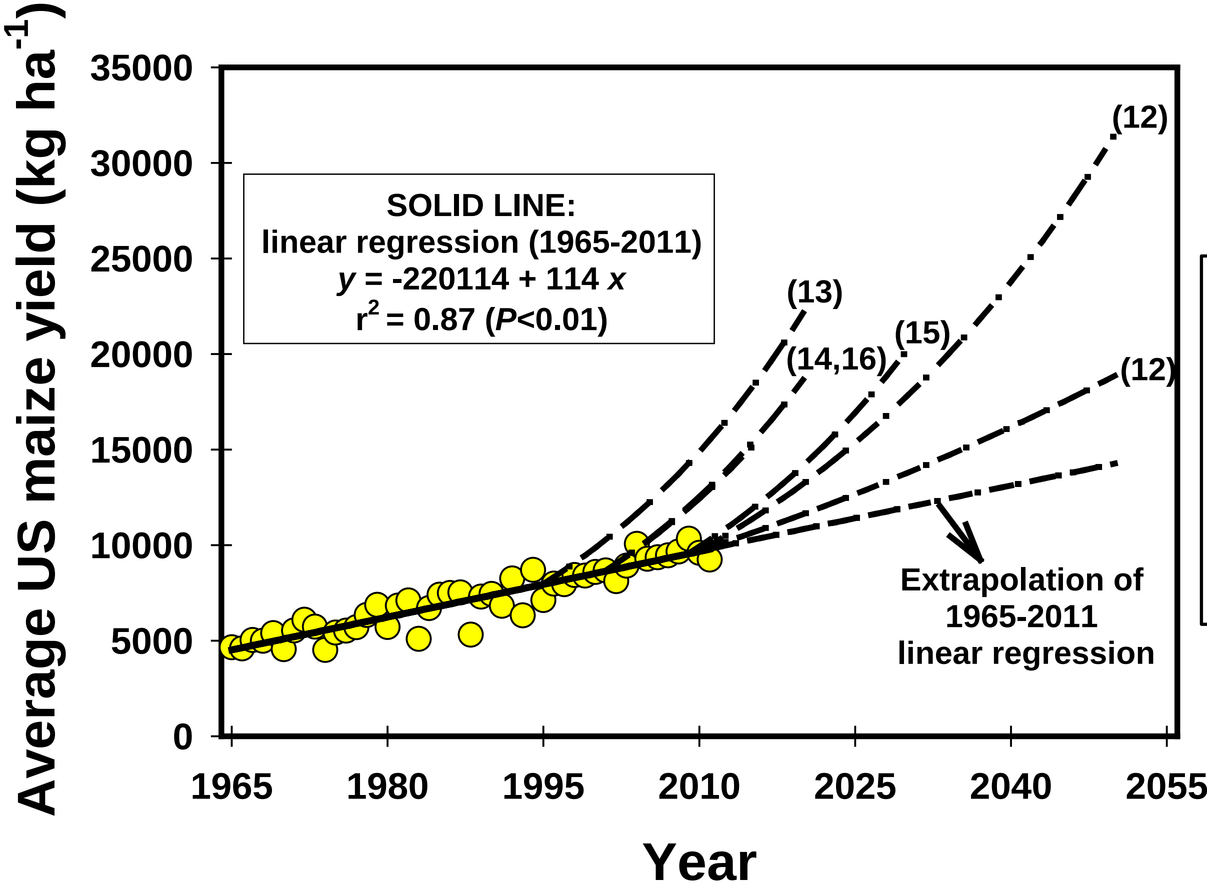
to the year 2

Dyson, T., 1999 World food trends and prospects to 2025. PNAS 96, 5929–5936

Hype *versus* reality in yield trends



(12) Nelson et al. (2010) & Rosegrant et al. (2013), IMPACT model, IFPRI, Washington D.C.
(13, 14) Reilly & Fuglie (1998) & Heisey (2009), USDA-ERS
(15) Edgerton (*Plant Phys.*, 2009), Monsanto Co.
(16) Hertel (*Bioscience*, 2010), GTAP model, Purdue Univ.

Grassini et al., *Nature Comms* (2014)

There is consensus that an increase of cereal production in the order of 50-70% by 2050** is required

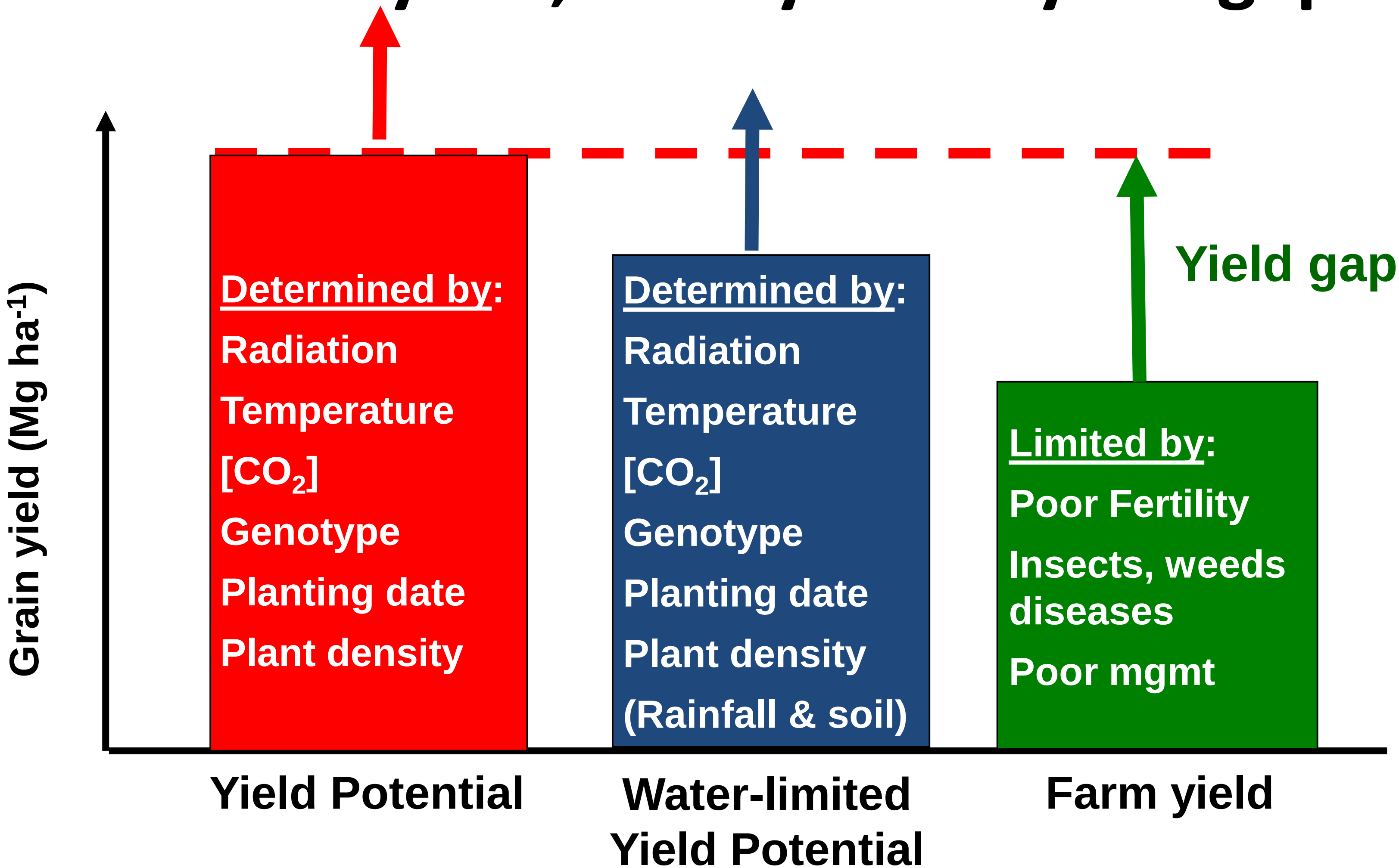
** 2050 = expected world population peak at 9.5+ billion

What are the available degrees of freedom?

