Sugarcane Biology, Yield, and Potential for Improvement

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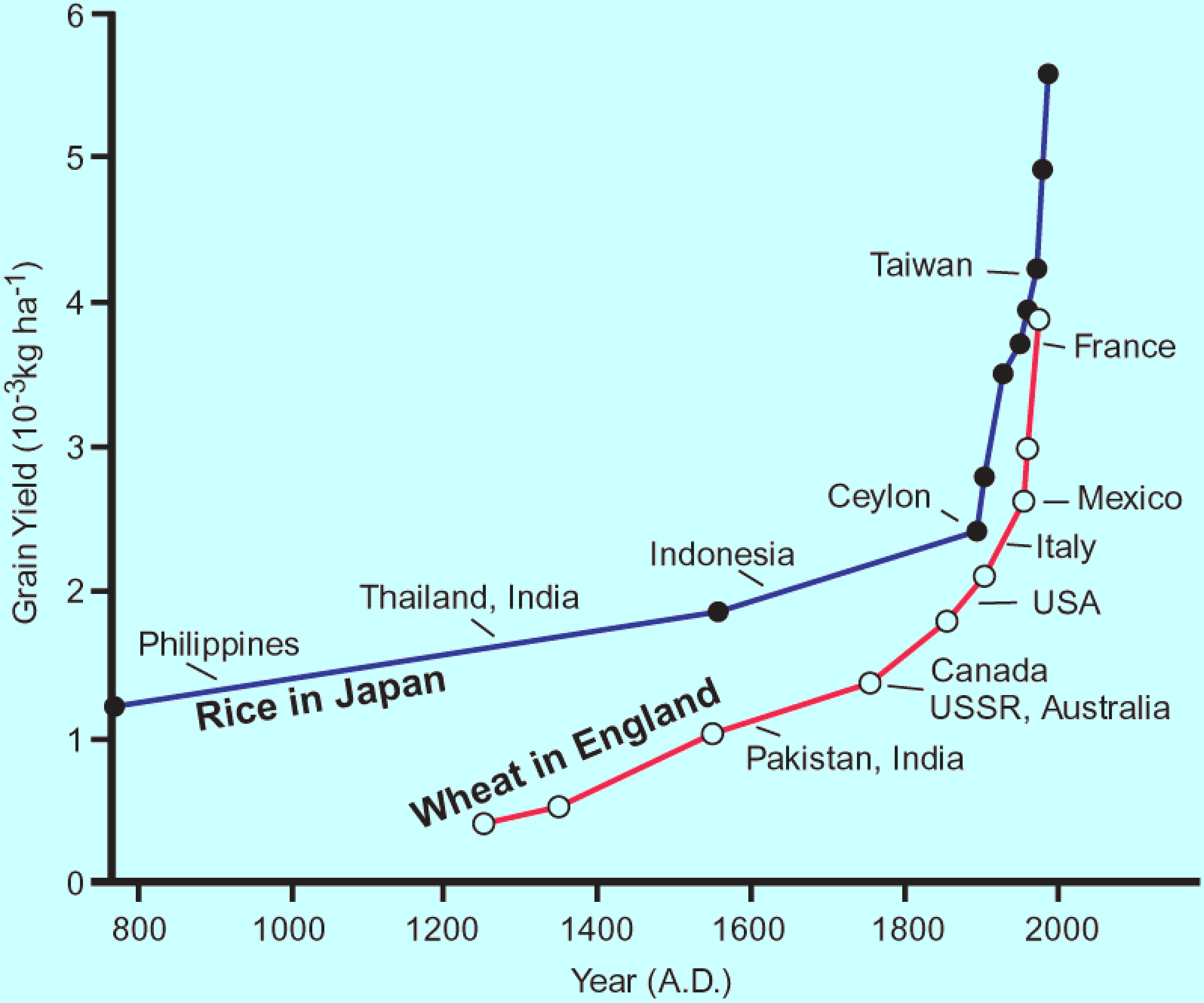
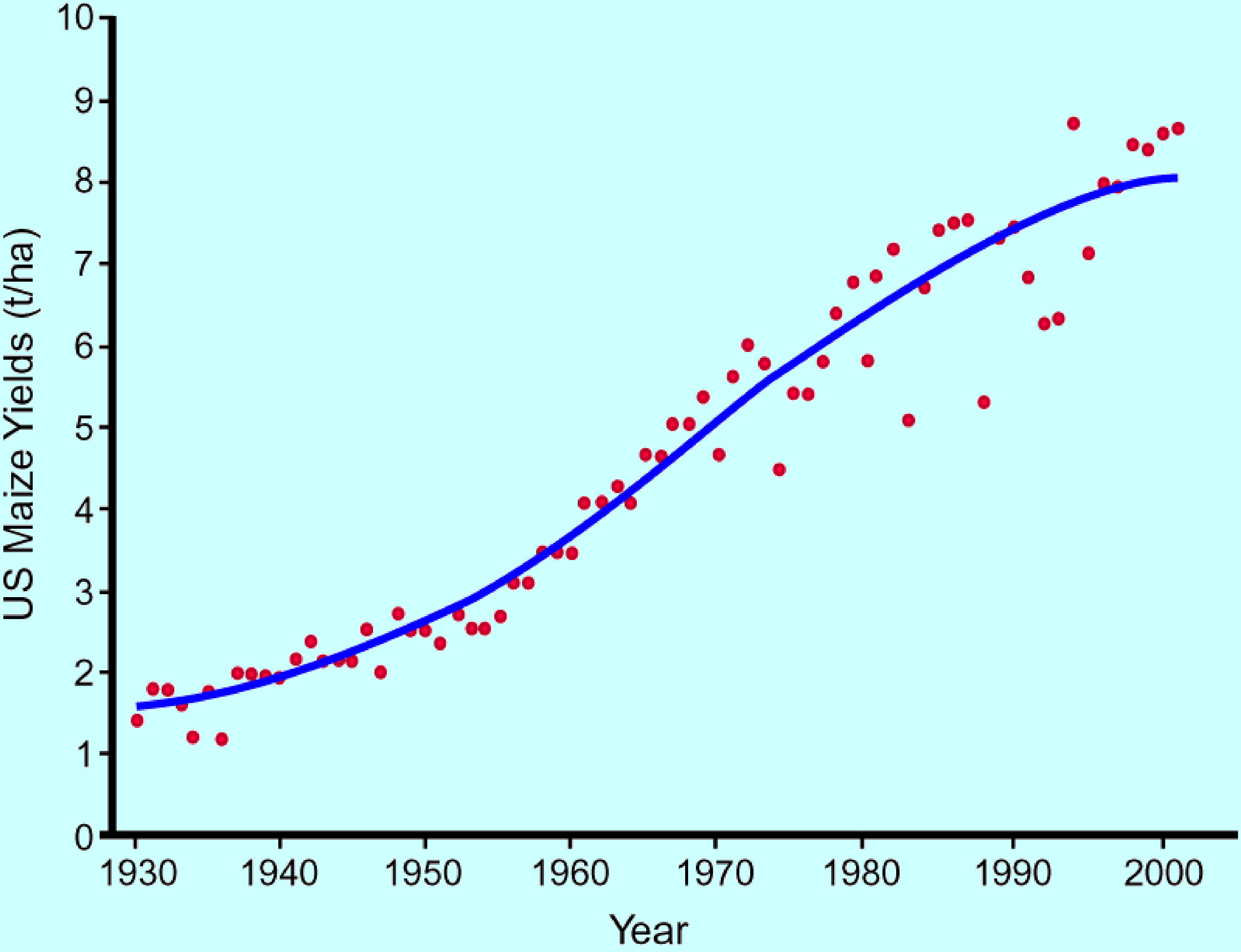
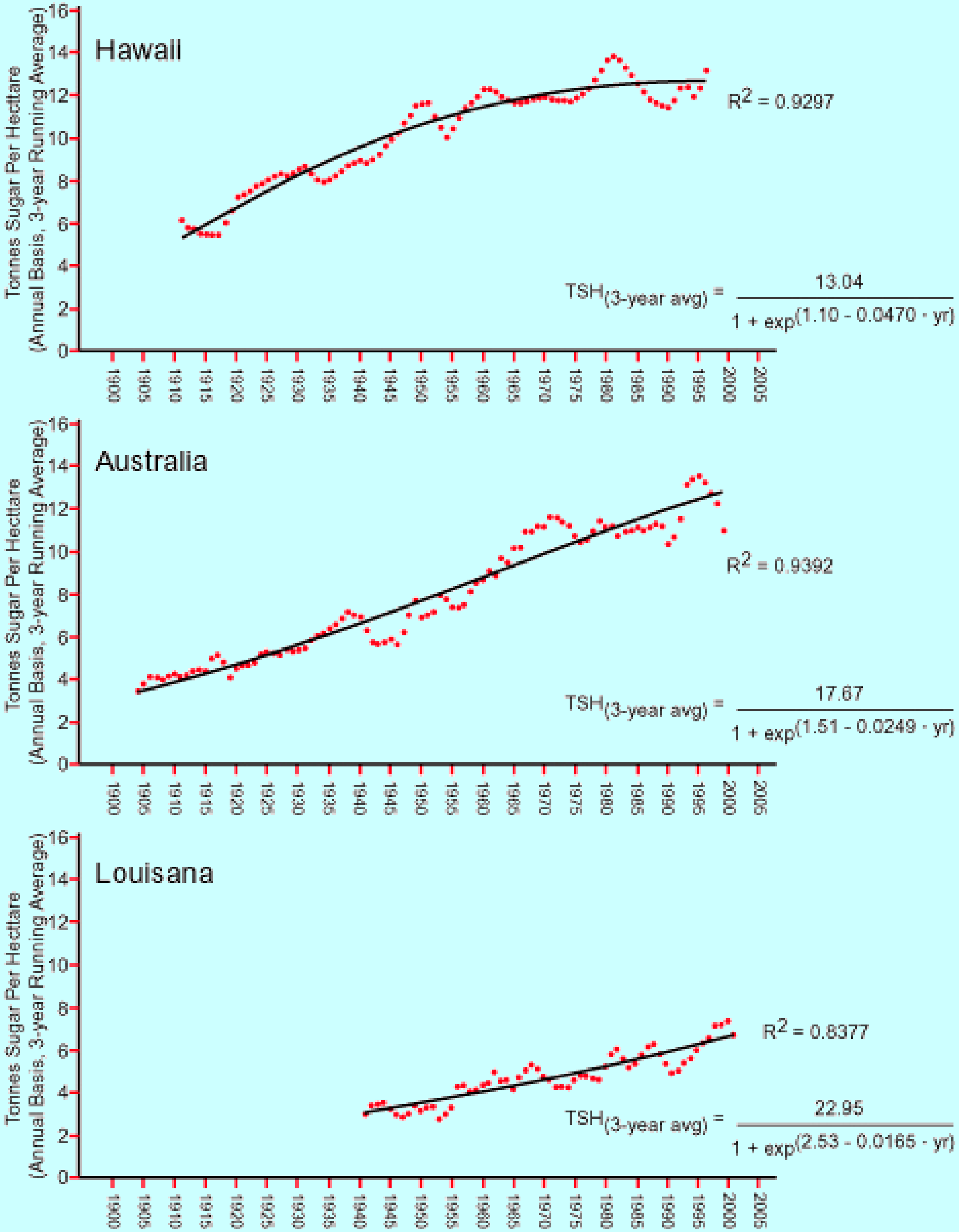
Outline

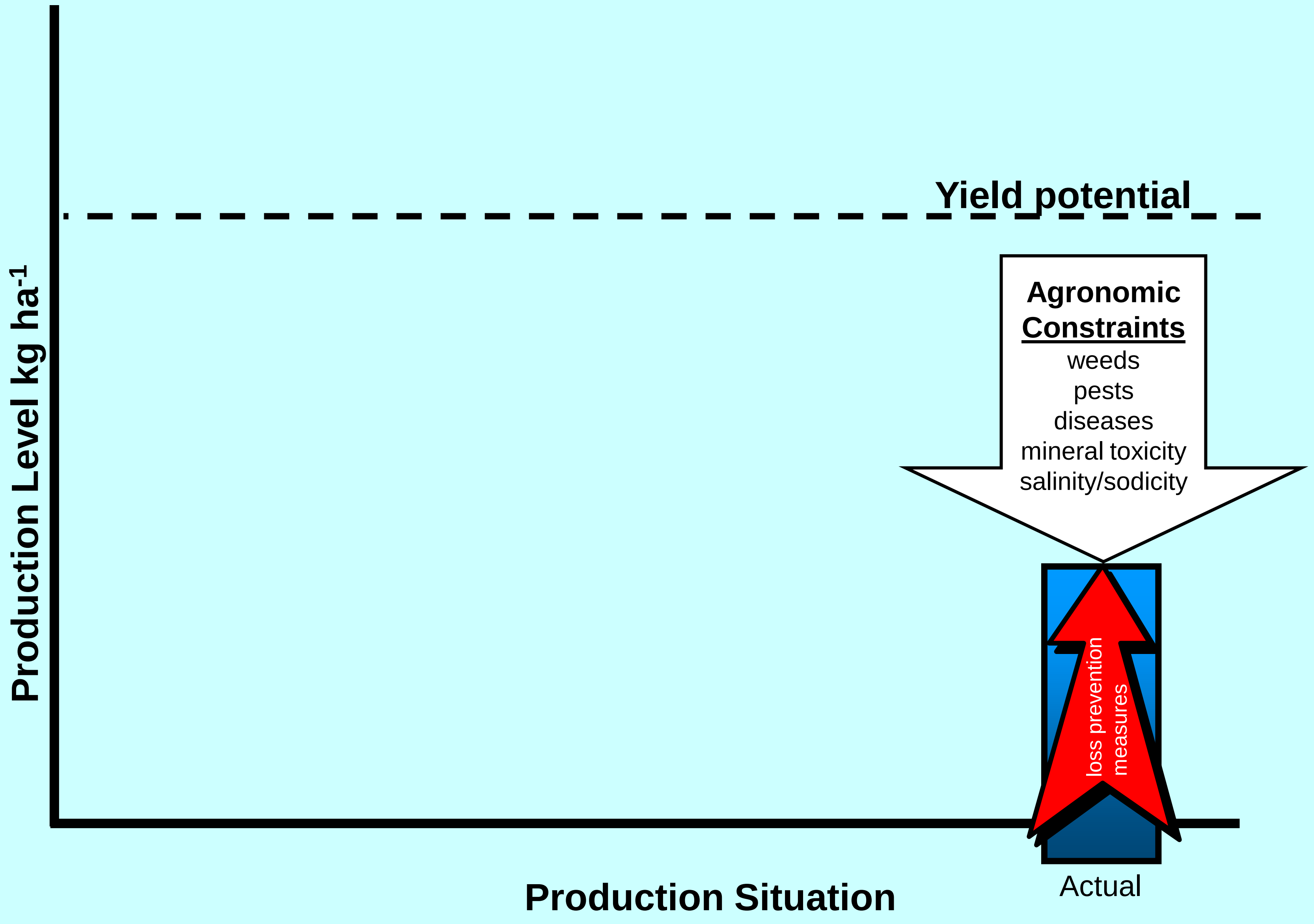
- Crop Yields
- Crop Physiology
- Systems Biology
- Modeling Growth and Production
- Putting it all together: gene-to-phenotype
- Potential Thrusts


