


BIO 235
Plants & People
Evolution &
Domestication
of Crops







Lecture 13 - Crop Breeding, the Green Revolution, Modern Food Production & Super-Domestication

- Limits to food production – land, water & energy
- Crop breeding, yield gains & the green revolution
- Modern industrial agriculture
- Super-domestication & genetic modification
- Ownership of genetic resources
- Terminator technology
- The C4 Rice Project - *Using the sun to end hunger*
- Has the relationship between plants and people fundamentally changed?

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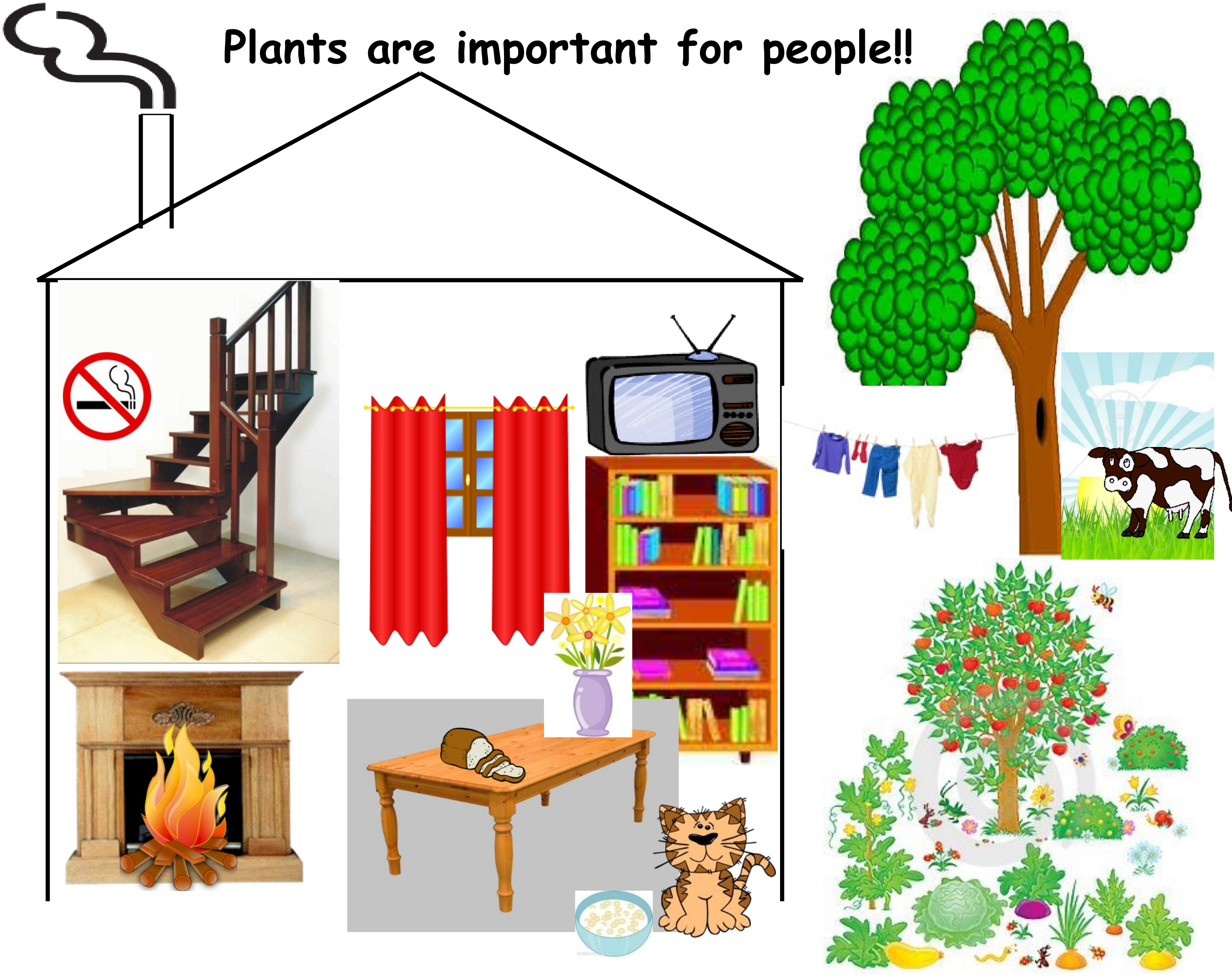
Plants are important for people!!