- Increasing cropping area or expanding irrigation
- Raising production limits (in relation to available radiation, water and nitrogen)
- Yield gap closure
- Reducing waste (harvest, storage, distribution, home)
- Changing diets
- Expanding aquaculture

Argentines: 143 lb beef/person/year (US: 88 lb; EU: 37 lb)

Conceptual framework: yield potential, water-limited yield, farm yield & yield gaps



Modified from van Ittersum and Rabbinge (1997)

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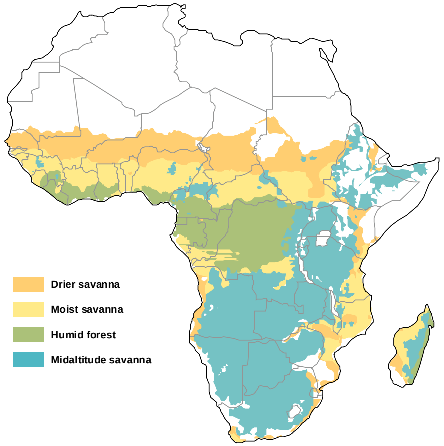


Global Yield Gap Atlas (GYGA)

Website: www.yieldgap.org

UNIVERSITY OF Nebraska Lincoln

Water for Food ROBERT B. DAUGHERTY INSTITUTE University of Nebraska

Global Yield Gap Atlas

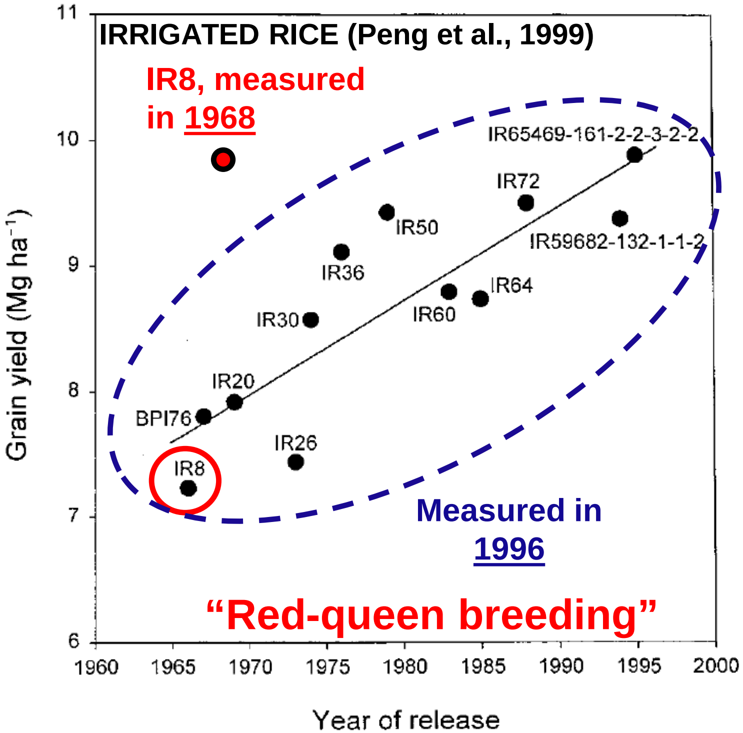
WAGENINGEN UNIVERSITY WAGENINGEN UR

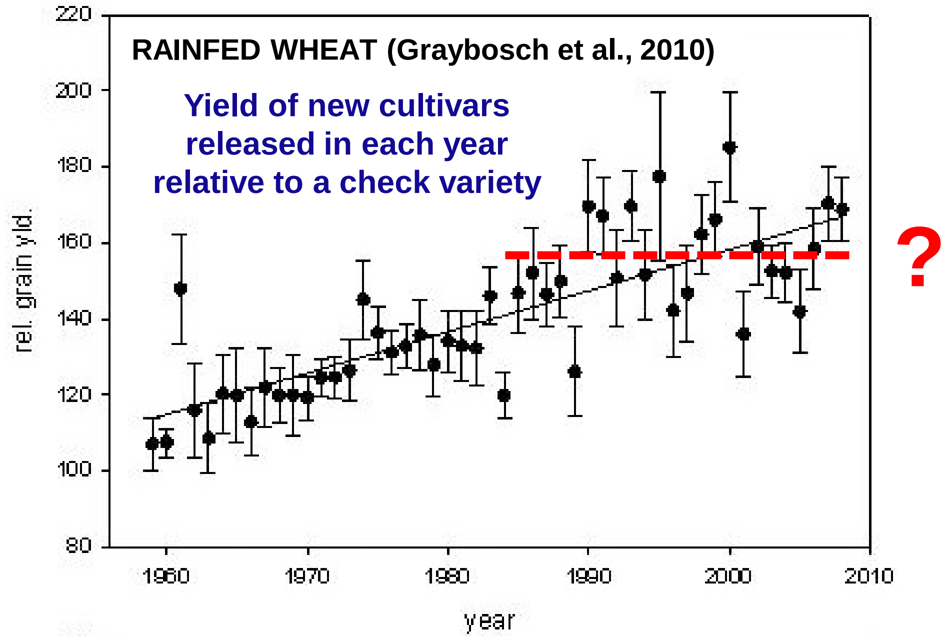
Today's presentation

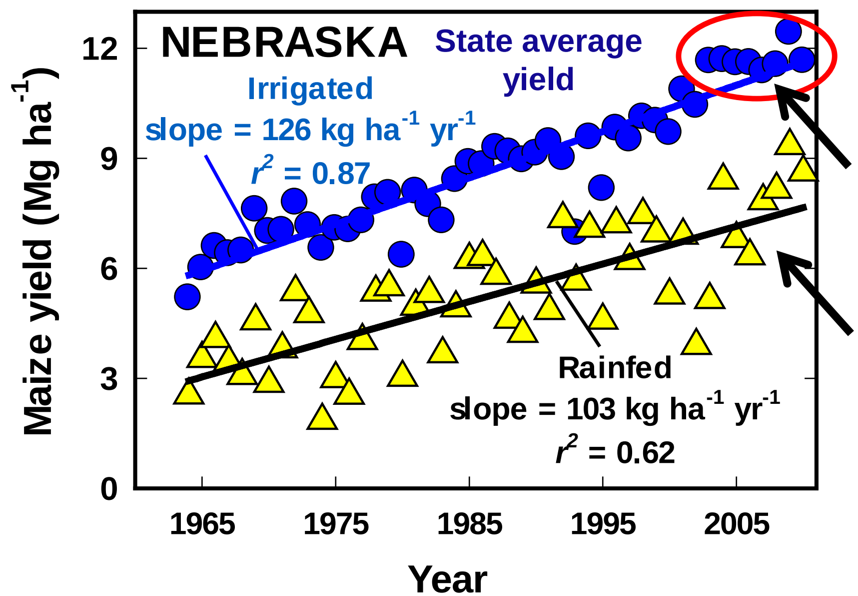
- Changes in yield potential and water-limited yield potential of major cereal crops (maize, wheat, and rice) over the last two decades (1990-2010)

- Genetic engineering & yield potential:
  - Conceptual framework
  - Proof of concept
  - Timeframe

Has yield potential of major cereal crops increased during recent decades?







Little or no change of yield potential of maize, wheat, and rice during recent decades

Change in yield potential in last two decades

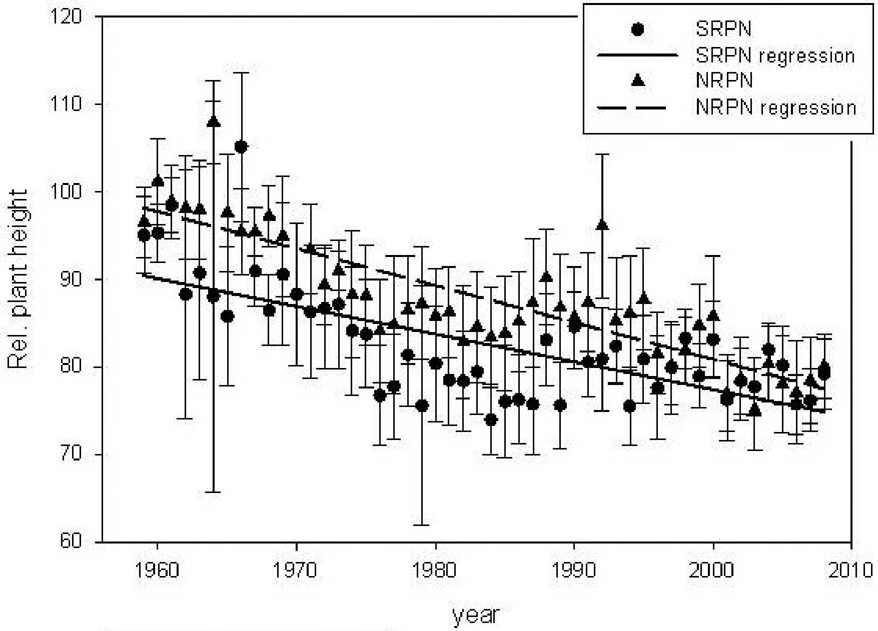
Rates are well below the required 1.2-1.3% per year