Grain Yield (10^-3 kg ha^-1)
6
5
4
3
2
1
0
800
1000
1200
1400
1600
1800
2000
Year (A.D.)
Rice in Japan
Wheat in England
Philippines
Thailand, India
Indonesia
Ceylon
Taiwan
France
Mexico
Italy
USA
Canada
USSR, Australia
Pakistan, India


US Maize Yields (t/ha)
Year
0
1
2
3
4
5
6
7
8
9
10
1930
1940
1950
1960
1970
1980
1990
2000

Tonnes Sugar Per Hectare For Hawaii, Australia, And Louisiana





Yield potential
Agronomic
Constraints
weeds
pests
diseases
mineral toxicity
salinity/sodicity
loss prevention measures
Actual
Production Level kg ha^{-1}
Production Situation

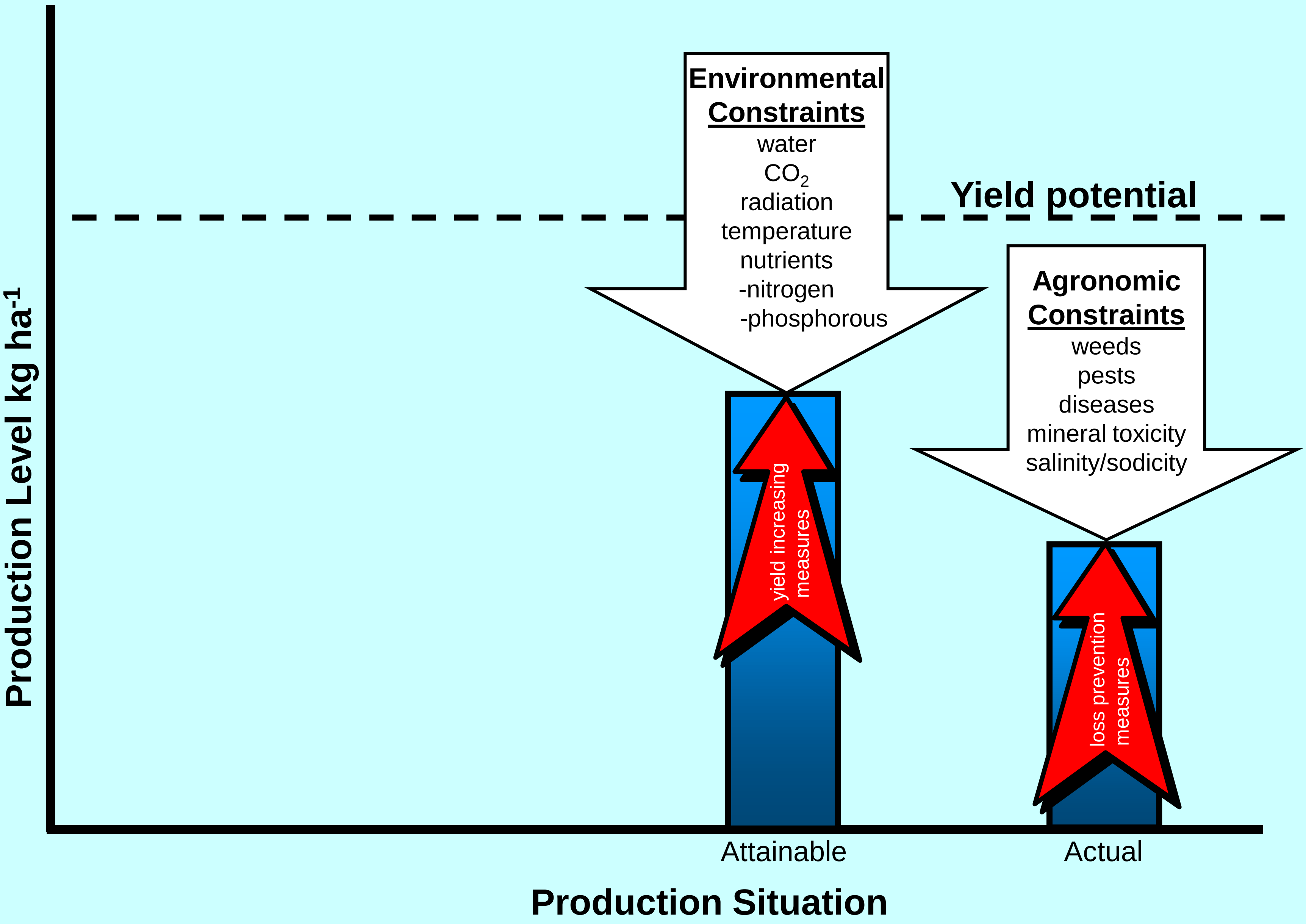
Record yields, average yields, and yield losses due to diseases, insects, and unfavorable physicochemical environments for major U.S. crops.

(Values in kg per ha)

Crop	Record yield	Average yield	Average losses			
			Diseases	Insects	Unfavorable environment*	
					Weeds	Other
Corn	19,300	4,600	750	691	511	12,700
Wheat	14,500	1,880	336	134	256	11,900
Soybeans	7,390	1,610	269	67	330	5,120
Sorghum	20,100	2,830	314	314	423	16,200
Oats	10,600	1,720	465	107	352	7,960
Barley	11,400	2,050	377	108	280	8,590
Potatoes	94,100	28,300	8,000	5,900	875	50,900
Sugar beets	121,000	42,600	6,700	6,700	3,700	61,300
Mean % of record		**21.6**	**4.1**	**2.6**	**2.6**	**69.1**

* Calculated as: Record yield – (average yield + disease loss + insect loss)

Boyer, J.S. **Science** 218:443-448. 1982



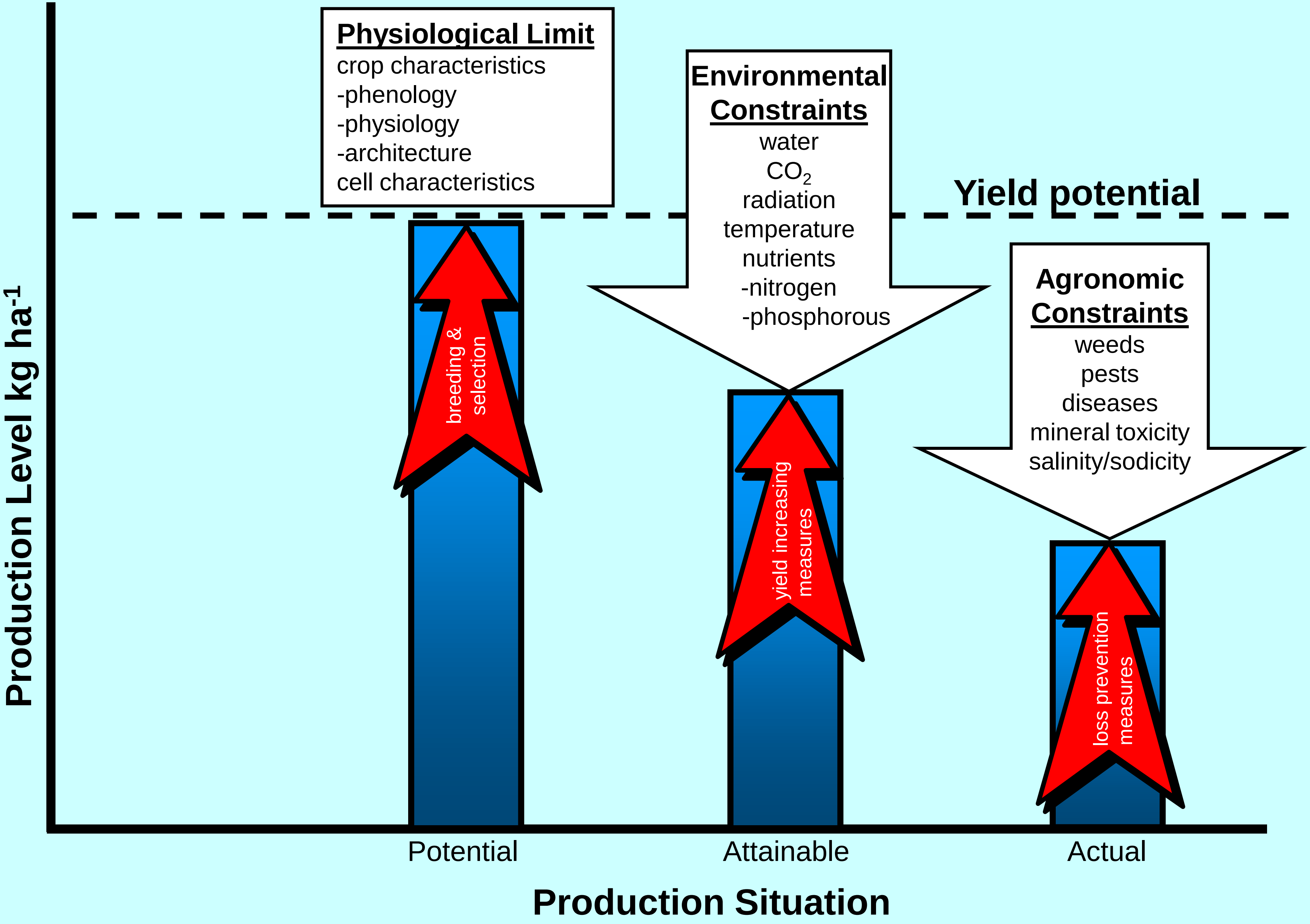
Environmental
Constraints
water
CO_2
radiation
temperature
nutrients
-nitrogen
-phosphorous

Agronomic
Constraints
weeds
pests
diseases
mineral toxicity
salinity/sodicity

Average and maximum sugarcane yields and the equivalent total dry matter production

Type (Australia, Colombia, South Africa)	Cane yield ($t\ ha^{-1}\ yr^{-1}$)	Biomass*	
		($t\ ha^{-1}\ yr^{-1}$)	($g\ m^{-2}\ d^{-1}$)
Average	84	39	10.7
Commercial maximum	148	69	18.8
Experimental maximum	212	98	27.0

* Cane yield was converted to biomass dry matter by first calculating stalk dry wt (t cane $ha^{-1}\ yr^{-1}$ x 0.30) then add the proportion of trash dry wt [0.65 (stalk dry wt)] as calculated from Thompson 1978 modified from Irvine 1983



Physiological Limit
crop characteristics
-phenology
-physiology
-architecture
cell characteristics

Environmental Constraints
water
CO_2
radiation
temperature
nutrients
-nitrogen
-phosphorous

Yield potential

Agronomic Constraints
weeds
pests
diseases
mineral toxicity
salinity/sodicity

YIELD POTENTIAL (Yp)

- “the yield of a cultivar when grown in environments to which it is adapted, with nutrients and water non-limiting, and with pests, diseases, weeds, lodging and other stresses effectively controlled” (Evans and Fisher 1999)

- **$Yp = \eta \cdot Pn$**

- **Pn** = the primary production (i.e. the total plant biomass produced over the growing season)
- **η** = the harvest index or efficiency with which biomass is partitioned into the harvested product