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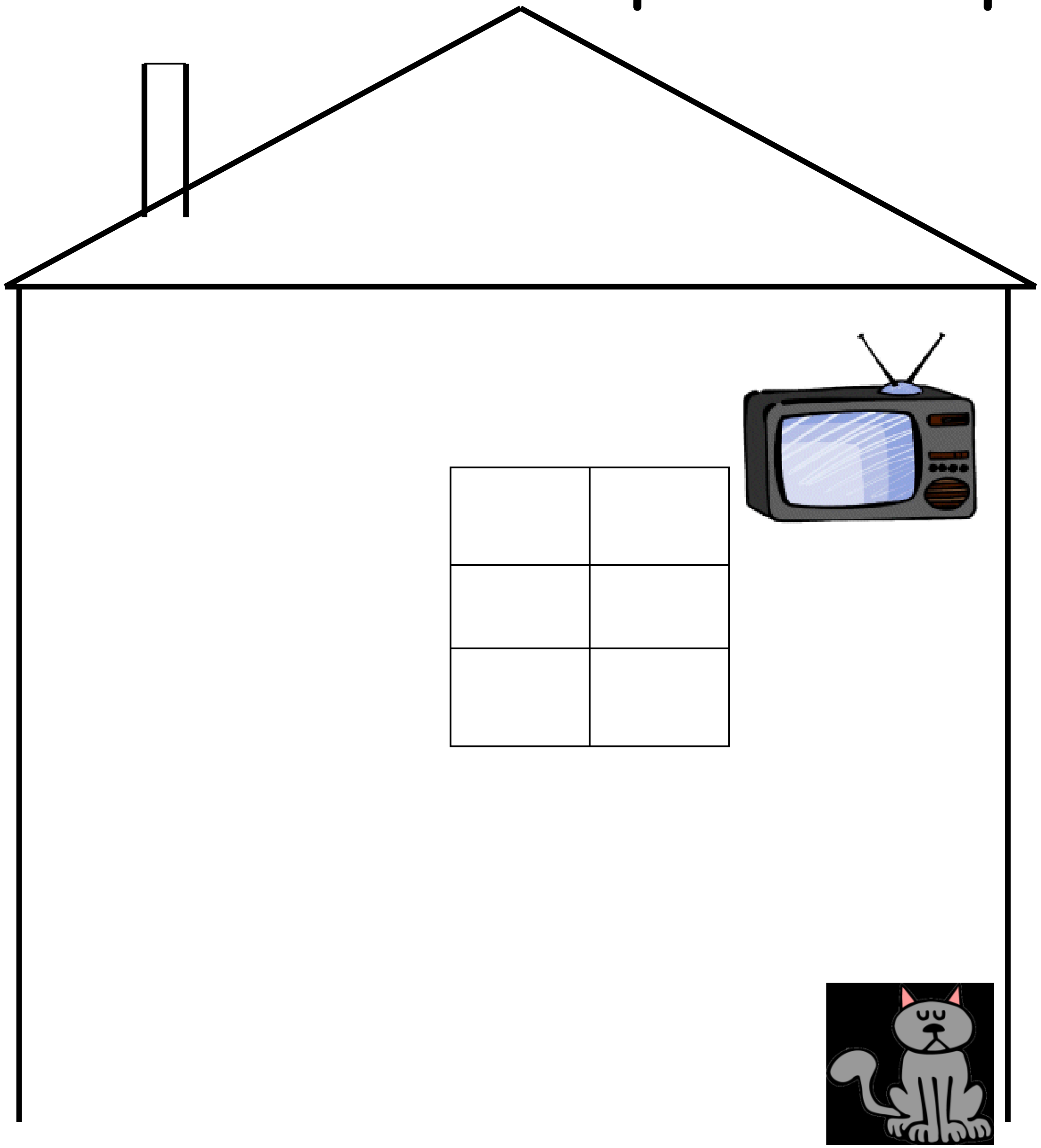
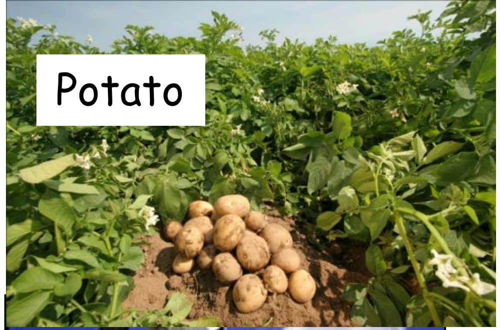
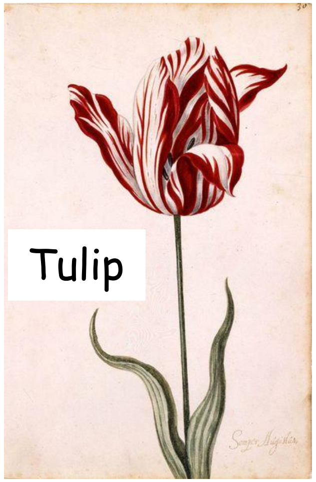
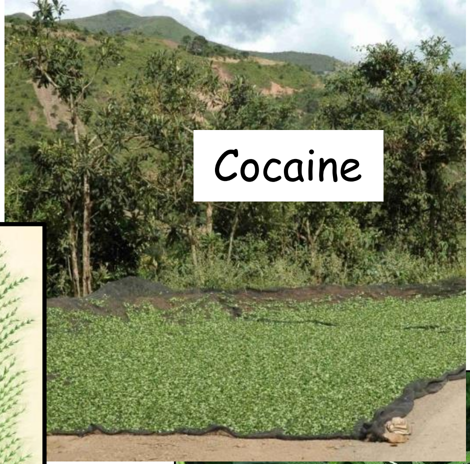
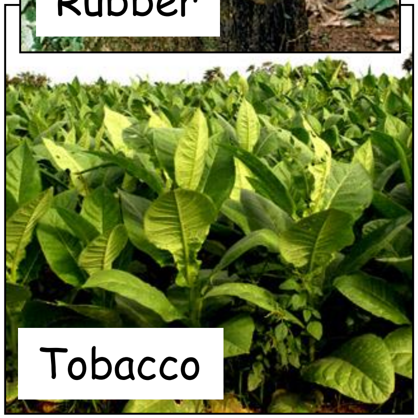