Crop	Yield potential (% per year)	Reference	Water-limited yield potential (% per year)	Reference
Maize	0 – 0.8	Duvick and Cassman (1999) Messina et al. (2009) Grassini et al. (2011, 2014)	0.6 – 0.8	Duvick and Cassman (1999) Messina et al. (2009)
Wheat	0.3 – 0.8	Fischer and Edmeades (2010) Reynolds et al. (2000) Zhou et al. (2007) Xiao et al. (2012) Mackay et al. (2011)	0 – 0.9	Graybosch and Peterson, 2010 Acreche et al. (2008) Fischer and Edmeades (2010) Sadras and Lawson (2011) Brisson et al. (2010) Rijk et al. (2013)
Rice	0 – 0.6	Peng et al. (1999, 2000, 2010) Li et al. (2009)	No data	

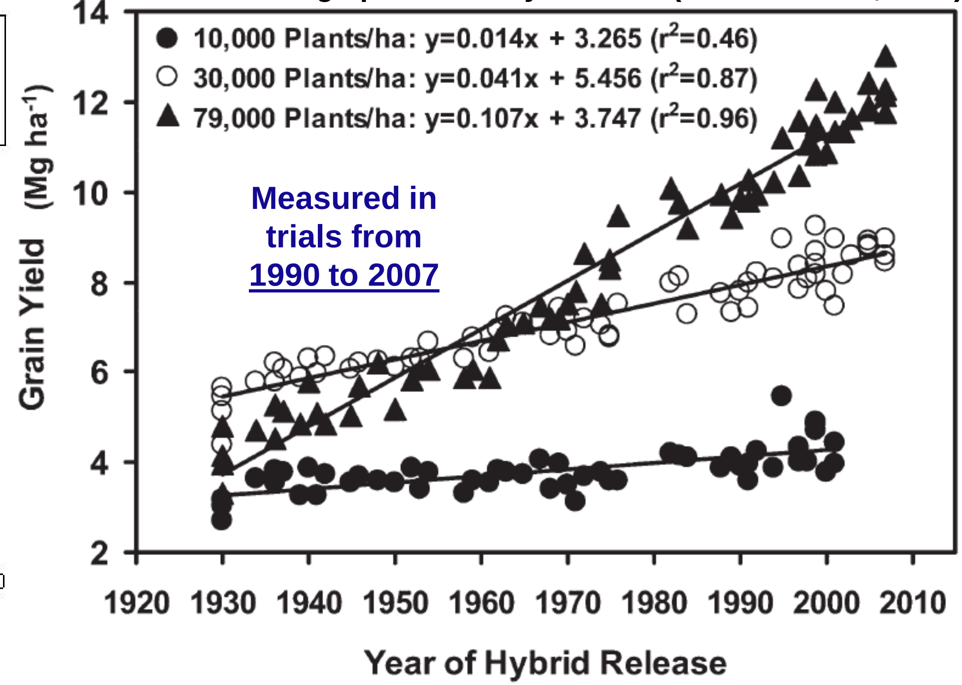
Adapted from Hall & Richards (2013)

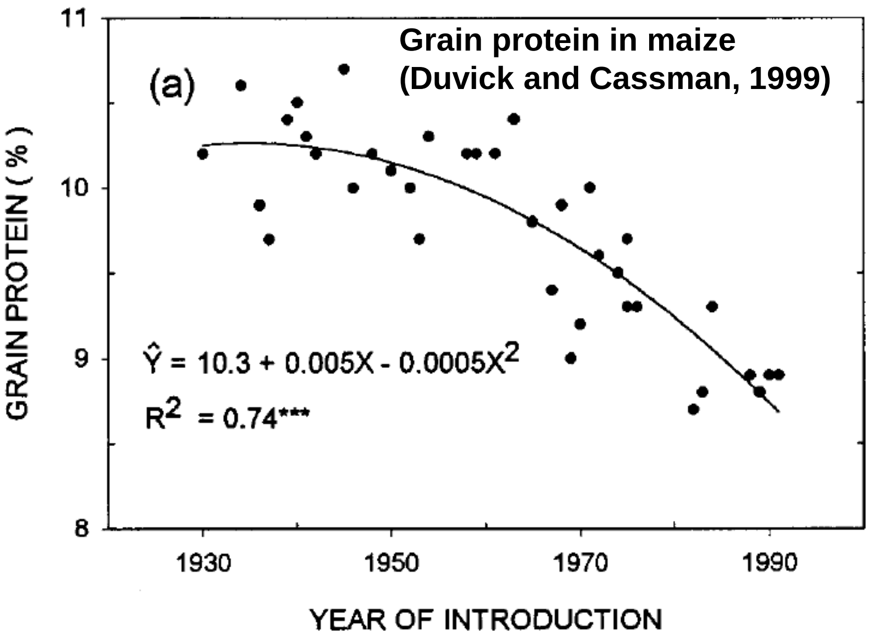
Which traits have changed over time?

Height in wheat (Graybosch et al., 2010)



Tolerance to high plant density in maize (Hammer *et al.*, 2009)