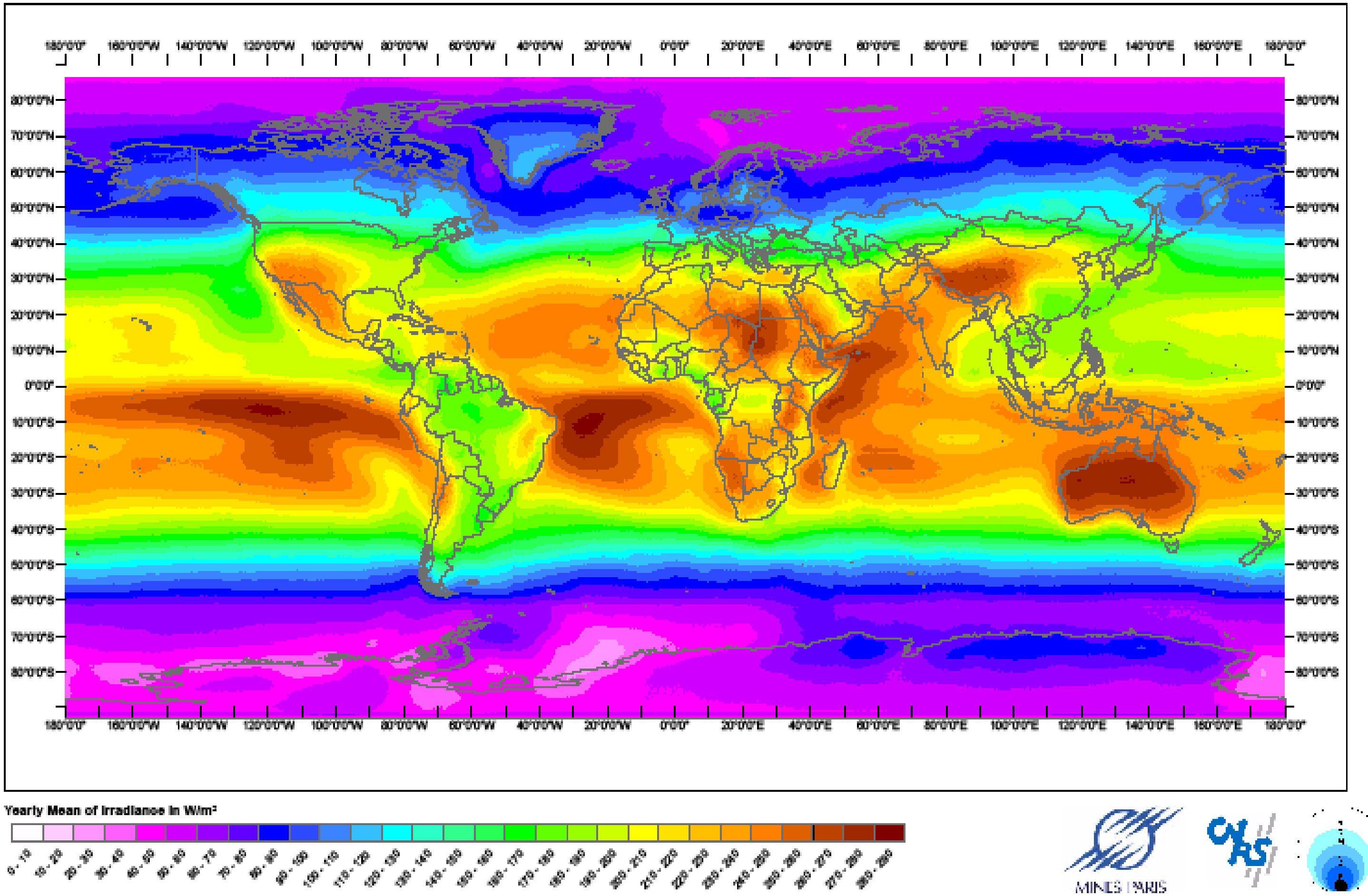
Primary production (*Pn*)

- $Pn = St \cdot \varepsilon i \cdot \varepsilon c / k$

- Where:
- $St \cdot$= annual integral of incident solar radiation (MJ m-2)
- εi = efficiency of light capture
- εc = efficiency of conversion of captured light
- k = energy content of the plant mass (~17.5 MJ kg-1)

Theoretical yield calculations (Monteith 1977)

Averaged Solar Radiation 1990-2004

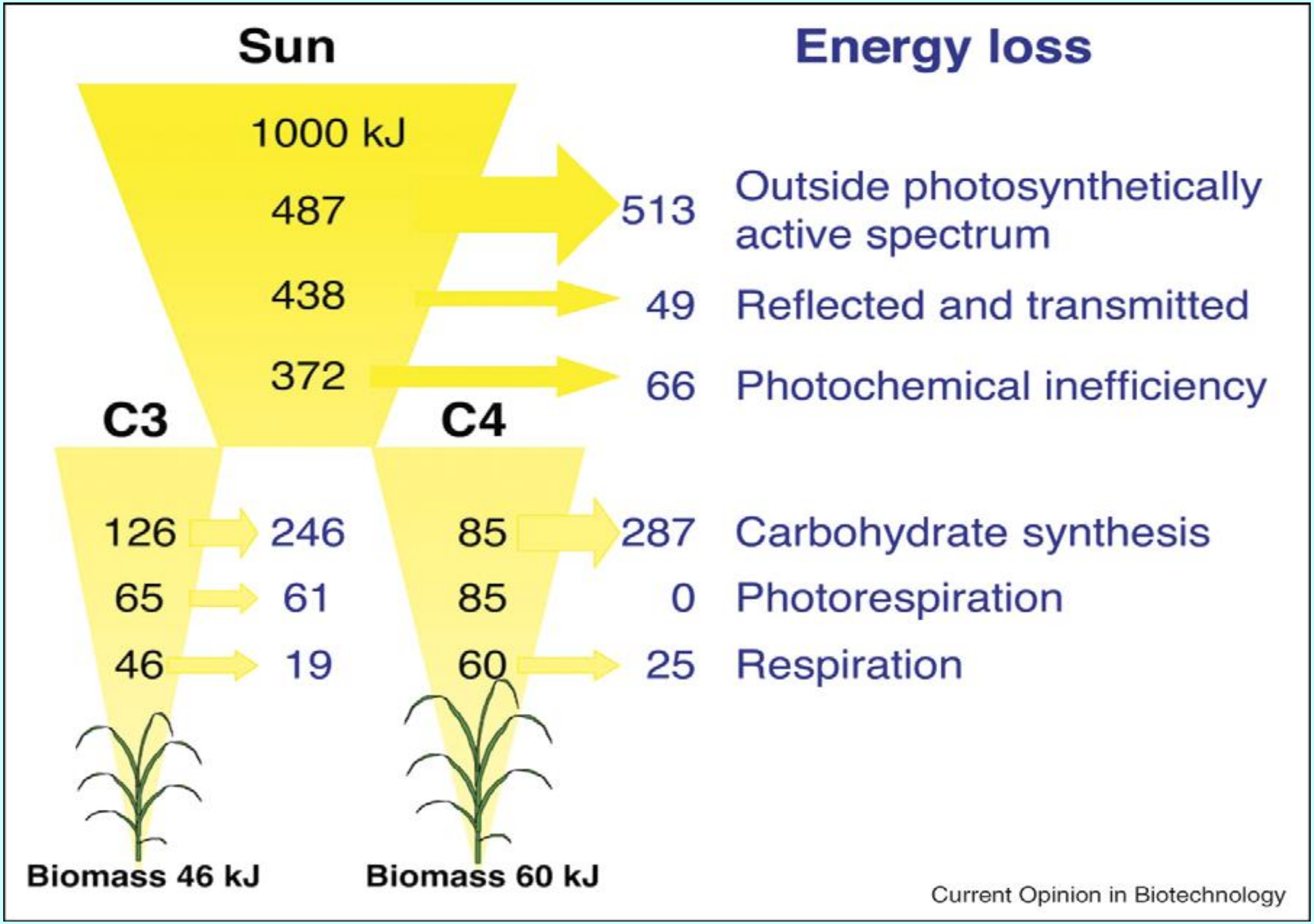


MINES PARIS

Realized by Michel Albuisson, Mireille Lefèvre, Lucien Wald.
Edited and produced by Thierry Ranchin. Date of production: 23 November 2006.
Centre for Energy and Processes, Ecole des Mines de Paris / Armines / CNRS.

Minimum energy losses in the plant photosynthetic process from light interception to formation of chemical energy stored in the biomass

Zhu et al. Curr Opin Biotech 19:153-159. 2008



Theoretical Maximum Yield

- Annual Mean Daily Irradiance in Sugarcane Production Areas
  $230 \text{ W m}^{-2} = 19.872 \text{ MJ m}^{-2} = 198{,}720 \text{ MJ ha}^{-1} \text{ d}^{-1}$
- Theoretical daily energy stored in biomass of C4 plants (.06)
  $198{,}720 \text{ MJ ha}^{-1} (.06) = 11{,}923 \text{ MJ ha}^{-1} \text{ d}^{-1}$
- Energy content of plant mass (~17.5 MJ kg^{-1})
  carbohydrate biomass (~15.9 MJ kg^{-1})

Theoretical Maximum Yield

- Theoretical biomass produced 11,923 MJ ha^{-1} (15.9 MJ kg^{-1}) = 749.87kg ha^{-1} d^{-1}

  = 0.750 t ha^{-1} d^{-1} = **273.70 t ha^{-1} yr^{-1}**

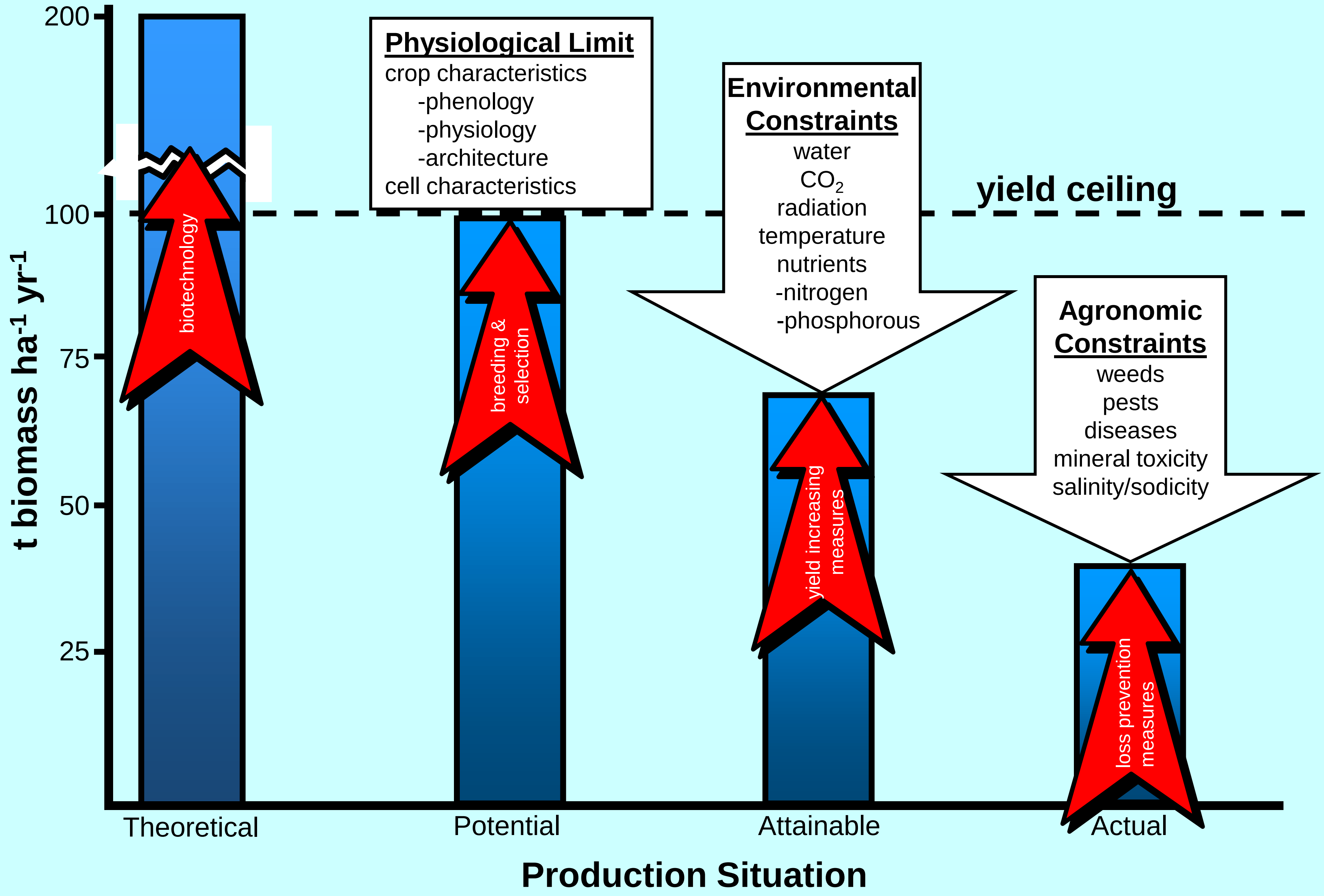
$Yp = \eta \cdot Pn$

η = the harvest index = 0.8

0.8 (273.70)=**218.9 t ha^{-1} yr^{-1}**

Average, maximum and theoretical sugarcane yields and total dry matter production