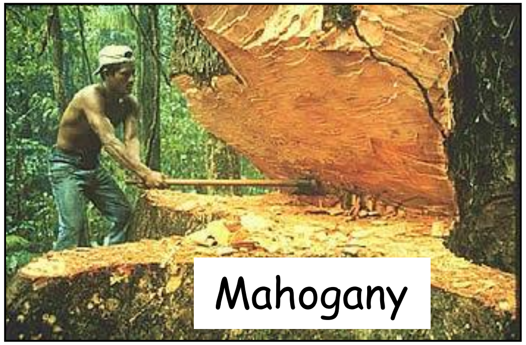
Plants that Changed the World

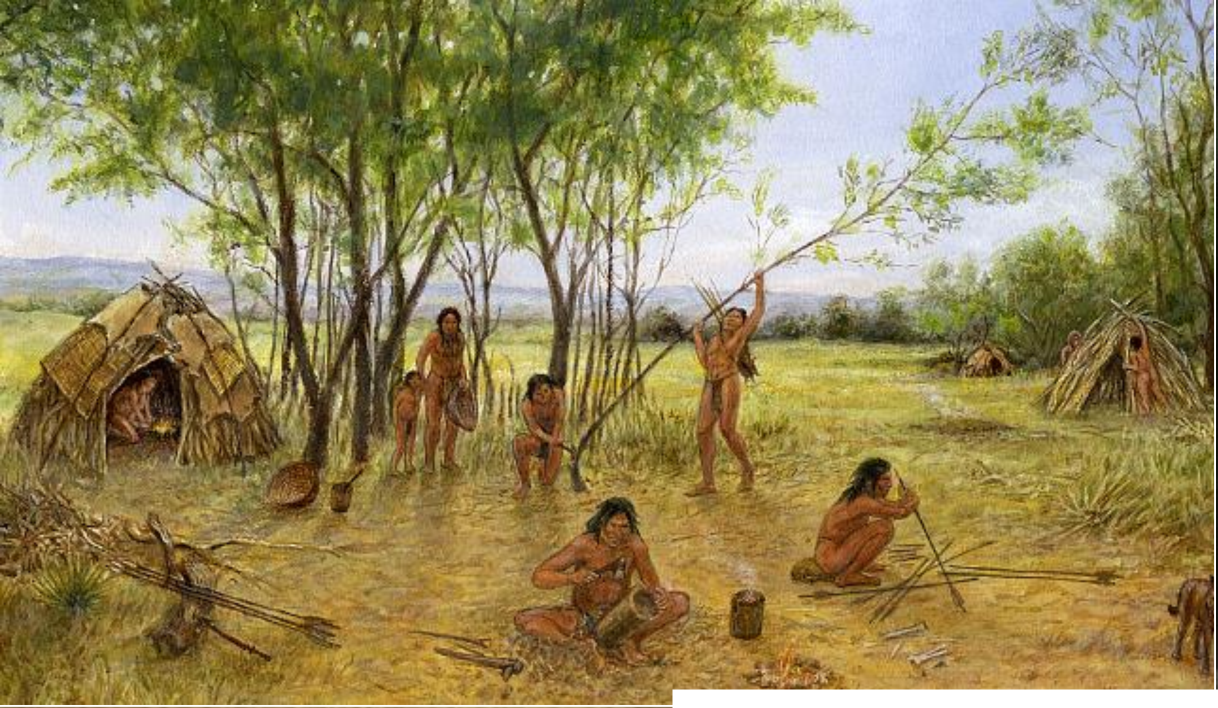






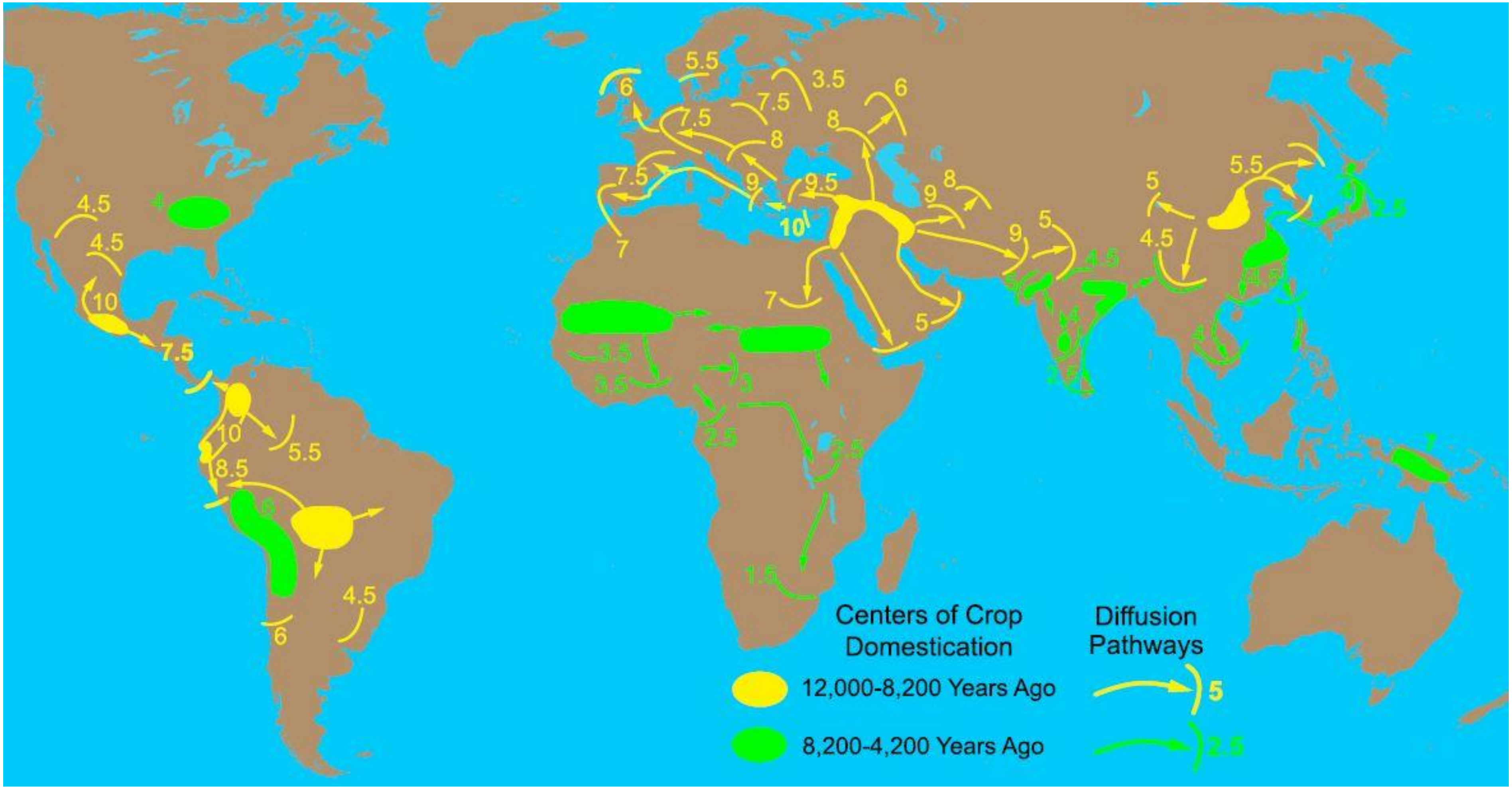