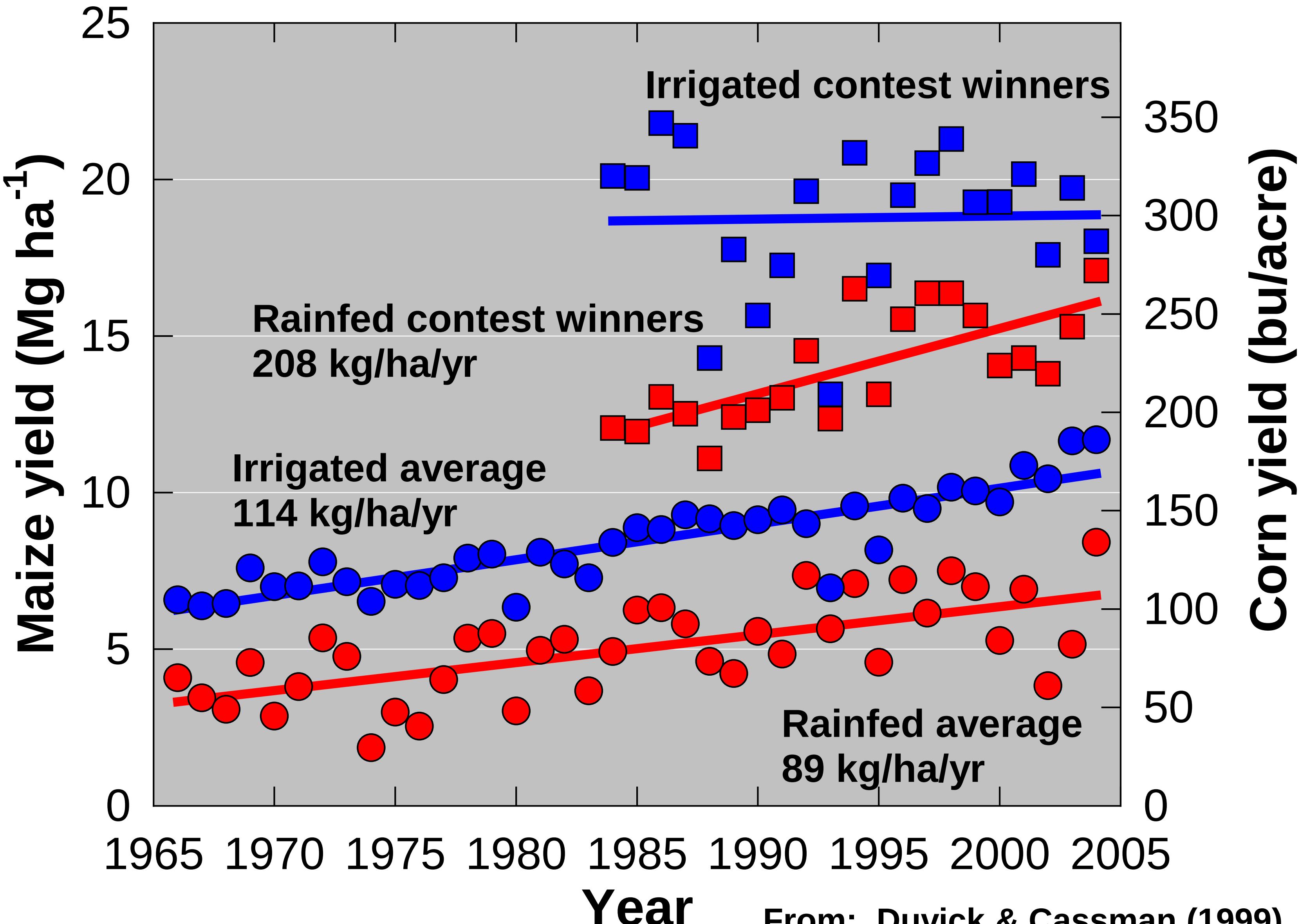




In many cases, increases in yield potential were related to changes in biomass partitioning, tolerance to high density (and stress in general), and grain biomass composition

Nebraska contest-winning and average yield trends

No increase in irrigated contest-winner yields since 1980s



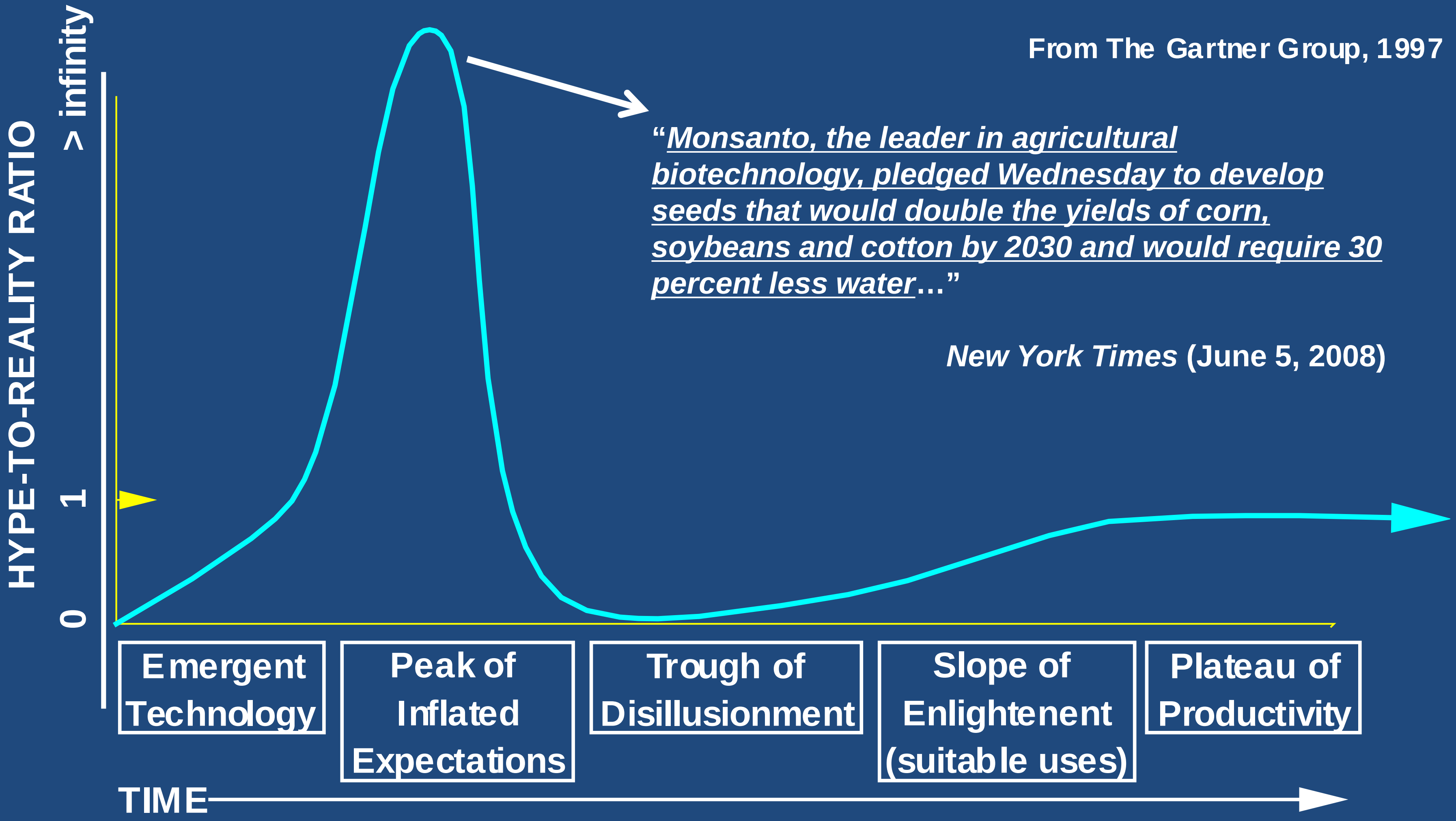
From: Duvick & Cassman (1999)

Can we visualize opportunities that will allow us, through genetic improvement, to increase current rates of gain in yield potential and water-limited yield?

Hall, AJ & Richards, R. 2012. Prognosis for genetic improvement of yield potential and water-limited yield potential of major grain crops. *Field Crops Res.* 143-18-33

Emerging Technologies - The Hype-To-Reality Ratio

From The Gartner Group, 1997



"*Monsanto, the leader in agricultural biotechnology, pledged Wednesday to develop seeds that would double the yields of corn, soybeans and cotton by 2030 and would require 30 percent less water*…"

New York Times (June 5, 2008)

TOOLS

- Conventional breeding (an indispensable business as usual)
- Targeted trait-based selection (using physiological or molecular markers)
- Genetic engineering (GE) of crop resource utilization capacity, or use of black(ish) box transgenes/transcription factors

TARGET ENVIRONMENTS

- Irrigated cropping systems → greater generality of useful traits
- Rainfed cropping systems → greater specificity of useful traits

A SHARED PROCESS FOR TRAIT-BASED SELECTION

Idea → Development → Proof of concept → Incorporation of trait into adapted cultivars

TIME (years) →

Modified from Hall and Richards (2013)

Current context

• A wave of journal articles aimed at identifying effective avenues (usually molecular) for increasing yields in irrigated and rainfed crops.

• A conceptual framework for many of these articles that is often lacking, incomplete, or worse.

• An experimental proof (if attempted) that is typically divorced from:

a) the realities of crops growing in farmer fields

b) the challenges facing breeders who must be able to use the potential attributes and tools in their daily work.

• An uncomfortable truth: commercial secrecy, which delays or impedes access to information that could be of value in a broader context. Also, what is the role of public research in this context?

A series of "blueprints for action", originated from both public and private sectors, that propose ways to improve yield potential and water productivity.