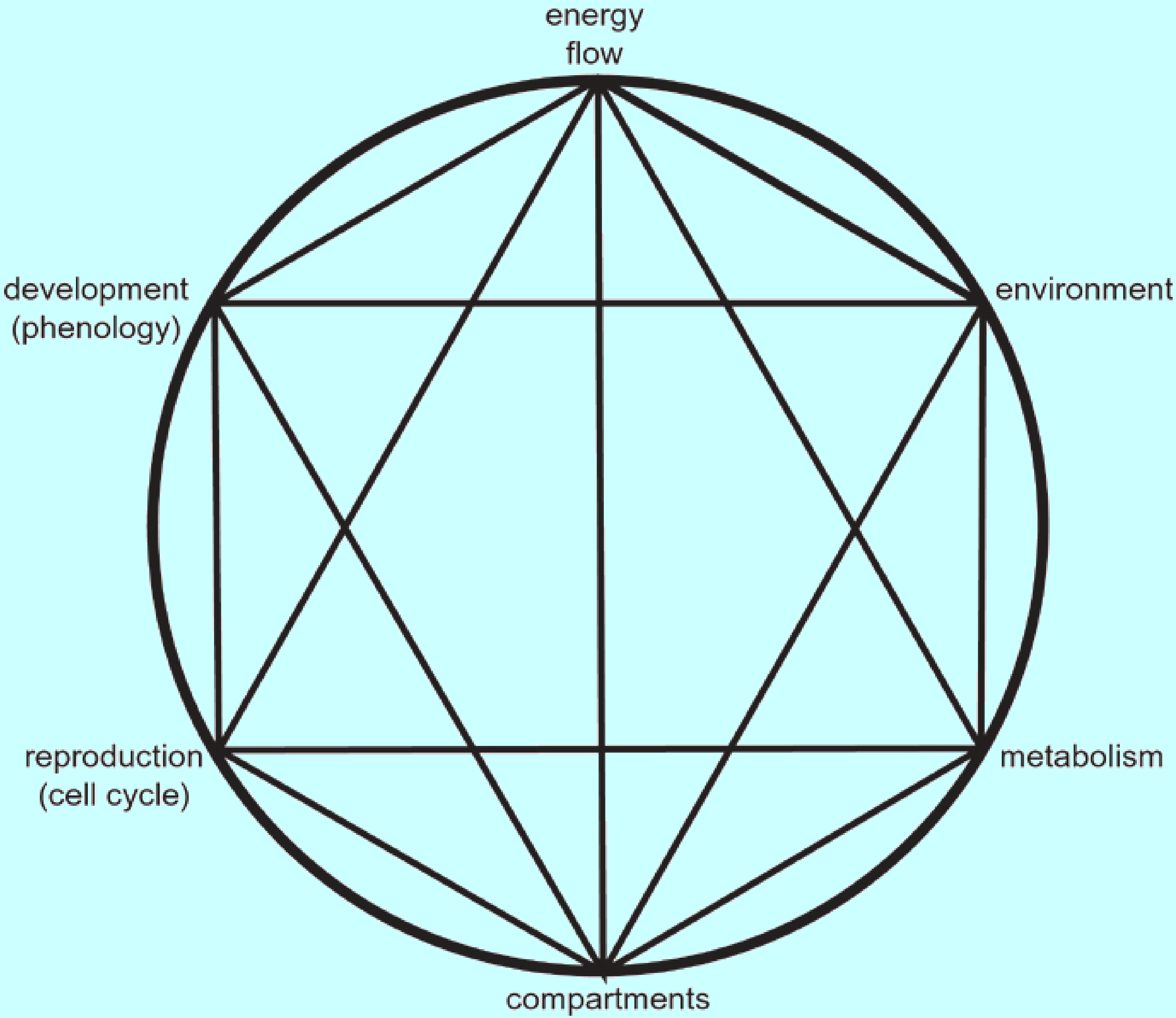
Type (Australia, Colombia, South Africa)	Cane yield ($t\ ha^{-1}\ yr^{-1}$)	Biomass*	
		($t\ ha^{-1}\ yr^{-1}$)	($g\ m^{-2}\ d^{-1}$)
Average	84	39	10.7
Commercial maximum	148	69	18.8
Experimental maximum	212	98	27.0
Theoretical maximum	472	219	72.4



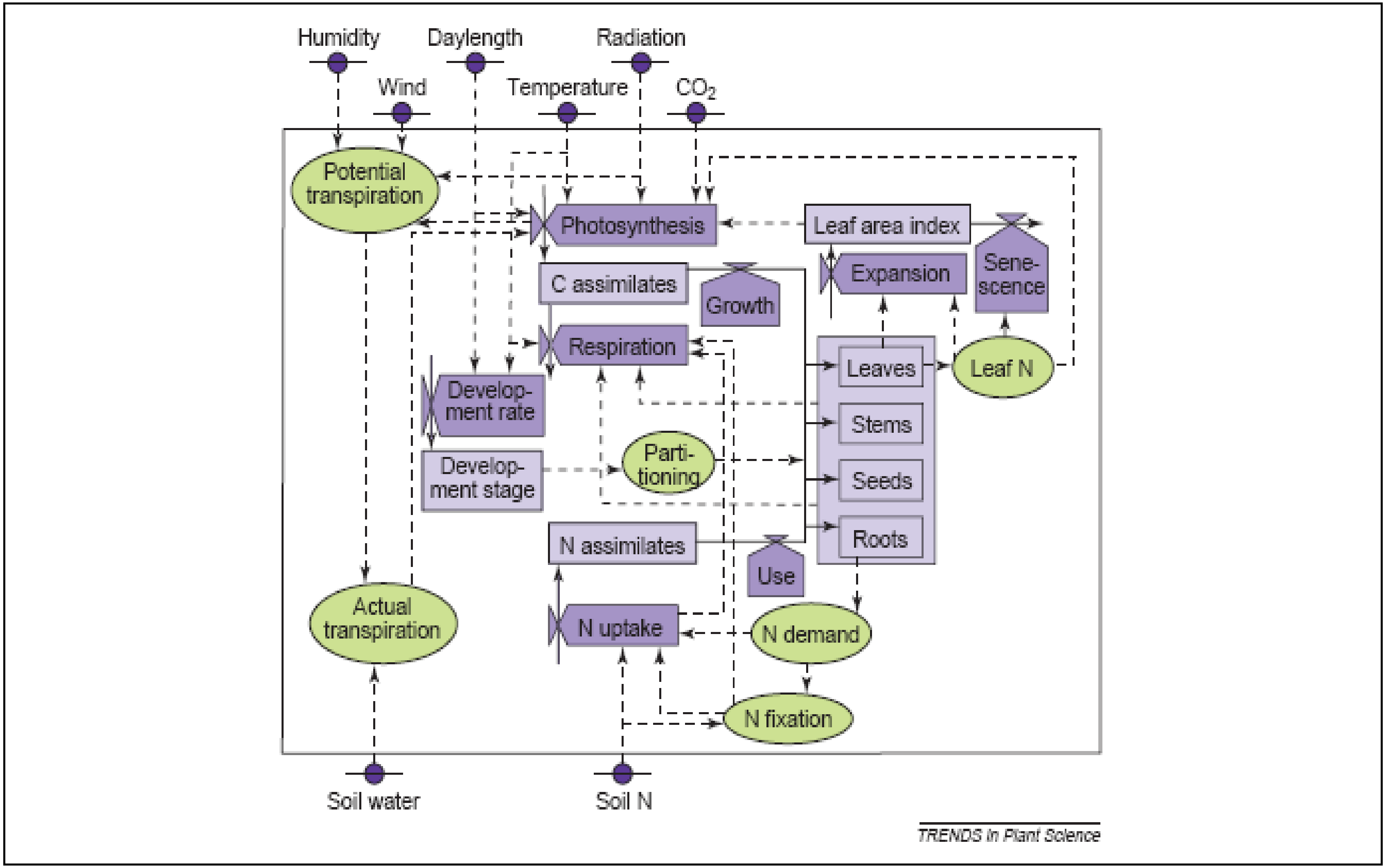
Physiological Limit
crop characteristics
-phenology
-physiology
-architecture
cell characteristics

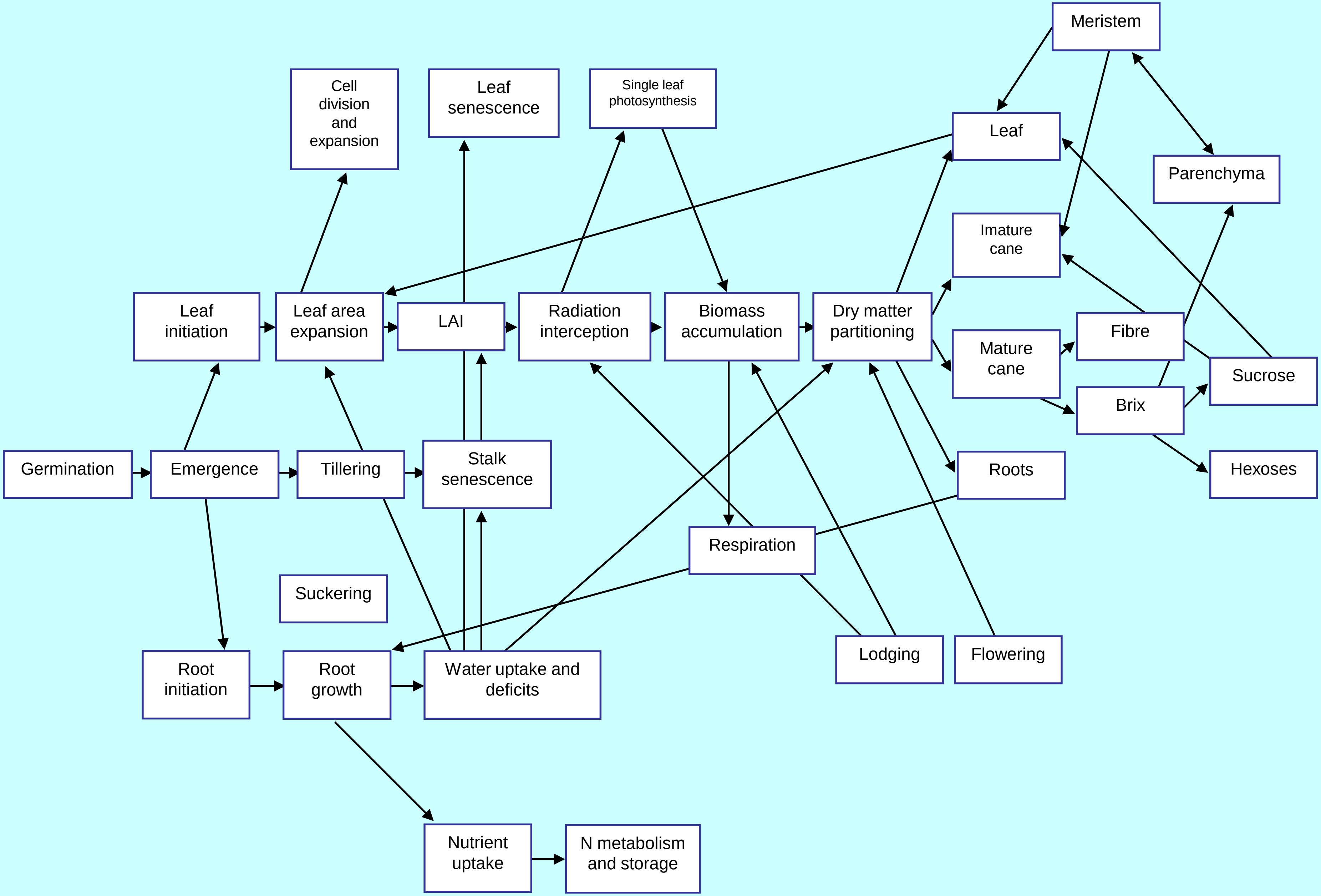
Environmental Constraints
water
CO_2
radiation
temperature
nutrients
-nitrogen
-phosphorous

Agronomic Constraints
weeds
pests
diseases
mineral toxicity
salinity/sodicity


energy flow
development (phenology)
environment
reproduction (cell cycle)
metabolism
compartments

Conceptual crop physiology model with environmental inputs and state and rate variables