Foraging to Farming

Origins of agriculture and spread of agricultural crops

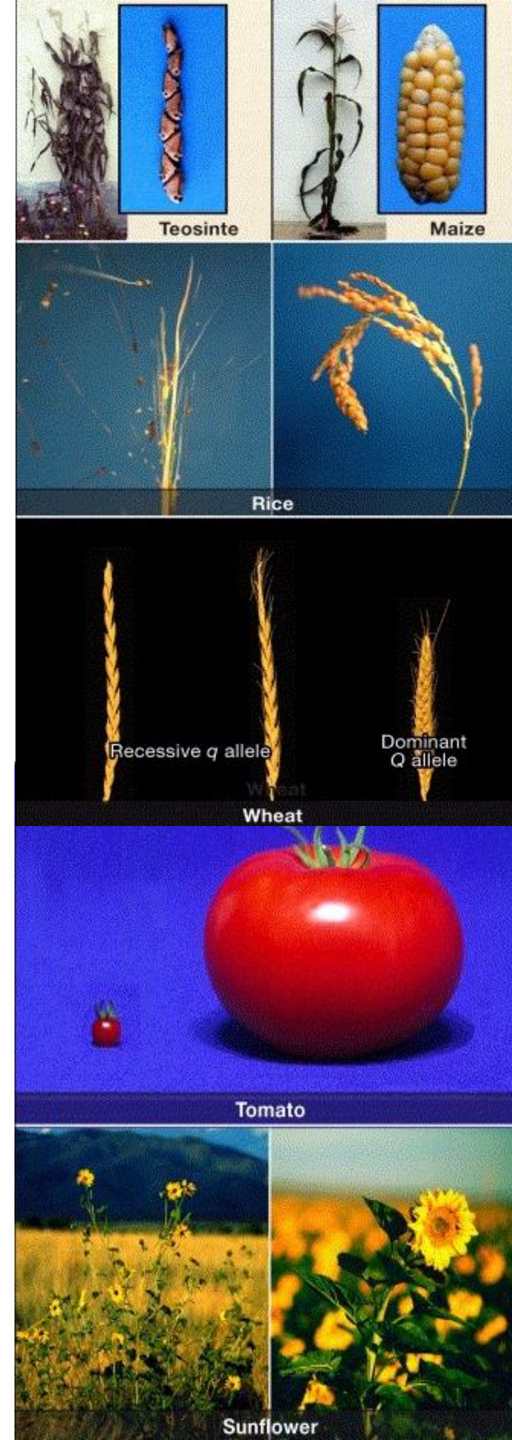


Ruddiman et al. (2015)