Strategies for developing Green Super Rice

Qifa Zhang*

National Key Laboratory of Crop Genetic Improvement, National Center of Plant Gene Research and National Center of Crop Molecular Breeding, Huazhong Agricultural University, Wuhan 430070, China

PNAS 42: 1…07

Editor's Choice Series on the Next Generation of Biotech Crops

Bacterial RNA Chaperones Confer Abiotic Stress Tolerance in Plants and Improved Grain Yield in Maize under Water-Limited Conditions[W]

Paolo Castiglioni[1], Dave Warner, Robert J. Bensen, Don C. Anstrom, Jay Harrison, M…

…iol. 147:446-55, 2008

Update on Increasing Crop Productivity

Increasing Crop Producti… …lobal Needs for Feed, Food, and Fuel

Michael D. Edgerton*

Monsanto Company, S…

Plant Physiol. 149:7-13, 2009

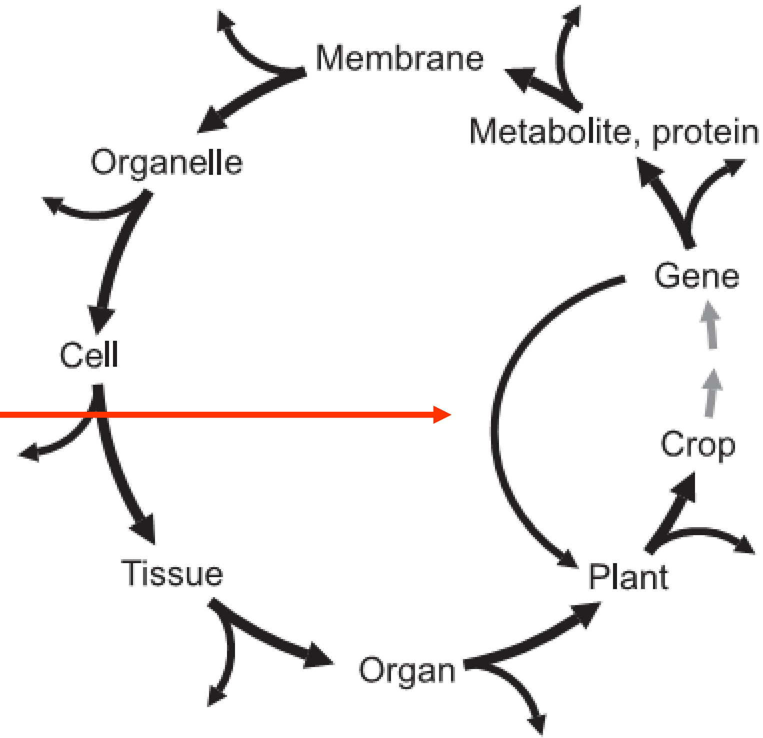
Mol… …nce to Break Yield Barriers

Ronald L. Phillips*

Crop Sci. 50: S99-S108, 2010

7000+ patents have been filed invoking "drought resistance", "plant breeding", and "transgenic". These are genes that people BELIEVE should confer drought tolerance without providing any proof of concept

Gene/Transcription factor mining and application, Issues with isolation techniques, initial testing techniques, scaling up to plant and crop.



Engineered drought tolerance in *B. napus* through constitutive expression of CBF1. Water witheld from 7-wk old plants for 1 week and rewatered for 2 wks. before picture was taken. CBF/DRE isolated from *At* plants exposed to 3 M mannitol and other stressors (Haake et al., Pl. Phys.130: 639-648, 2002).

Zhang et al. Pl. Physiol. 135: 615-621, 2004

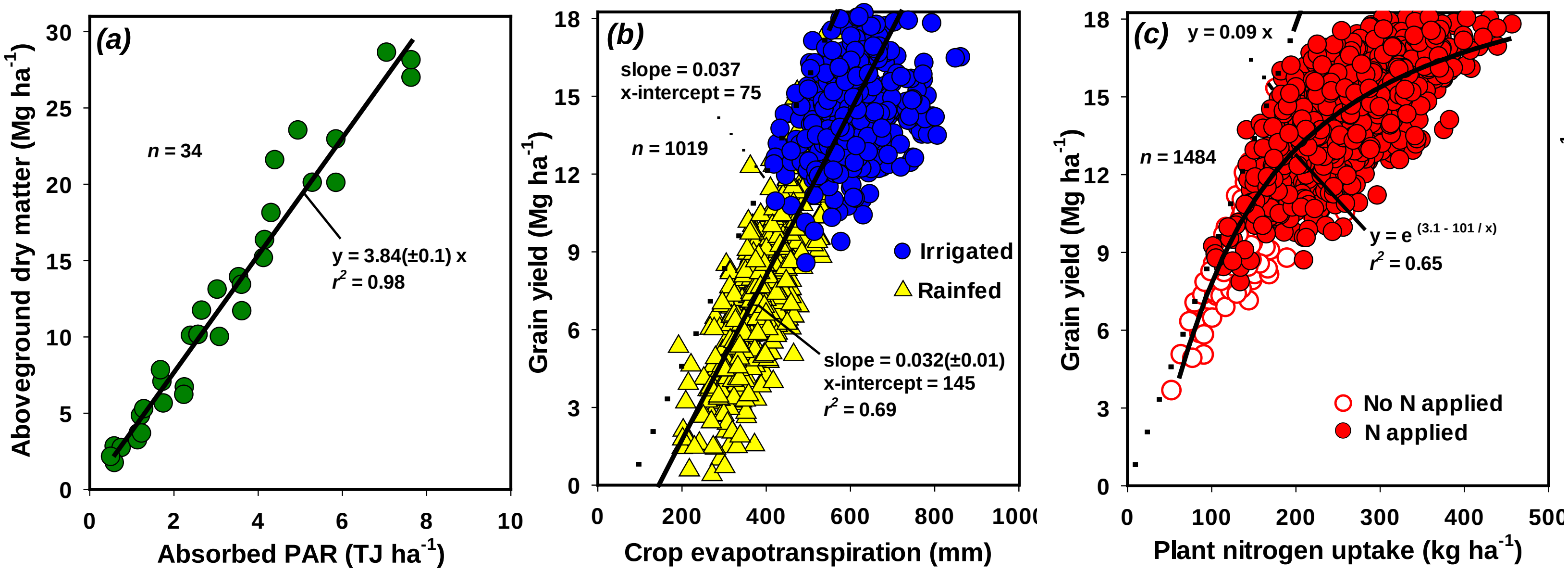
Fig. 2. A modification of Fig. 1 to illustrate scaling up (anticlockwise flow) from fine levels of organisation to whole plants and crops. The direct path from gene to plant works well for genes that are not involved in vital processes, such as *Bt*, herbicide resistance and nutritional quality of seeds. Adaptation to stress requires an anticlockwise flow of ideas through several levels of organisation to attain success at the level of the crop. Many ideas that do not explicitly consider the problems of scaling up fail, as depicted by the arrows leaving the loop -

Passioura, FPB 37: 585-591, 2010

SURVIVAL, NOT YIELD LOSS MITIGATION, AS CRITERION FOR GENE IDENTIFICATION

Conceptual framework

Proposed avenues to increase in yield potential should be considered (and tested) in view of well-known relationships between crop growth, light, water, and N



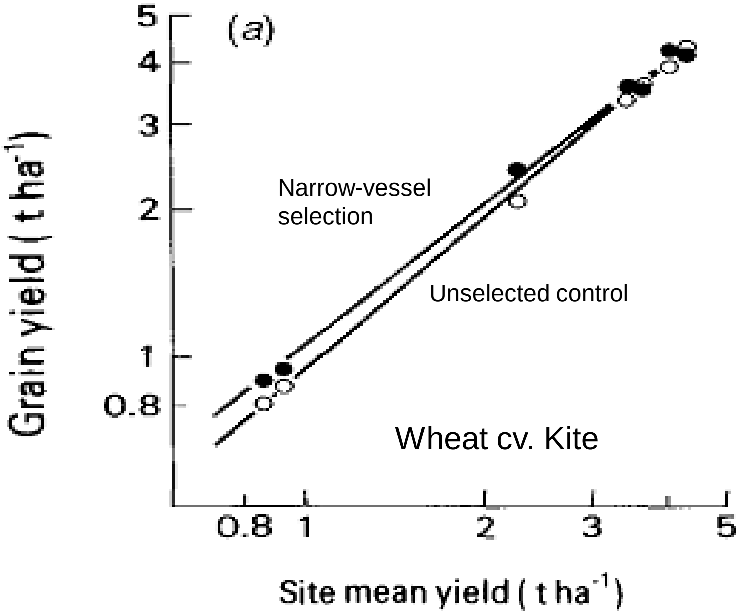
Example for maize from Grassini *et al.* (2014)

Yield = Resource capture x Conversion efficiency x Harvest Index (HI)

Example: Yield = Water Use x Water-use efficiency x HI (Passioura, 1978)

A DEFINITION OF PROOF OF CONCEPT FOR IMPROVED YIELD POTENTIAL IN CROP SPECIES

Multi-year (3-4 y minimum) and multi-environment trials across a range of water availability showing a consistent yield advantage for the cultivar carrying the attribute(s) or gene (s) of interest without changes in phenology with respect to the check cultivars (isolines but also best 'elite' lines)