Meristem

Cell division and expansion

Leaf senescence

Single leaf photosynthesis

Leaf

Parenchyma

Imature cane

Leaf initiation

Leaf area expansion

LAI

Radiation interception

Biomass accumulation

Dry matter partitioning

Fibre

Mature cane

Sucrose

Brix

Germination

Emergence

Tillering

Stalk senescence

Roots

Hexoses

Respiration

Suckering

Root initiation

Root growth

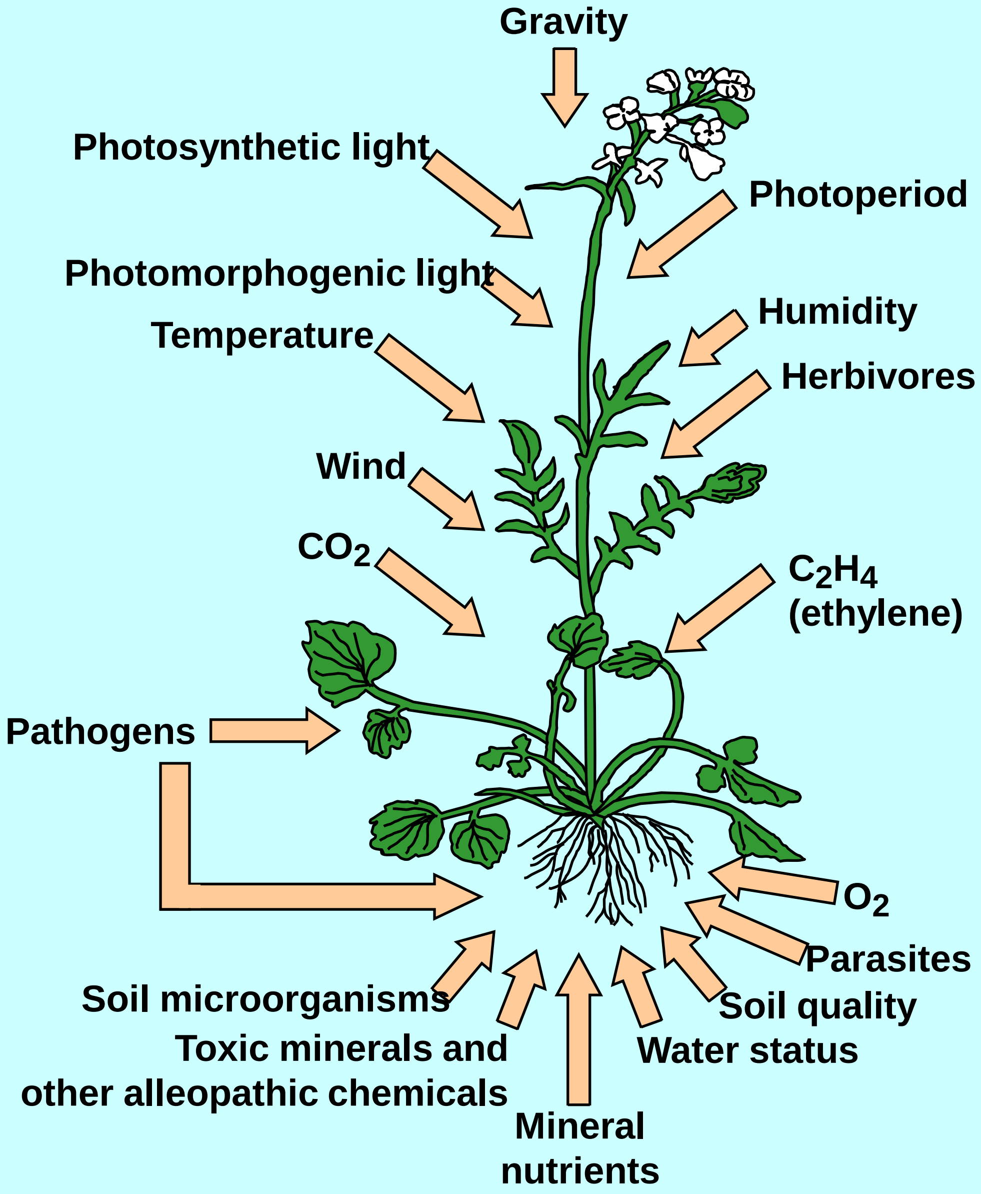
Water uptake and deficits

Lodging

Flowering

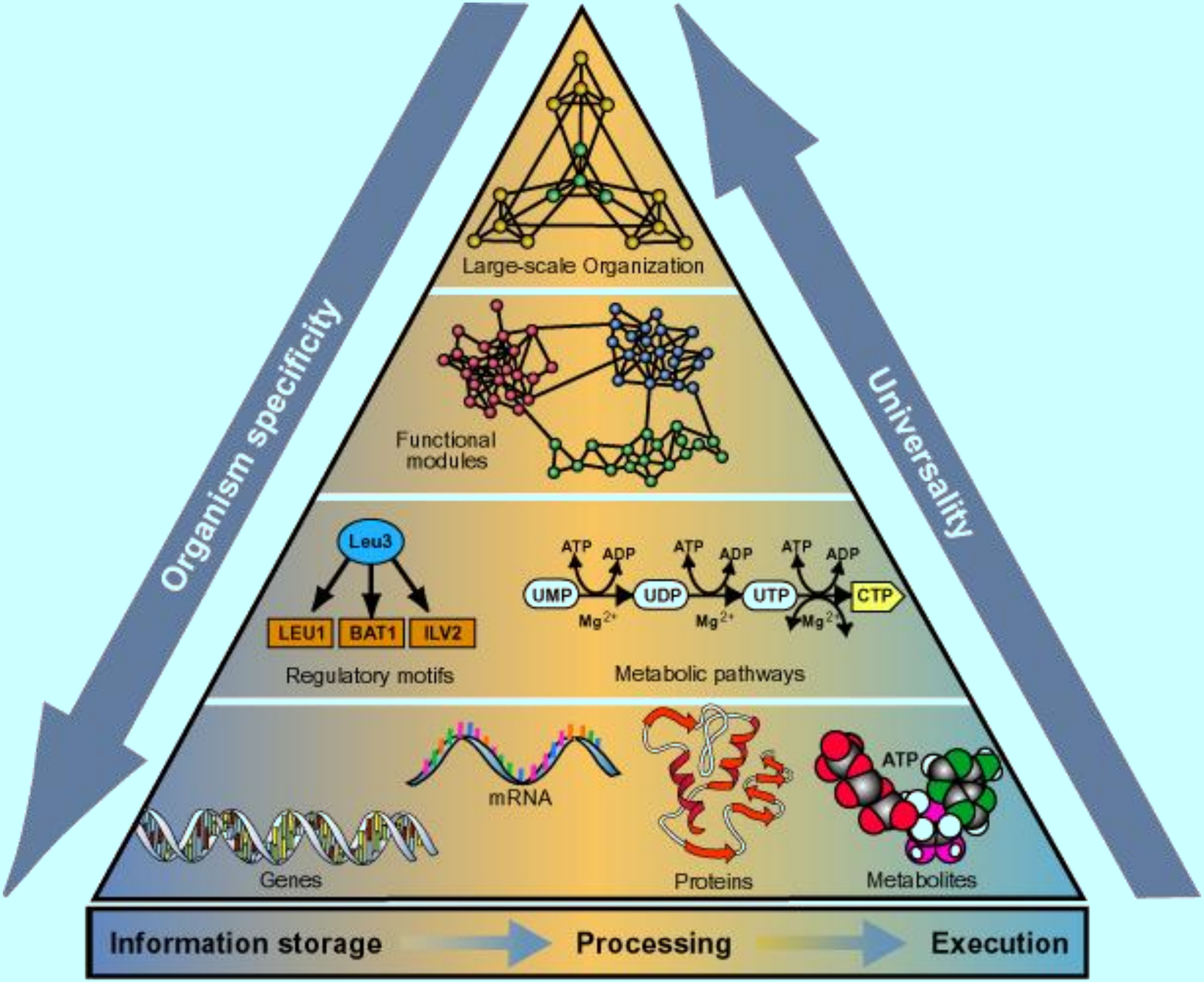
Nutrient uptake

N metabolism and storage


Gravity
Photosynthetic light
Photoperiod
Photomorphogenic light
Humidity
Temperature
Herbivores
Wind
CO_2
C_2H_4 (ethylene)
Pathogens
O_2
Parasites
Soil microorganisms
Soil quality
Toxic minerals and other alleopathic chemicals
Water status
Mineral nutrients

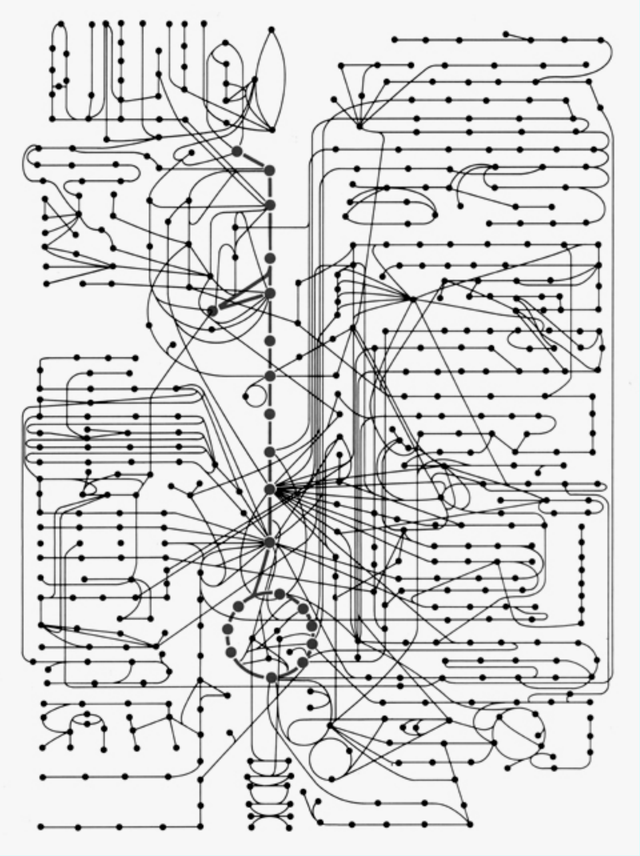
Systems Biology

- Defined as the study of the interactions of key elements such as DNA, RNA, proteins, and cells with respect to one another and the integration of information through modeling of extensive data sets that are scale free


Organism specificity
Universality
Large-scale Organization
Functional modules
Leu3
LEU1
BAT1
ILV2
Regulatory motifs
ATP
ADP
UMP
UDP
UTP
CTP
Mg^{2+}
Metabolic pathways
mRNA
ATP
Genes
Proteins
Metabolites
Information storage
Processing
Execution

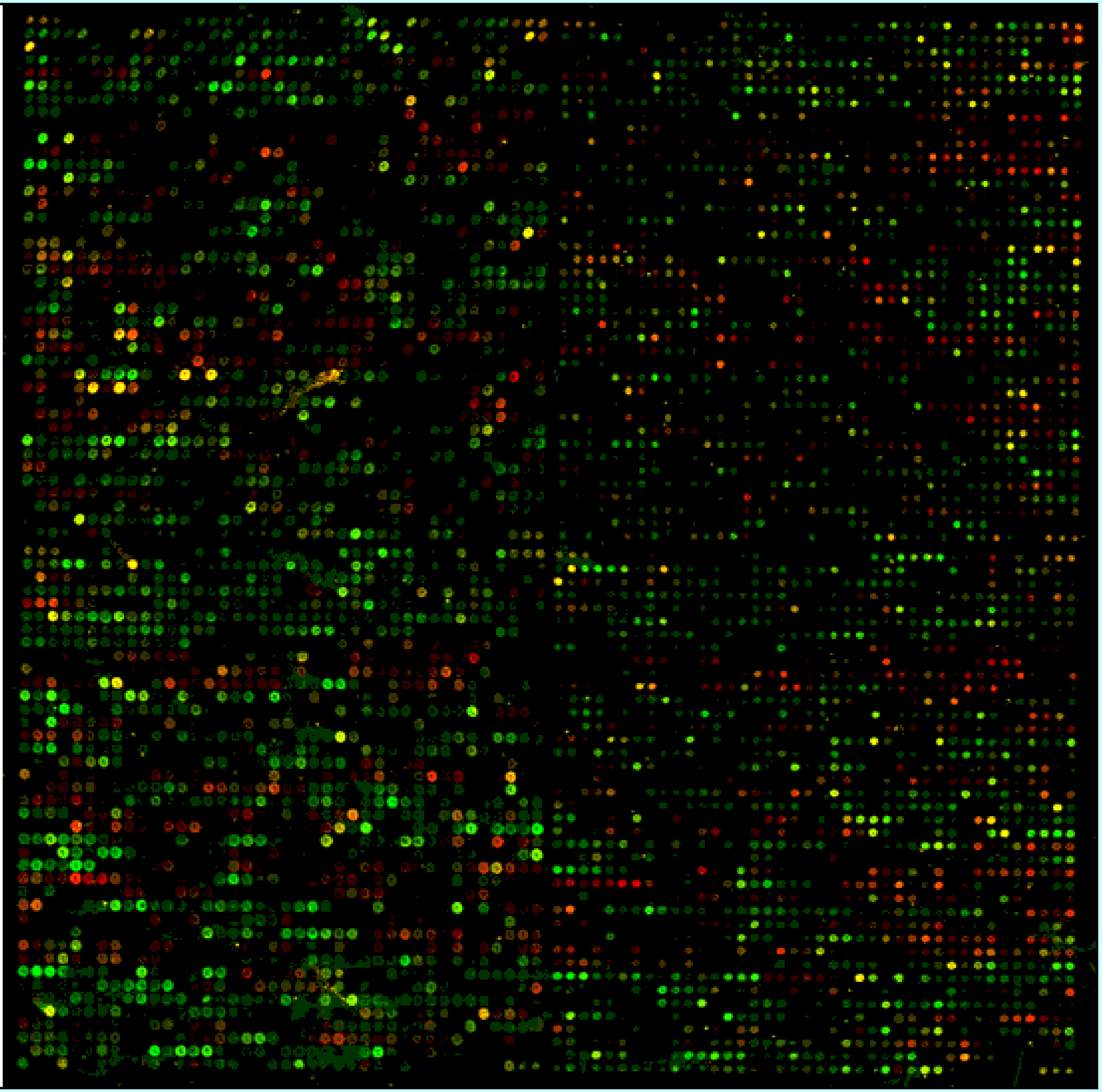
Biology in the ERA of ..... ***‘OMICS***

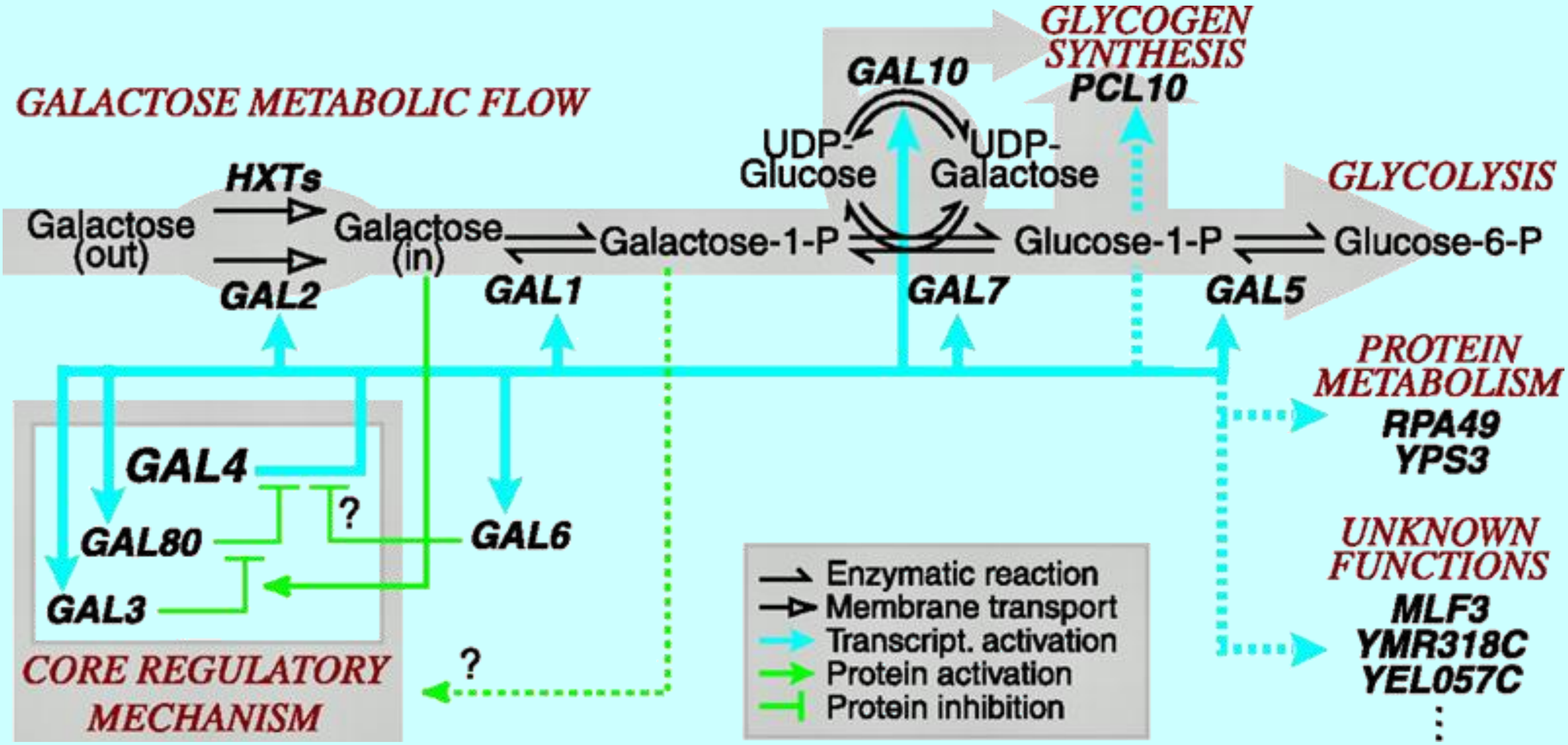
- ✓ **Genomics (DNA)**
- ✓ **Post genomics**
  - transcriptomics = gene expression analyses (RNA)
  - proteomics = protein analyses (protein)
  - metabolomics = (metabolites)