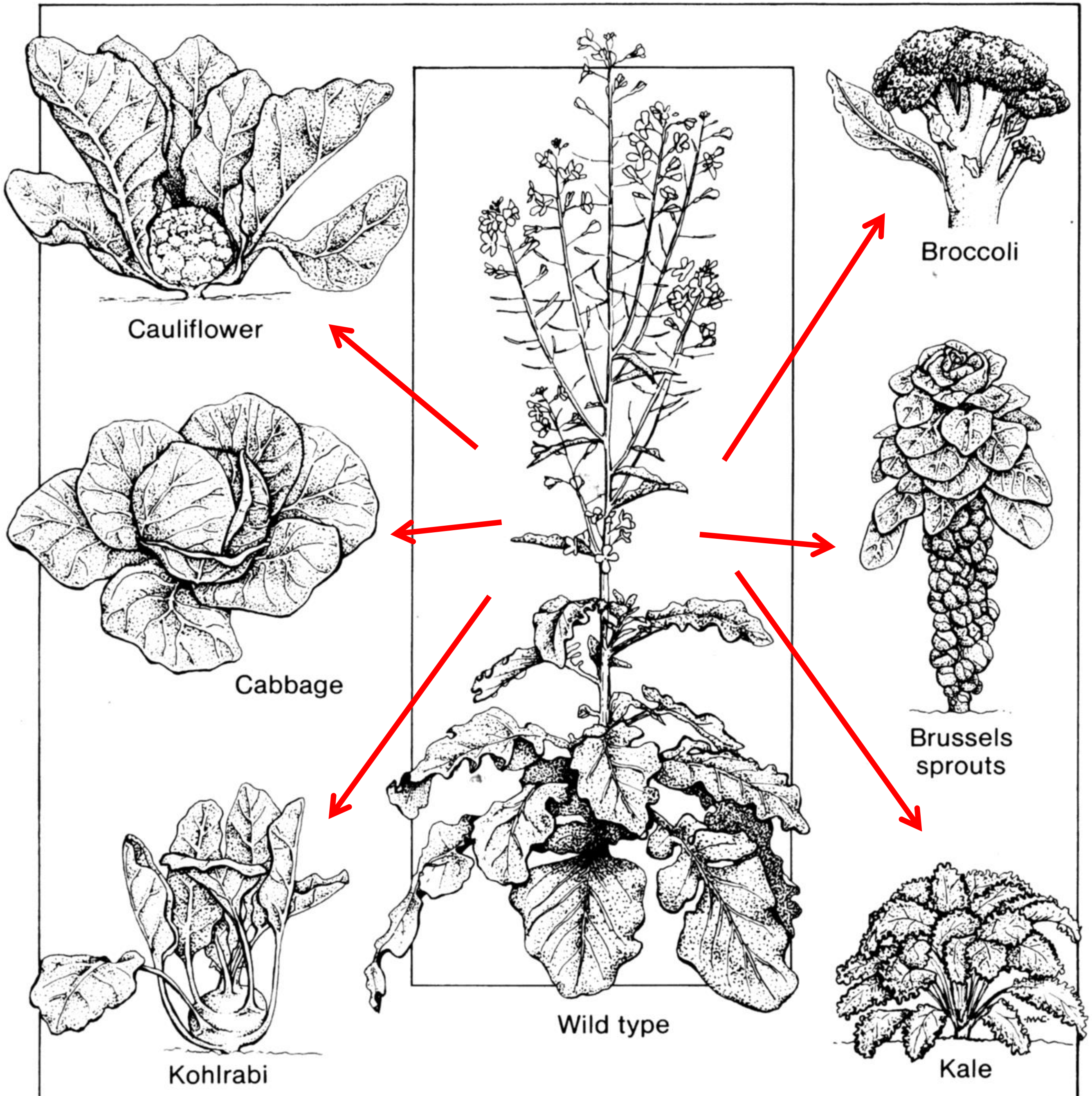
Crop Domestication

Plant Domestication = Genetic modification of a wild species to create a new form of plant altered to meet human needs

Fully Domesticated = For many, but not all crops, domesticated crops are completely dependent on humans and unable of propagating in the wild (e.g. maize, cauliflower)