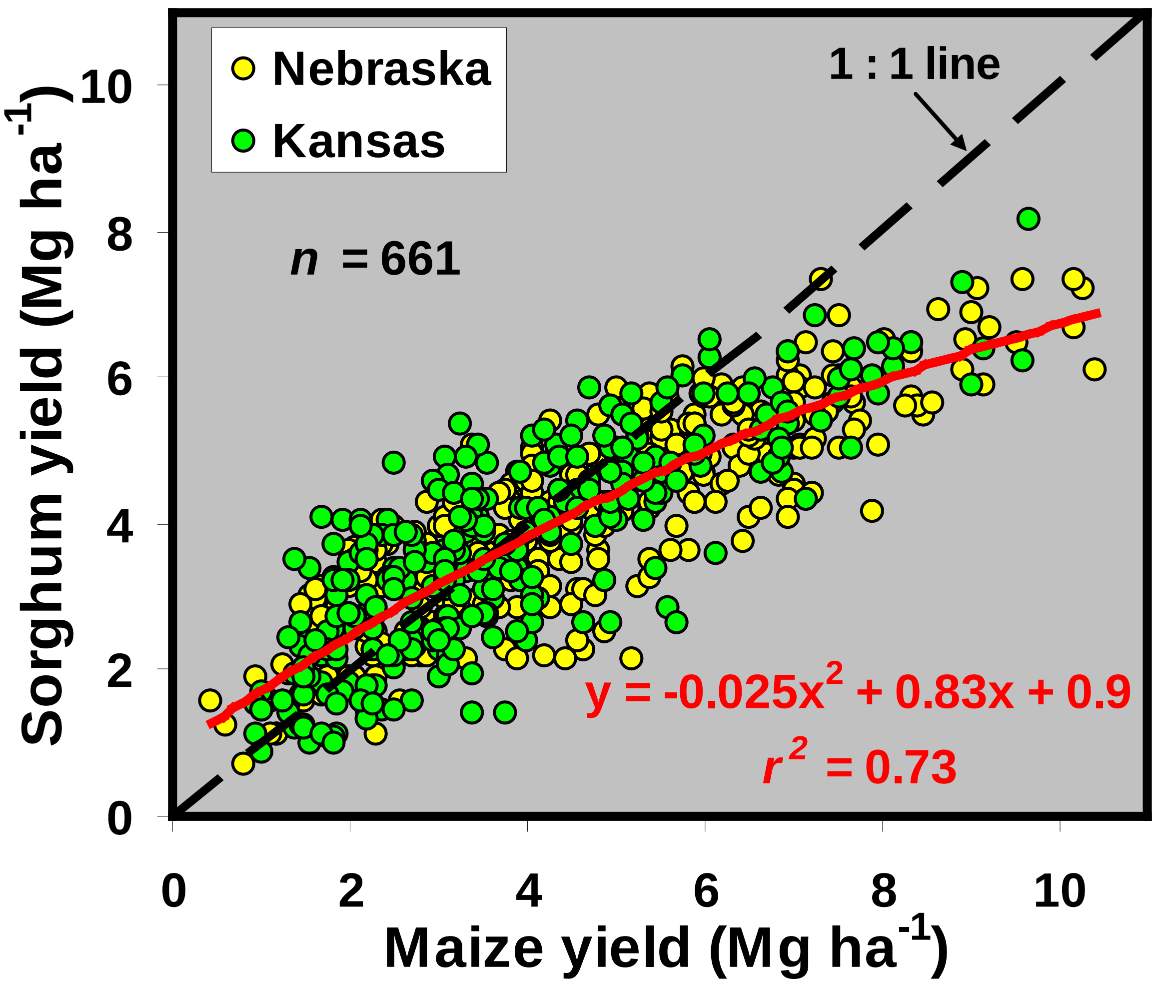
Richards & Passioura, AJAR 40: 943-950, 1989

Multi-year & multi site testing is needed to account for year-to-year and site-to-site variations in temperature, radiation, and rainfall

Apparent effects of attributes/genes in model plants or in pots can be a step on the way but are not definitive

Trade-offs between drought tolerance and potential yield

Sorghum *versus* maize county yield averages in Nebraska and Kansas
Each data point represents a county-year average



Resilient crop?
Drought tolerance?
Yield resistance?

Grassini et al., In Press

R.F. Denison's Hypothesis

(Darwinian Agriculture: when can humans find solutions beyond the reach of natural selection? *Quart Rev Biol.* 78, 145-168)

- **Traits conferring general advantages to individual plant fitness in competing against other plants of the same or different species would likely be optimized by evolution over million of years and would therefore not easily be improved (photosynthesis, respiration, drought tolerance, nitrogen-use efficiency)**
- **Good news is that evolution did not have the time to optimize traits that confer collective advantages to a community of similar plants of the same species as we found now in a farmer field**
- **Traits likely to increase yield potential and amenable to rapid genetic improvement, via both biotechnology and conventional breeding, are those that involve trade-offs between individual *versus* community fitness (e.g. shorter wheat varieties, more erect leaves in corn)**
- **Other traits amenable of improvement (but not related with yield potential) are those related with resistance to evolving pests and grain quality**

An alternative approach is suggested by serious practitioners of genetic engineering:

“Let´s re-engineer photosynthesis and associated processes to raise yield potential”

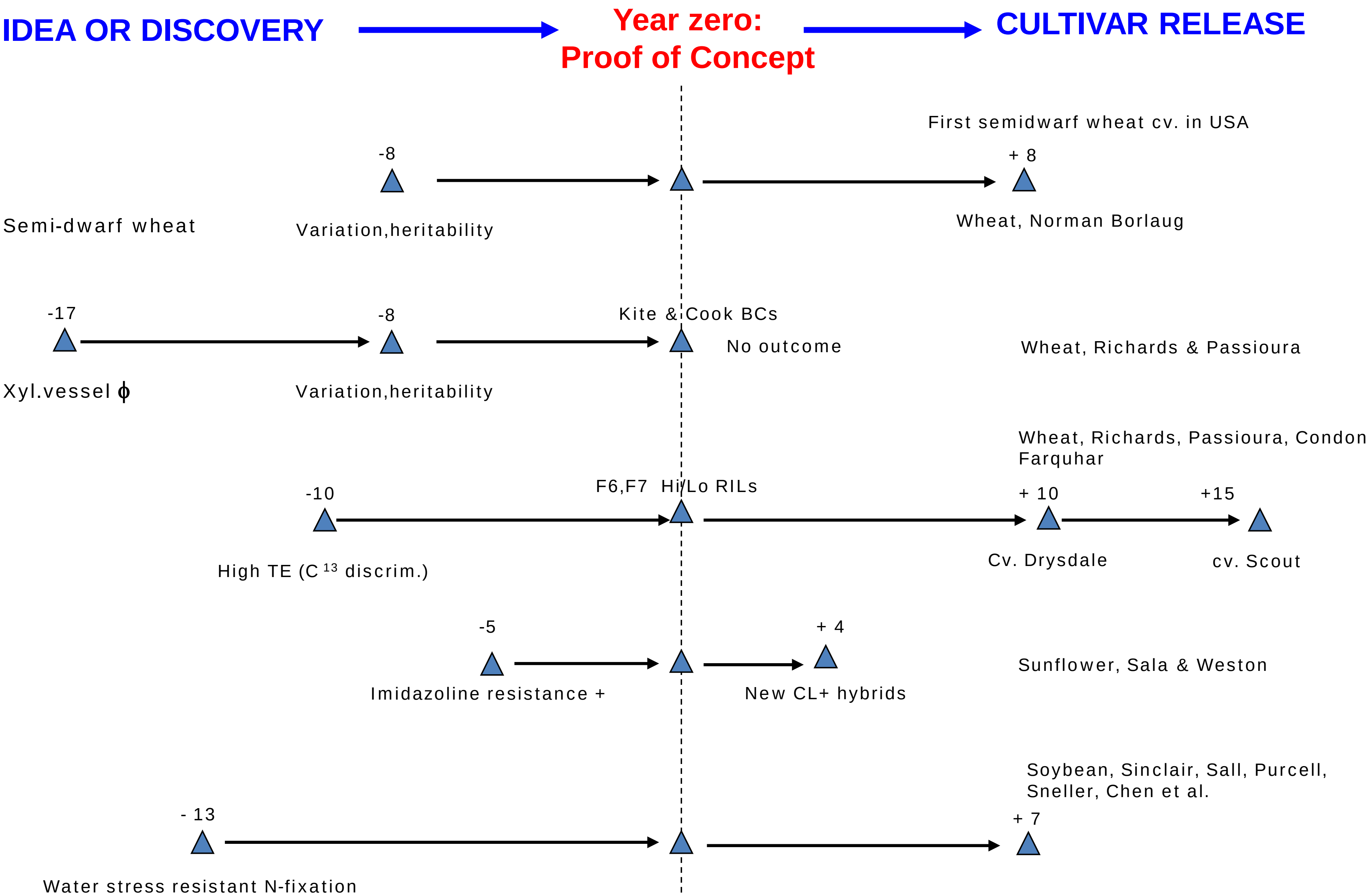
% increase in daily integral of crop carbon uptake, sunny day, mid-latitude