The complete S. cerevisiae genome on a microarray chip

hybridised to RNA from cultures in anaerobic and aerobic stationary phase





GALACTOSE METABOLIC FLOW

Galactose (out)

HXTs

GAL2

Galactose (in)

GAL1

Galactose-1-P

GAL10

UDP-Glucose

UDP-Galactose

GAL7

Glucose-1-P

GAL5

Glucose-6-P

GLYCOGEN SYNTHESIS

PCL10

GLYCOLYSIS

PROTEIN METABOLISM

RPA49
YPS3

UNKNOWN FUNCTIONS

MLF3
YMR318C
YEL057C
⋮

GAL4

GAL80

GAL3

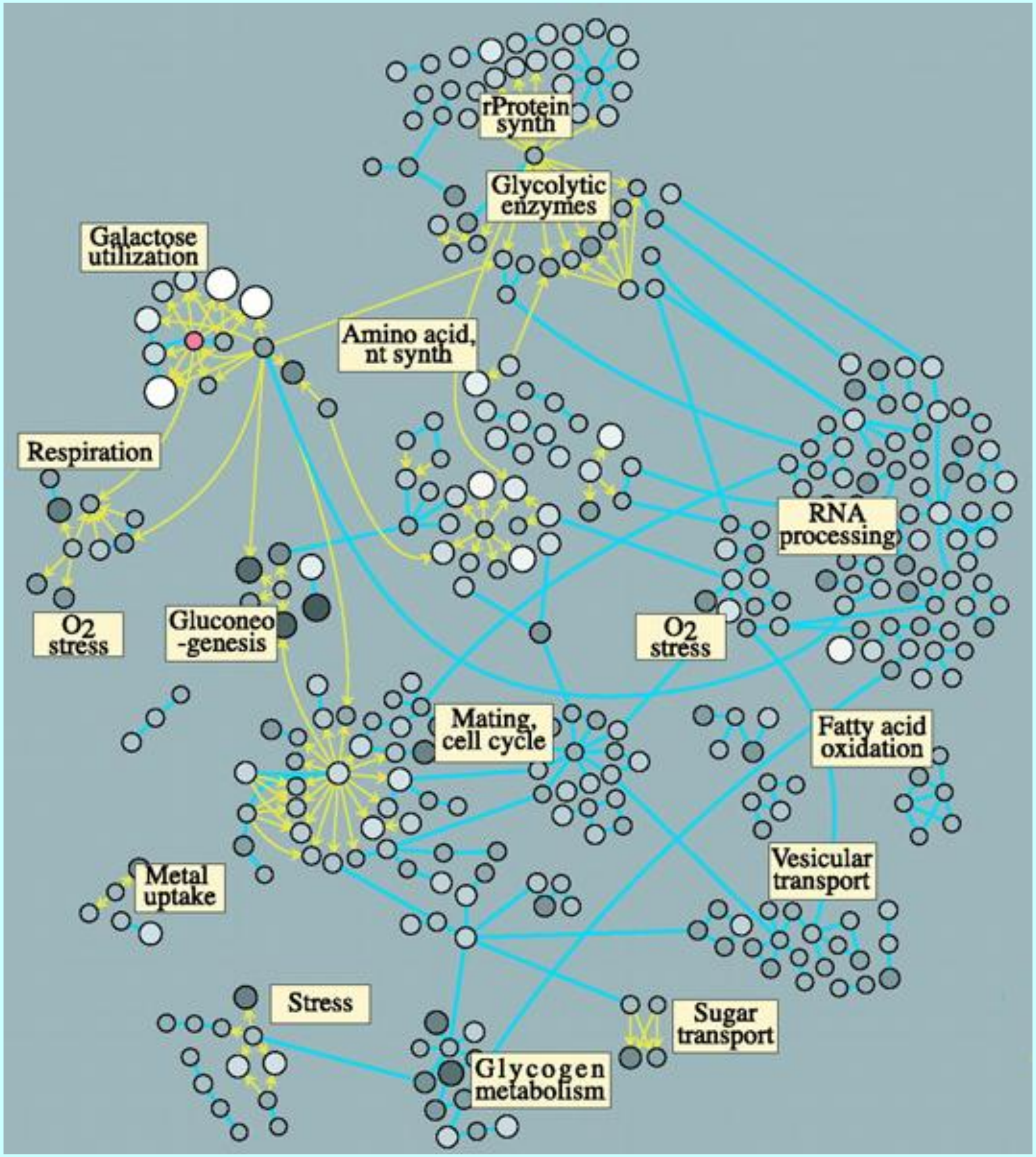
GAL6

?

?

CORE REGULATORY MECHANISM

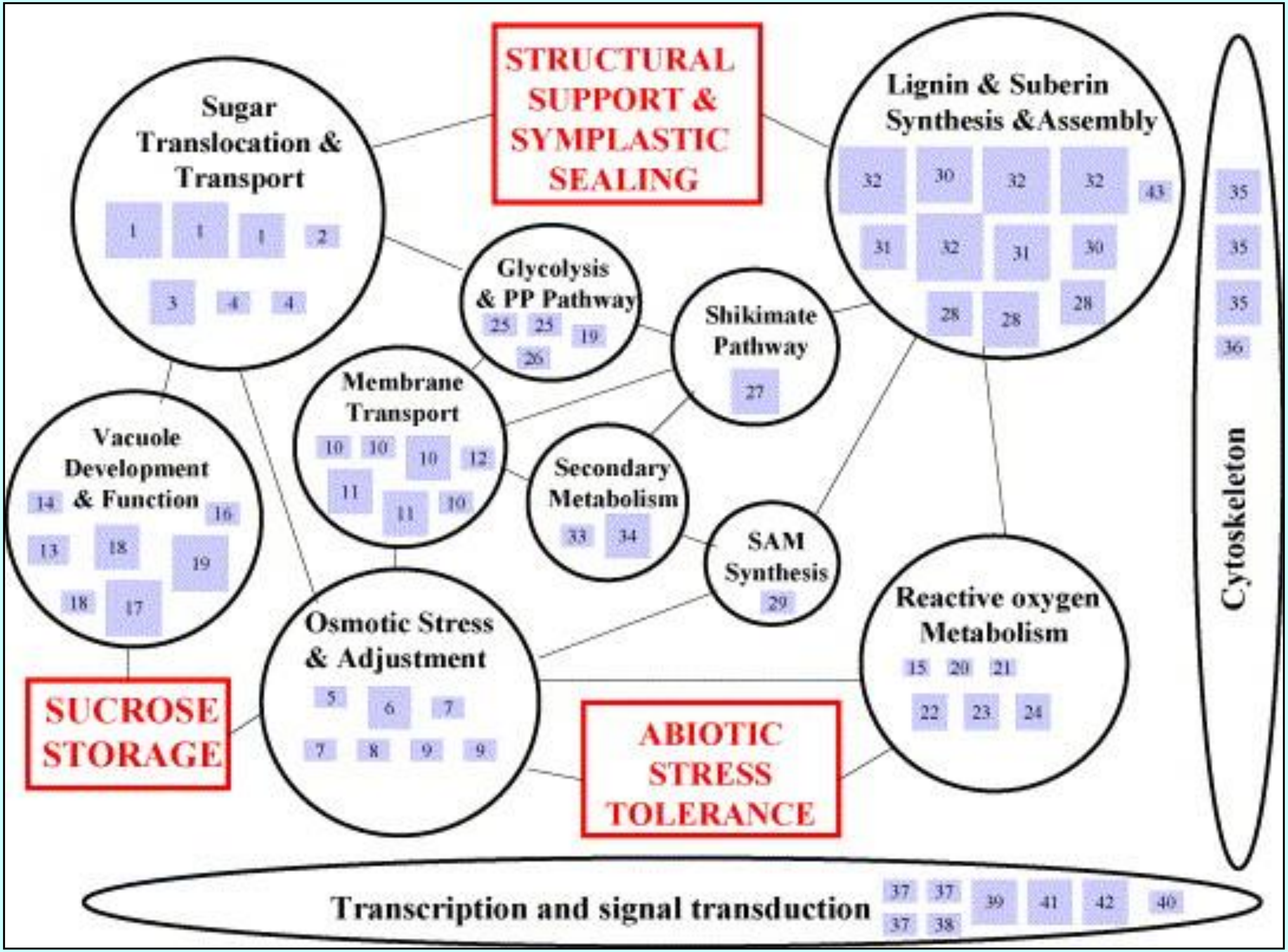
Enzymatic reaction
Membrane transport
Transcript. activation
Protein activation
Protein inhibition


rProtein synth
Glycolytic enzymes
Galactose utilization
Amino acid, nt synth
Respiration
O2 stress
Gluconeo -genesis
RNA processing
O2 stress
Mating, cell cycle
Fatty acid oxidation
Vesicular transport
Metal uptake
Stress
Sugar transport
Glycogen metabolism

Functional grouping and ranking (by abundance in the collections) of maturing cane stem (MCS) and young cane stem (YCS) ESTs

Casu et al. Plant Mol Biol 54:503-517 (2004)

Functional grouping	Number in MCS	% in MC	Rank for MC	Number in YCS	% in YC	Rank for YCS
Protein synthesis and processing	*836*	*22.0*	*1*	*175*	*26.2*	*1*
Primary metabolism	*753*	*19.8*	*2*	*109*	*16.3*	*2*
Gene expression and RNA metabolism	369	9.7	3	54	8.1	4
Signal transduction	336	8.8	4	43	6.4	6
Membrane transport	290	7.6	5	49	7.3	5
Defence/stress-related proteins	238	6.3	6	38	4.6	8
Carbohydrate metabolism	180	4.7	7	27	4.0	9
Fibre biosynthesis and degradation	167	4.4	9	1	0.1	16
Chromatin and DNA metabolism	163	4.3	10	62	9.3	3
Cytoskeleton	95	2.5	11	23	3.4	10
Vesicular trafficking, protein sorting and secretion	91	2.4	12	13	1.9	13
ATP synthesis/electron transport	37	1.0	13	14	2.1	12
Cell wall structure or metabolism	34	0.9	14	15	2.2	11
Cell division cycle	25	0.7	15	3	0.4	15
Secondary and hormone metabolism	17	0.4	16	8	1.2	14
Miscellaneous	174	4.5	8	41	6.1	7