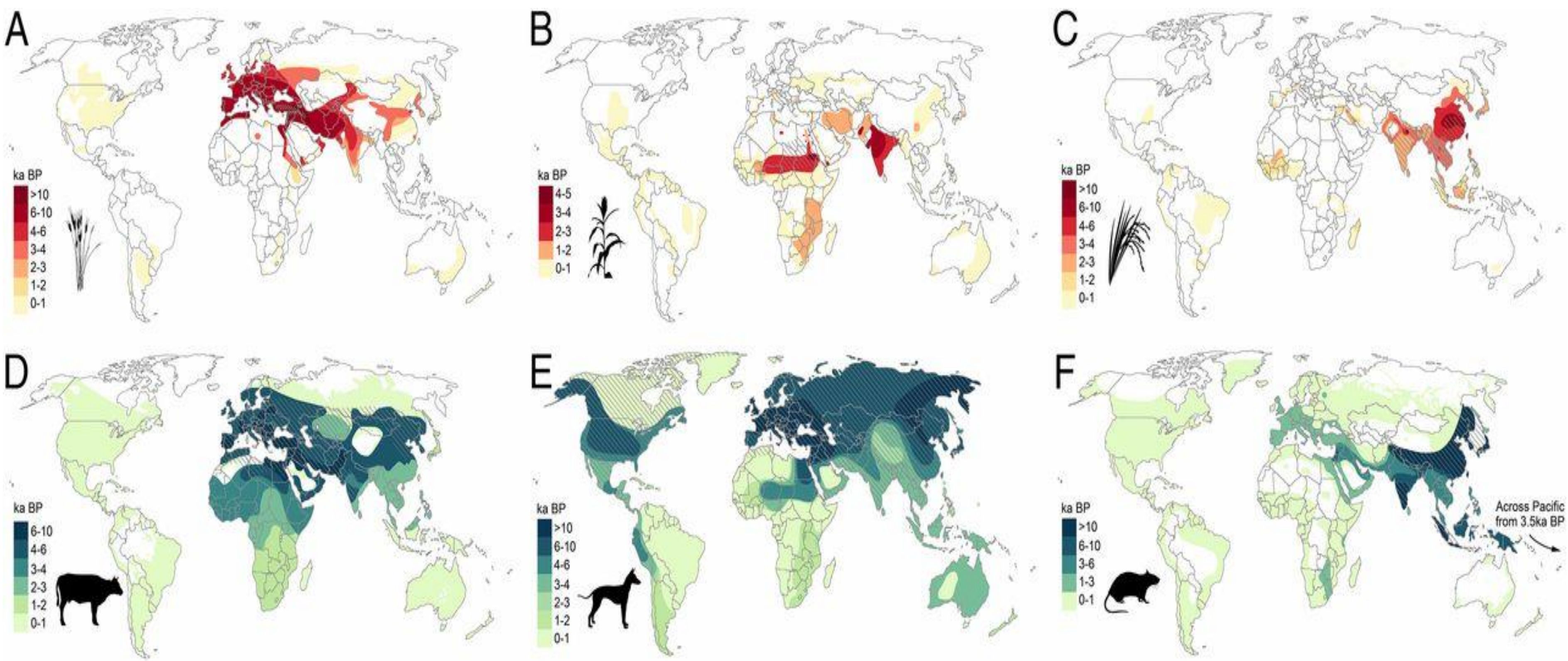


Crops originating from *Brassica olearacea* subsp. *oleracea*



Cacao, *Theobroma cacao* is native in the lowland wet forests of the neotropics in Central & S America; most of the cacao imported to Europe is grown in West Africa, e.g. Ghana; most of the chocolate eaten in Europe is manufactured in Europe