Table 2 Timeline for improving photosynthetic efficiency

Time horizon	Change to be made	[a]Increase in ε_c (%)	Major obstacle(s) to implementation
Long-term[b] Theoretical basis missing. Not enough known to determine if answer can be bought.	Rubisco with dramatically decreased oxygenase activity	30	Determining which molecular features of Rubisco control specificity
	Increase mesophyll conductance	20	Determining which physiological factors control mesophyll conductance
	Conversion of C3 to C4	30	Identifying suite of genes that control morphological and biochemical conversion
Mid-term[c] Important science missing. Substantial focussed investment to resolve in 20 yrs.	Increased rate of recovery from photoprotective state	15	Determining combination of components in PSII photoprotective pathway to be altered
	Introduction of Rubisco with increased carboxylation rate	25	Developing efficient transformation technologies
Near-term[d] Basic science in place. Hurdles technical. Given adequate investment, possible in 10 yrs.	Photorespiration bypass	13	Maximizing bypass flux; introducing into crop plants
	Improved canopy structure	30	Identifying genetic variability
	Rebalancing of RuBP regeneration rate with increased carboxylation	30	Demonstrating proof of concept experiments in crop plants; developing efficient transformation technologies
	Optimize canopy chlorophyll content	30	Developing optimization models; determining metabolically most efficient mode of reducing chlorophyll content

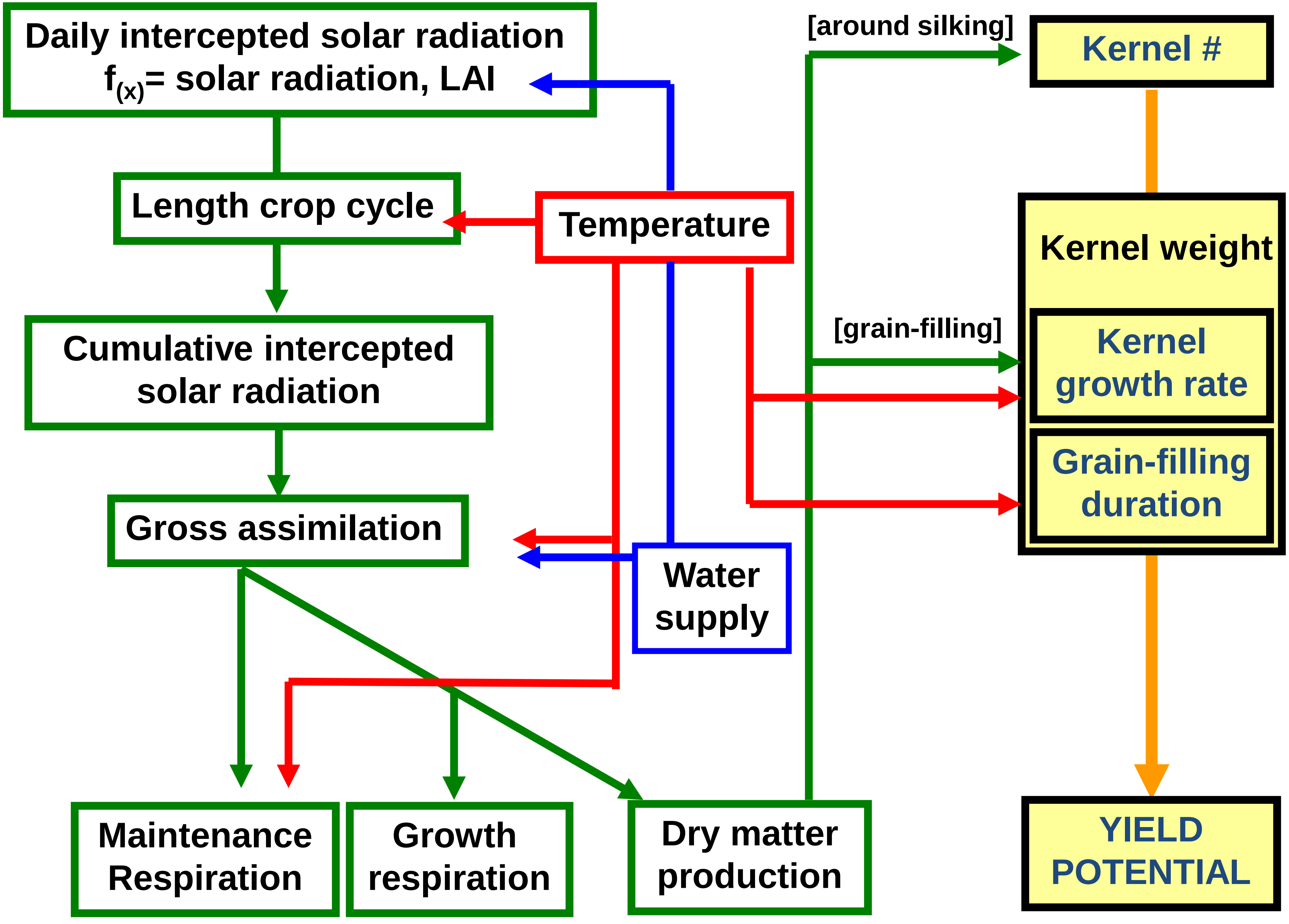
Zhu, Long, Ort. Annu. Rev. Plant Biol. 2010. 61:235–61

HOW MUCH TIME IS NEEDED ?: Indications from some case-histories



Adapted from Hall & Richards (2013)

Guidance from *in-silico* modelling to breeders seeking to identify useful traits while handling with the G x E in rainfed environments (e.g., maize, Chenu et al., 2009)