STRUCTURAL SUPPORT & SYMPLASTIC SEALING

SUCROSE STORAGE

ABIOTIC STRESS TOLERANCE

Sugar Translocation & Transport
1 1 1 2
3 4 4

Glycolysis & PP Pathway
25 25 19
26

Membrane Transport
10 10 10 12
11 11 10

Vacuole Development & Function
14 16
13 18 19
18 17

Osmotic Stress & Adjustment
5 6 7
7 8 9 9

Shikimate Pathway
27

Secondary Metabolism
33 34

SAM Synthesis
29

Lignin & Suberin Synthesis & Assembly
32 30 32 32 43
31 32 31 30
28 28 28

Reactive oxygen Metabolism
15 20 21
22 23 24

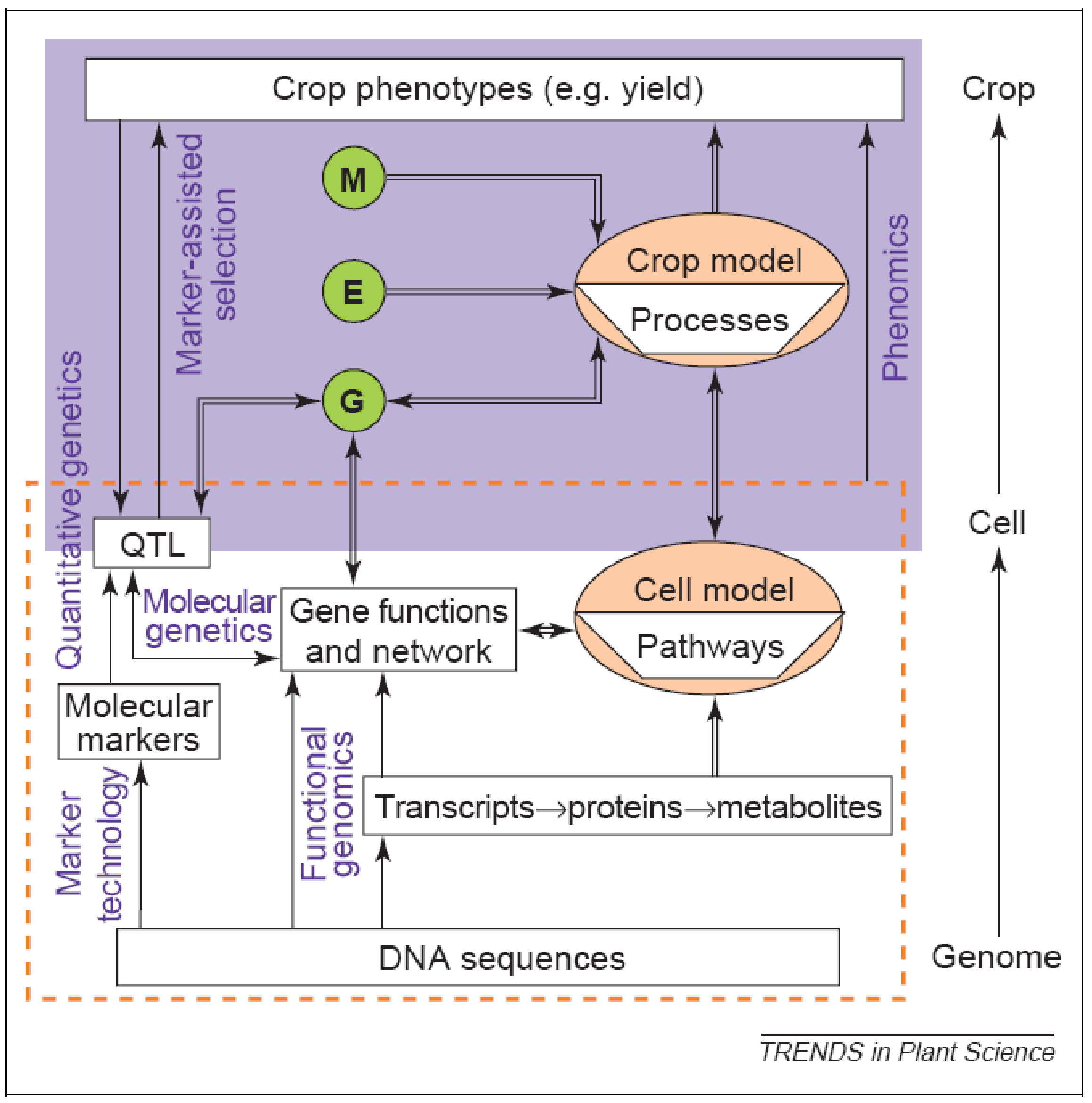
Cytoskeleton
35
35
35
36

Transcription and signal transduction
37 37 39 41 42 40
37 38

Model based approach for predicting crop performance

- Create a crop model that predicts complex traits based on relations between elementary processes and environmental variables
- Evaluate capability of model to predict the complex trait across a wide range of GXE combinations
- Identify QTL for model-input traits using a genetic QTL approach
- Develop a QTL-based model by replacing original model input traits with QTL-based inputs
- Validate the QTL-based model across environments

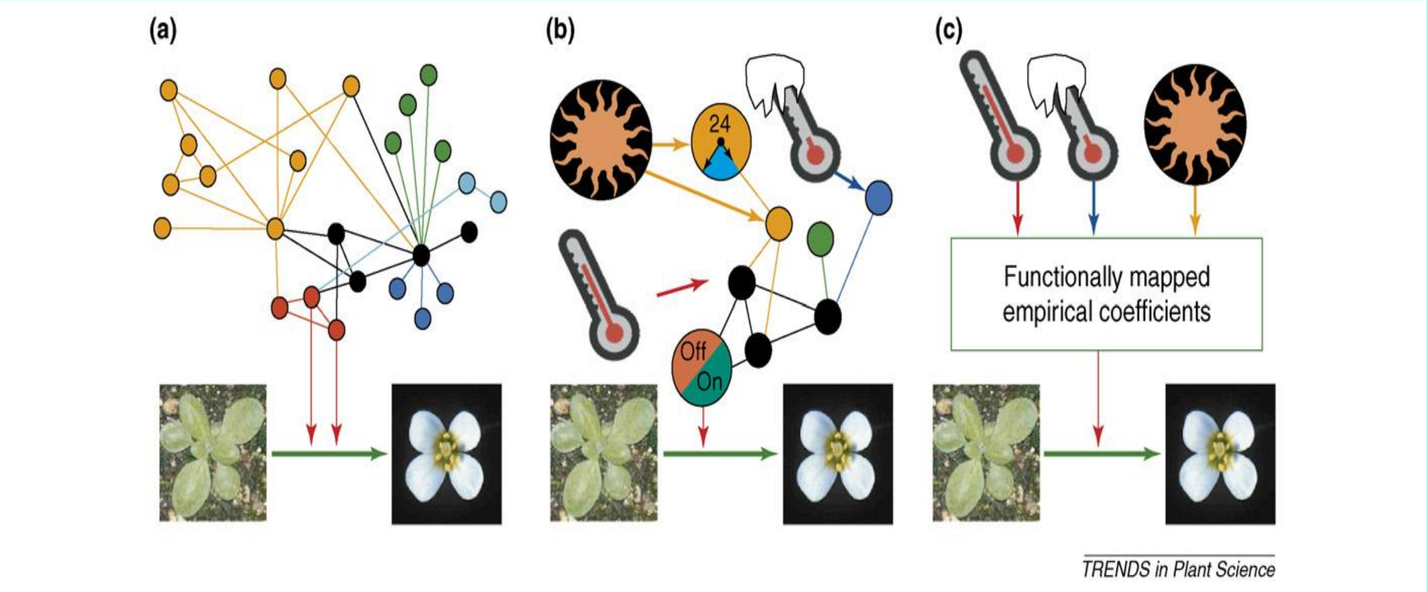
Integration of genomics into crop physiology for crop improvement



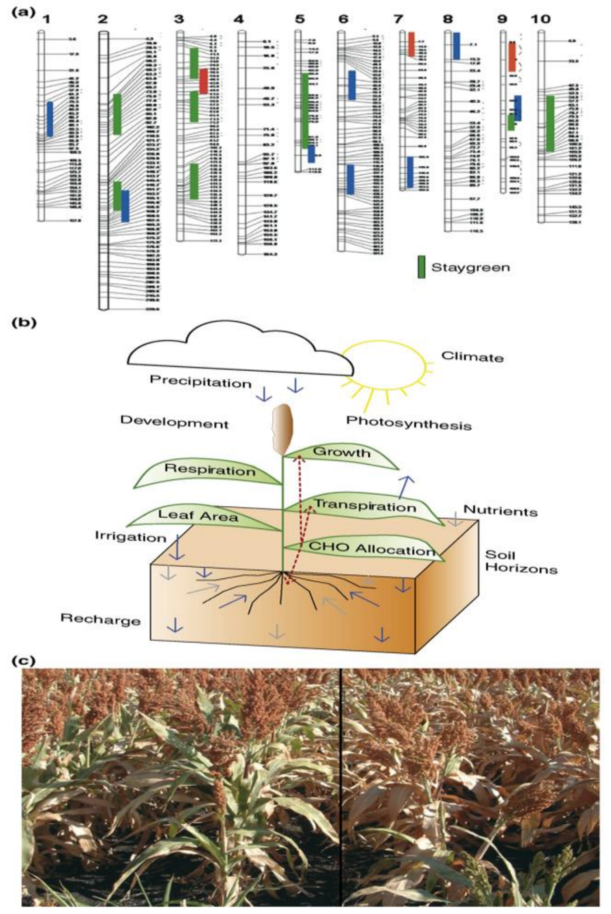
TRENDS in Plant Science

Modeling transition to flowering in Arabidopsis

- (a) genetic network control
  (b) gene network with environmental drivers
  (c) empirical photothermal model for prediction



Multi-trait gene-to-phenotype modeling



- (a) map of QTLs regulating adaptive traits
  (b) crop process model
  (c) contrasting phenotypes

Hammer et al. 2006

Flowering, Cane and Sugar Yields in Response to 30 2-hr Light Breaks During Autumn Induction of Flowering

Treatment		Flowering %		Yield	
1st Year	2nd Year	1st Year	2nd Year	Cane (t ha^{-1})	Sugar (t ha^{-1})
0	0	36.2	16.7	304	34.3
0	+	26.0	0.8	343	36.8
+	0	0.0	10.3	365	41.8
+	+	0.3	0.8	349	40.0
			L.S.D.	25.7	3.46

Ewa test 1951, cv. H37-1933

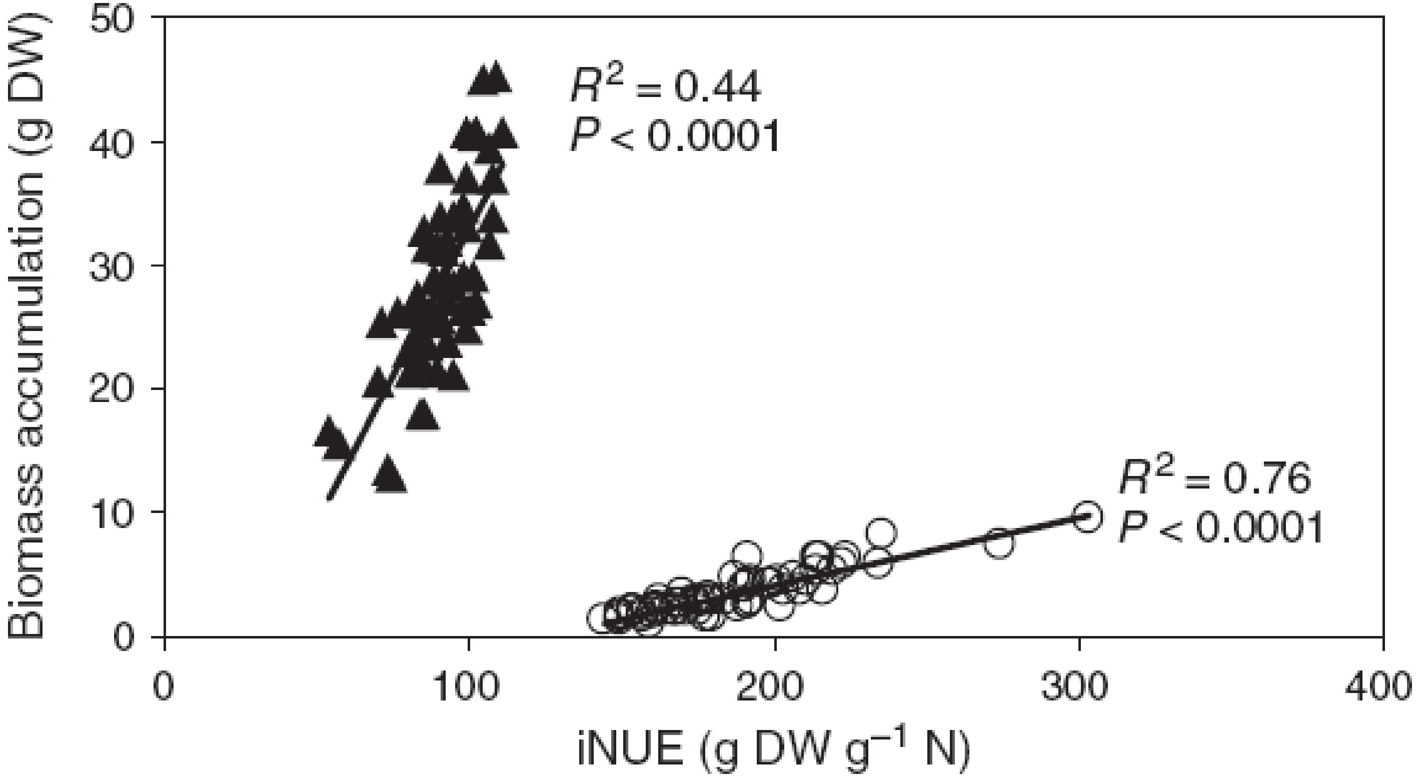
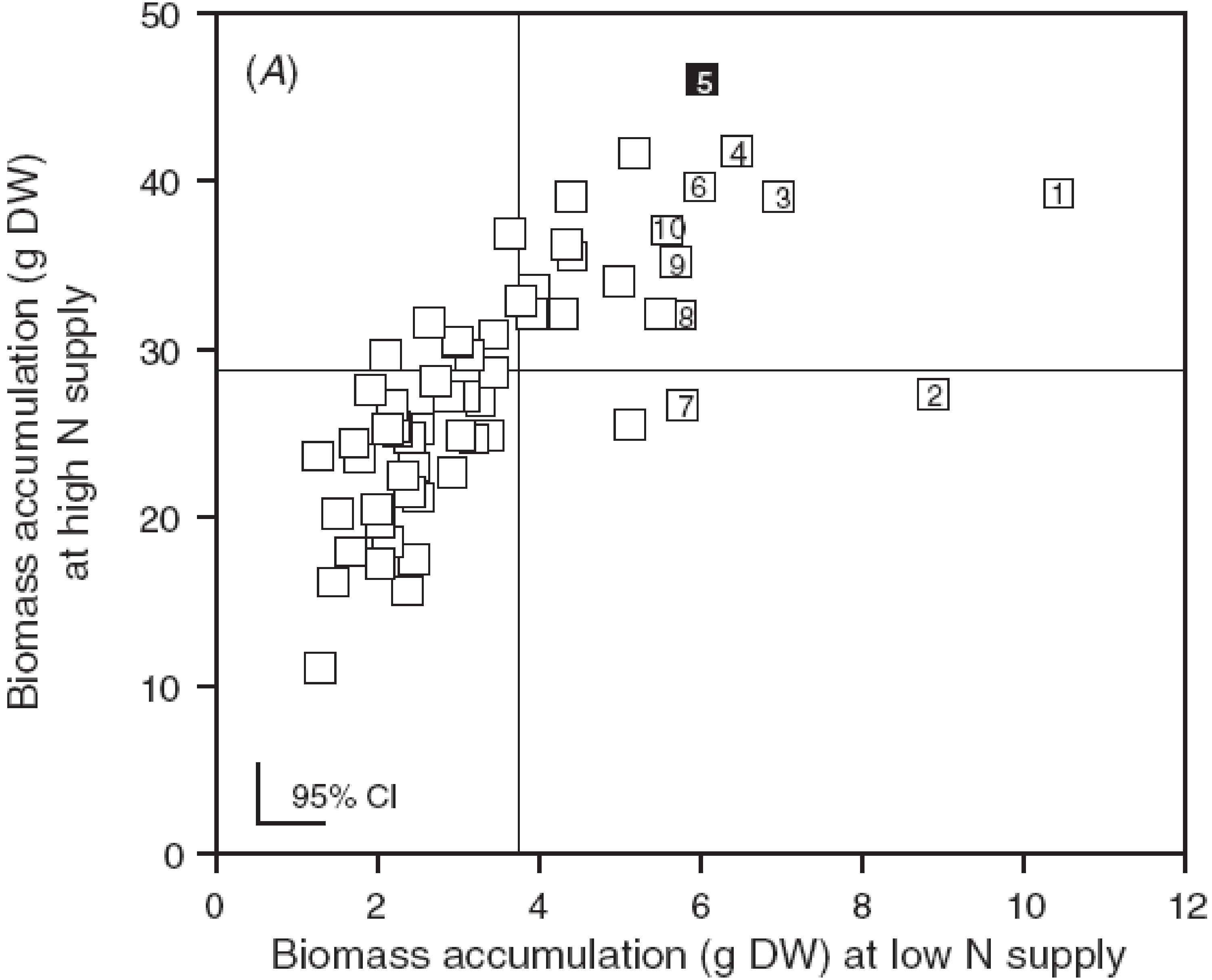
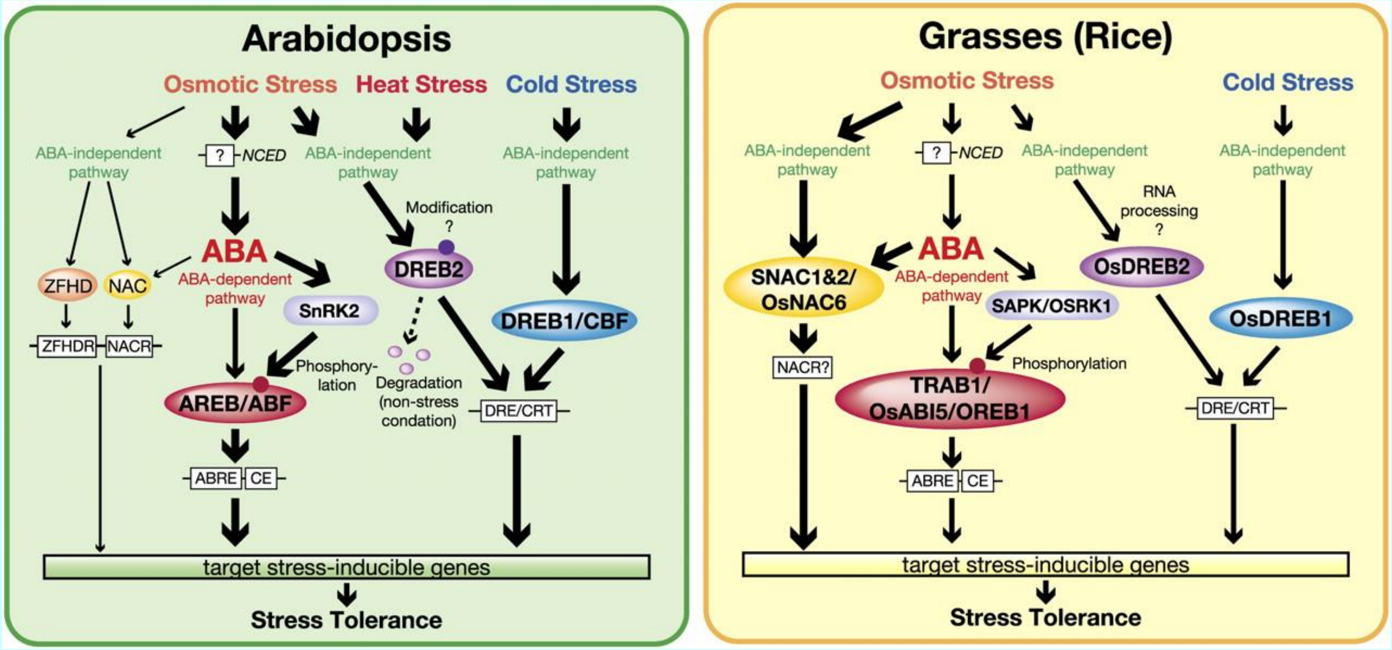