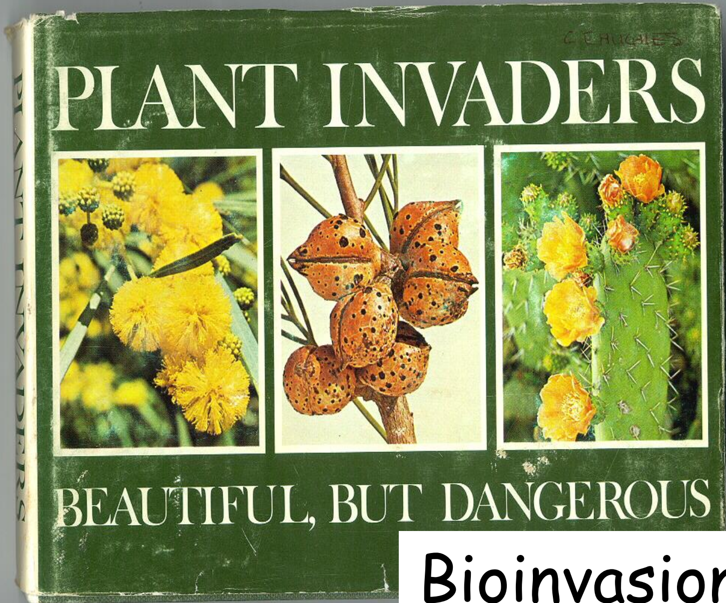
Global spread of food crops

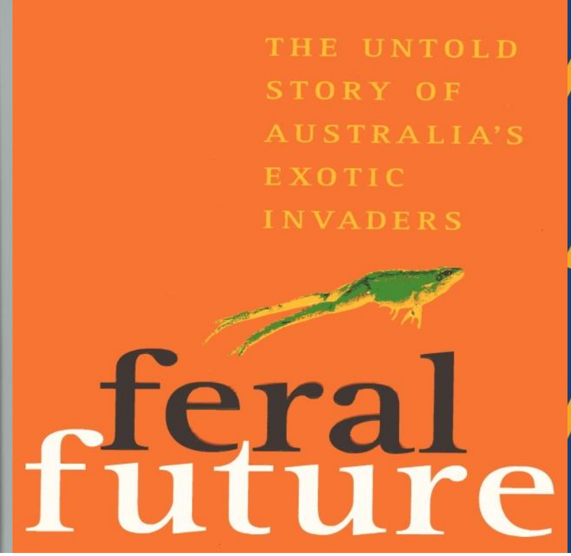


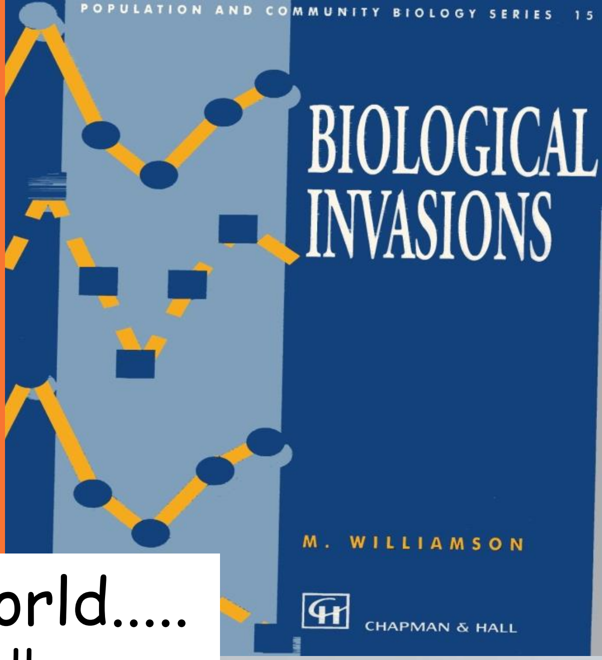
Boivin et al (2016)

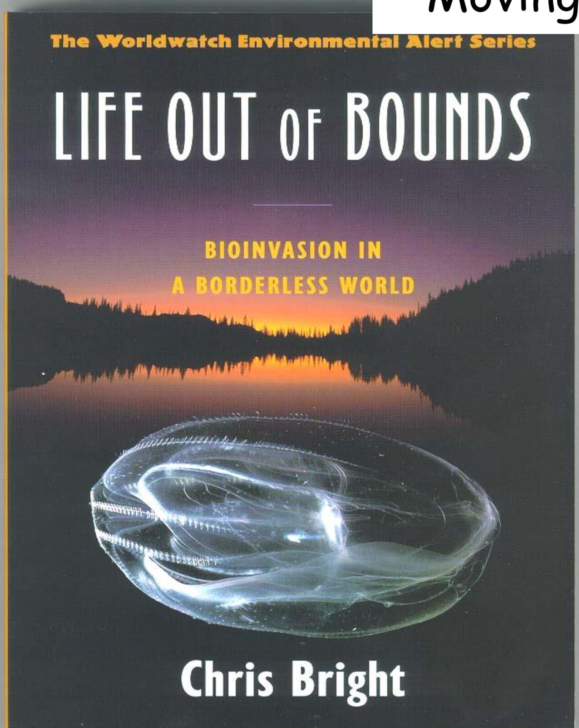
Bioinvasion in a Borderless World.....

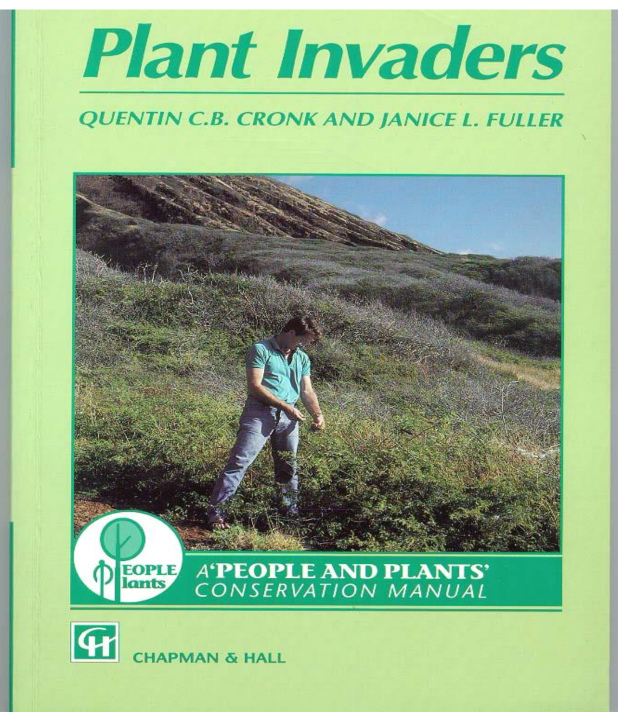
- Moving whole genomes intercontinentally