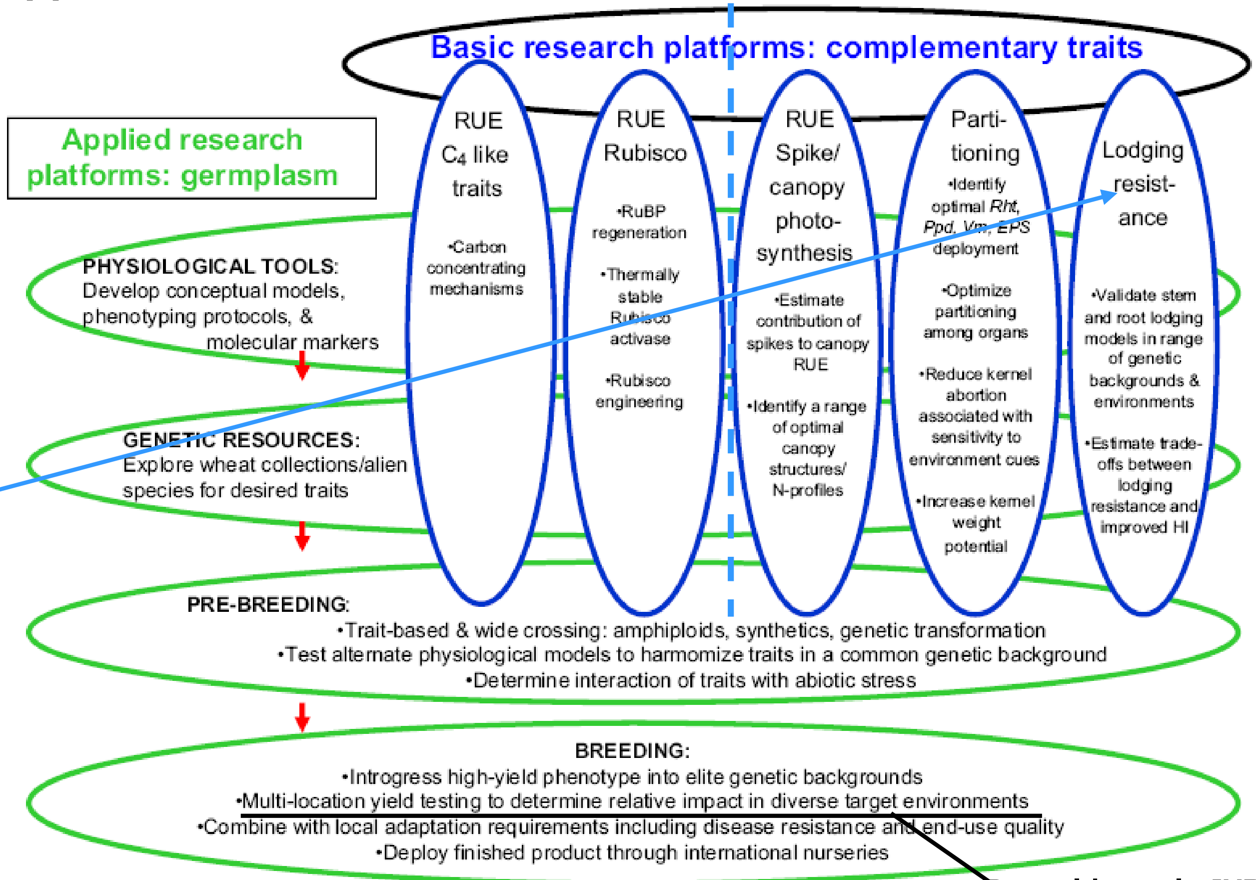


Wheat Yield Consortium:
A robust , comprehensive and interdisciplinary nuts and bolts approach

Genetic engineering

Exploration of trait (gene) variability in wheat and related species, trait modeling, inter-trait trade-offs, basic science (e.g., signalling pathways), etc.

Physiological understanding
>>>>>>>>>>>
Tool develop--ment
>>>>>>>>>>>>
Available genotypic variability
>>>>>>>>>>>
High throughput phenotype screening
>>>>>>>>>>>
Marker assisted breeding (QTLs & whole genome)



Reynolds et al., JXB 62: 439-452, 2011

Fig. 1. A research strategy to improve yield potential of wheat.

Proof of concept !

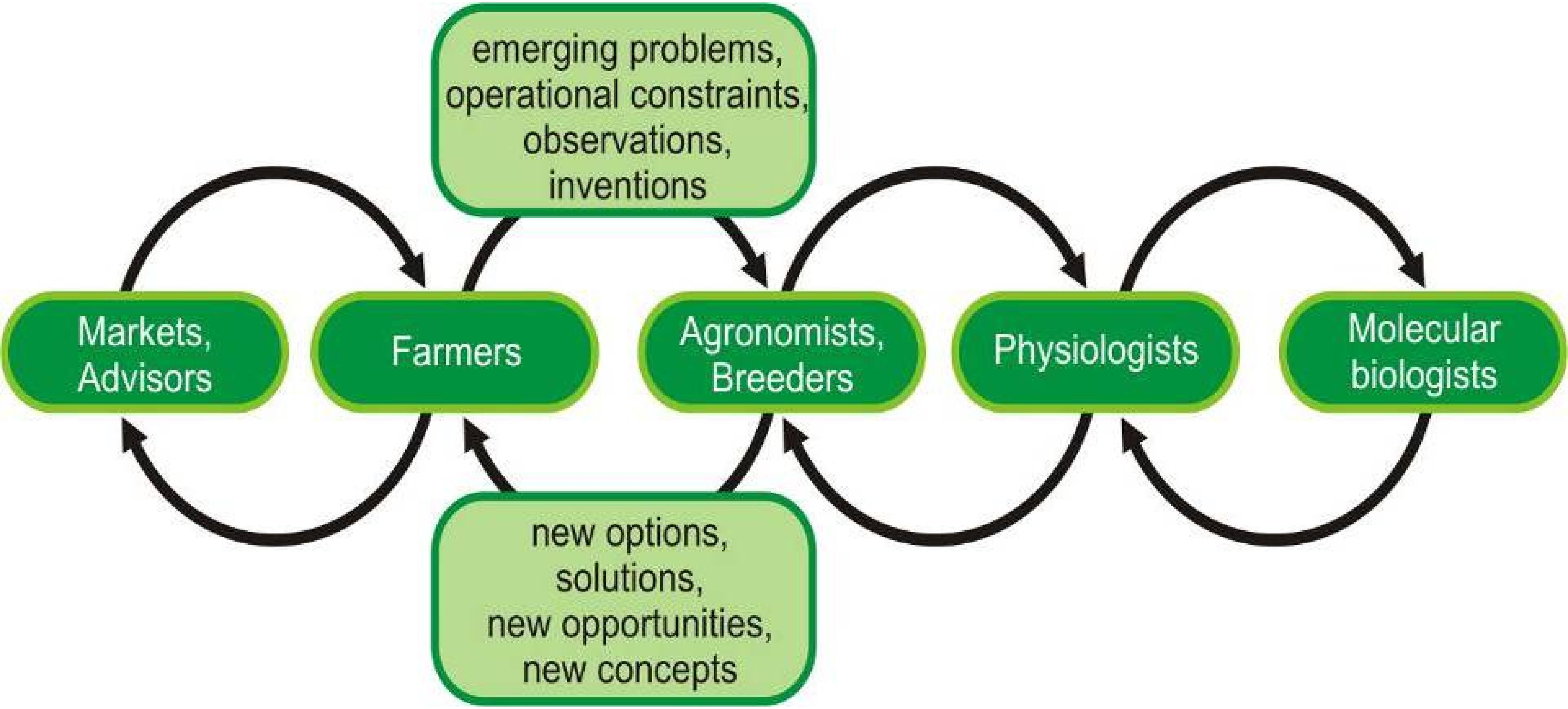
Note from authors: (the WYC is expected to require at least 20 years to achieve its goals).

Conclusions

- **There are opportunities to keep raising yield potential through conventional breeding in some crops but much smaller room than 50 years ago. Trait-based selection can help with simple traits, but complex ones are a much harder and need to be matched to the specifics of the target environments**
- **Genetic engineering of photosynthesis and associated processes might increase potential yields, but will take a LONG TIME before producing any useful progress (i.e., farmer-ready cultivars)**
- **Prospects for genetic engineering of water productivity are unlikely if techniques for gene isolation and testing are not congruent with conditions experienced by crops under drought and ignore issues of scaling up**
- **Genetic engineering, especially if it forms part of an integrated effort covering all links from the lab to breeders plots and producer fields, may contribute to raise yield potential some time in the future, however, the time frame for success in this effort cannot be regarded with optimism in the context of a 2050 deadline.**

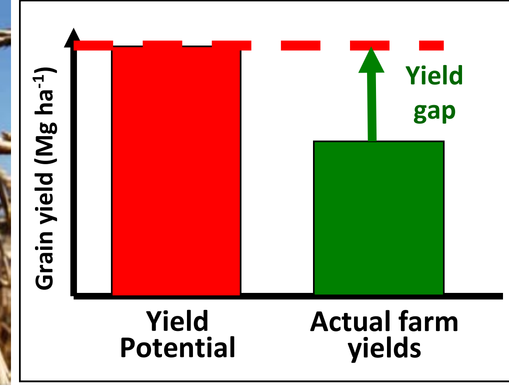
Agricultural Research:

Scaling down from the field then back up again



Passioura (2010), Scaling-up: the essence of effective agricultural research



If you cry ‘forward’, you must without fail explain in which direction you must go

Anton Chekhov, *Notebooks*

Thanks!

Questions?

International Workshop on Engineered Crops
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Key References

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- **Denison, RF. 2006. When can intelligent design of crops by humans outperform natural selection? In: Spiertz J.H.J., Struik P.C., and van Laar H.H. (eds.). Scale and Complexity in Plant Systems Research, Gene-Plant-Crop Relations. Springer, the Netherlands. pp 287-302.**
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- **Passioura, J.B., 2010. Scaling up: the essence of effective agricultural research. *Func. Plant Biol.* 37, 585–591.**
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