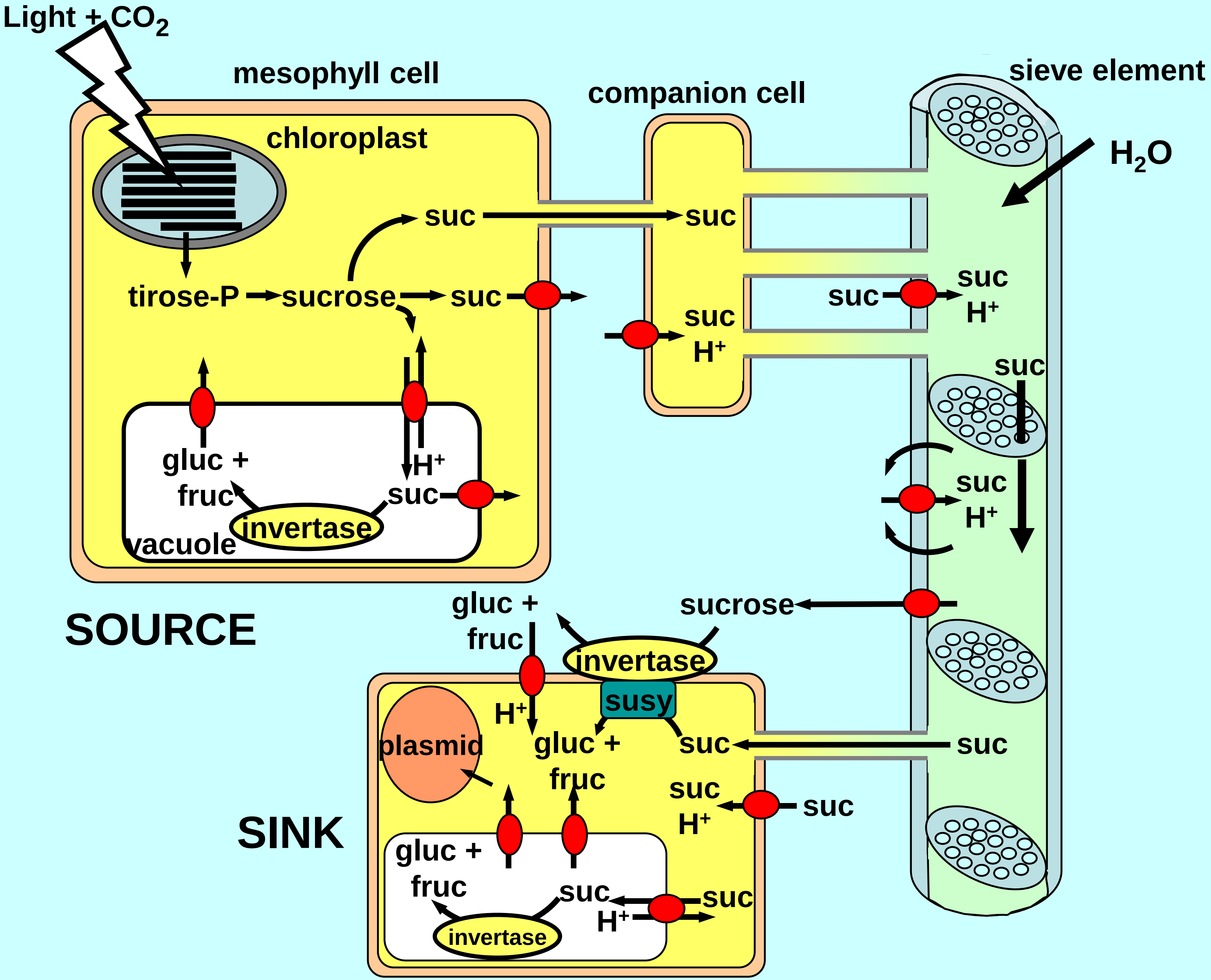
Fig. 3. Relationship between total plant biomass (g DW) and internal nitrogen use efficiency (iNUE, g DW g^{-1} N) for 61 genotypes of sugarcane at low (circles) and high (triangles) N supply. Regression equations for relationship between biomass and iNUE are $y = 0.47x + 14.26$ (high N supply) and $y = 0.05x + 6.72$ (low N supply).


(A)
Biomass accumulation (g DW) at high N supply
Biomass accumulation (g DW) at low N supply
95% CI
0
10
20
30
40
50
0
2
4
6
8
10
12
1
2
3
4
5
6
7
8
9
10

Major transcriptional regulatory networks of cis-acting elements and TFs involved in abiotic stress-responsive gene expression in Arabidopsis and grasses such as rice



Nakashima, K., et al. Plant Physiol. 2009;149:88-95


Light + CO2
mesophyll cell
chloroplast
companion cell
sieve element
H2O
tirose-P
sucrose
suc
suc
suc
suc
H+
suc
H+
gluc +
fruc
H+
suc
invertase
vacuole
suc
suc
H+
suc
SOURCE
gluc +
fruc
sucrose
invertase
susy
H+
plasmid
gluc +
fruc
suc
suc
suc
H+
suc
SINK
gluc +
fruc
suc
H+
suc
invertase

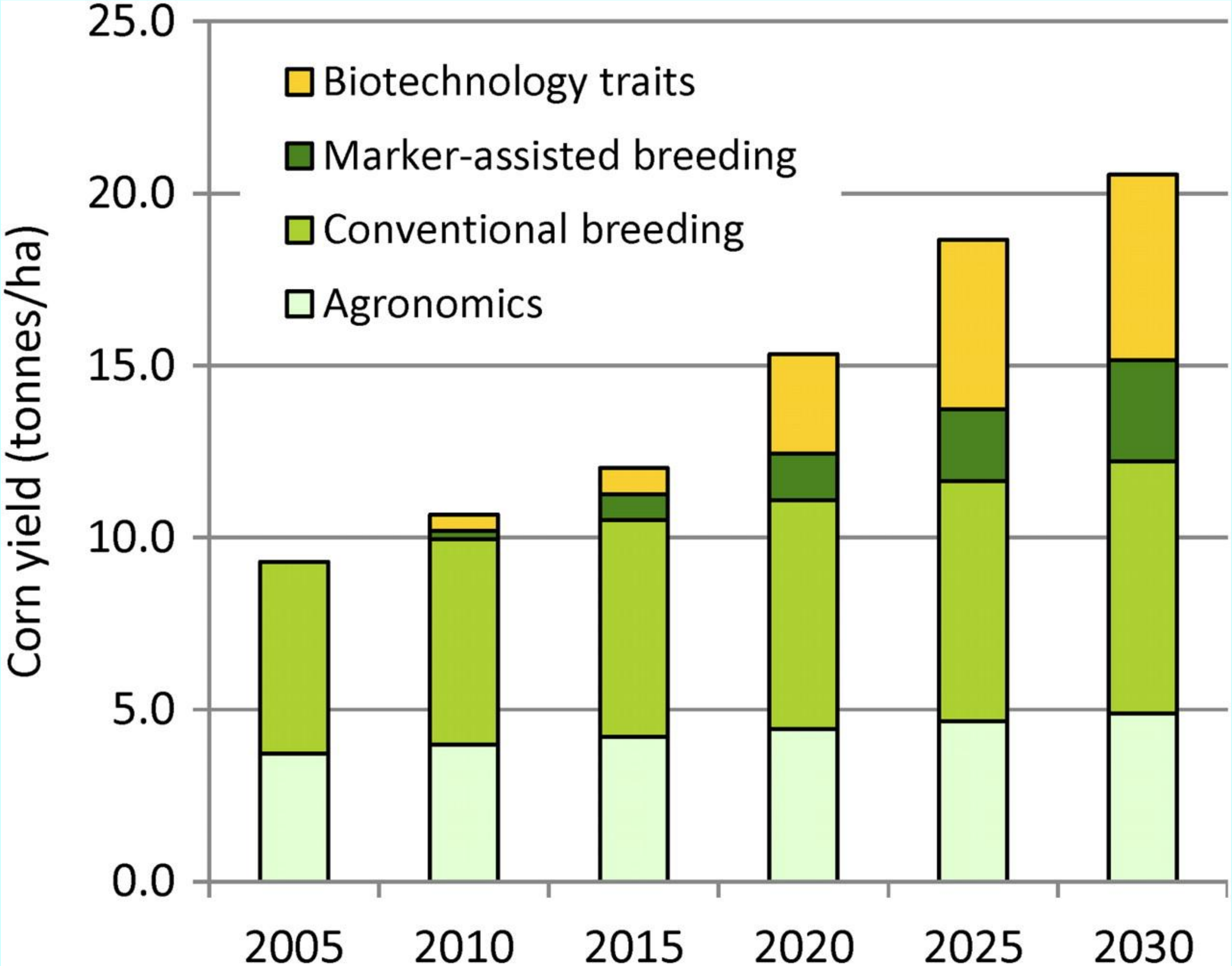
Conclusions

Sugarcane yields may be increased locally through increasing management inputs and using traditional genetic approaches.

The sugarcane yield ceiling will **<u>not</u>** likely be broken by:

- ❖ increasing management inputs (fertilizer, water, pesticides, growth regulators)
- ❖ traditional genetic approaches to optimize resistance to pests & diseases, improve sucrose storage, optimize development, etc.

Anticipated impact of improvements in agronomics, breeding, and biotechnology on average corn yields in the United States



Edgerton,M. D. Plant Physiol. 2009;149:7-13

Conclusions

(continued)

The sugarcane yield ceiling **will likely** be broken by using high-throughput genomic approaches to produce large data sets that can be analyzed with appropriate models in a **Systems Approach** for producing knowledge to:

- produce varieties with improved physiological attributes (e.g. photosynthetic efficiency, carbon partitioning between sucrose and fiber, water use efficiency, N use efficiency, multi-gene pest and pathogen resistance). Improvements that could not be made previously because of the biological **system** complexity
- provide technologies to growers for optimum management of multi-gene developmental pathways, e.g. germination, tillering, lodging, flowering, ripening, lodging

THE FUTURE LOOKS EXCITING AND THE OUTLOOK BRIGHT