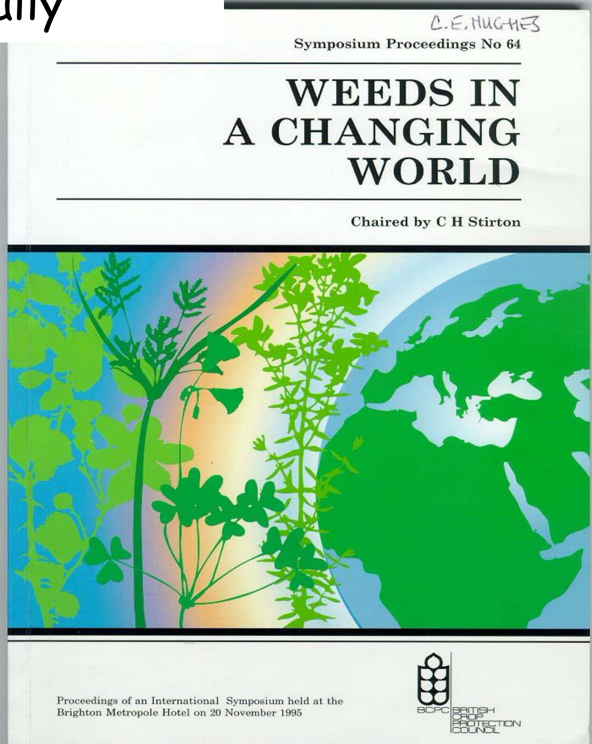




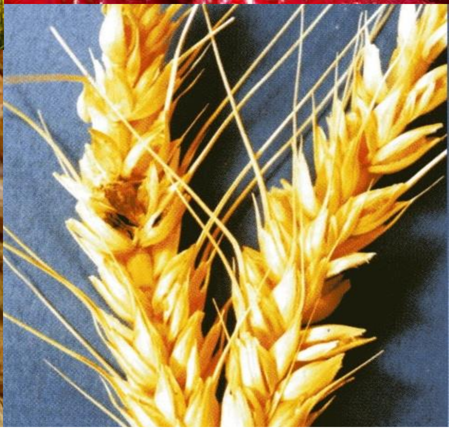


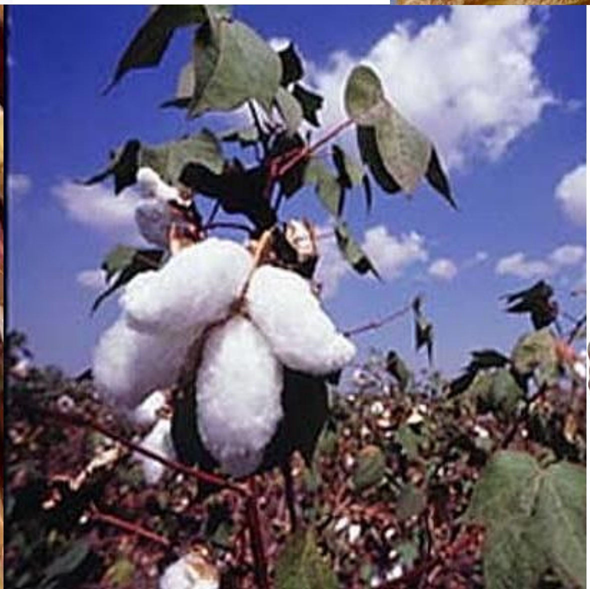




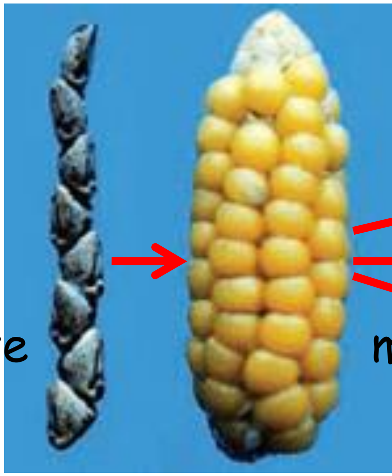


Polyploidy & Crops



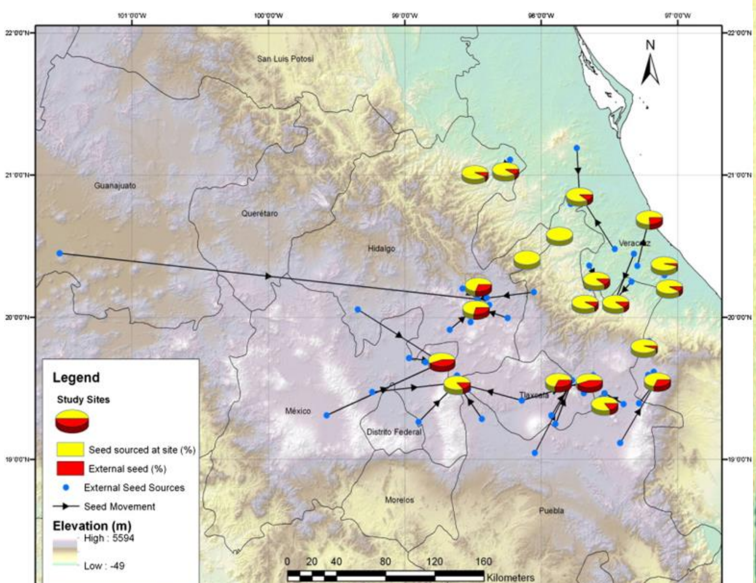


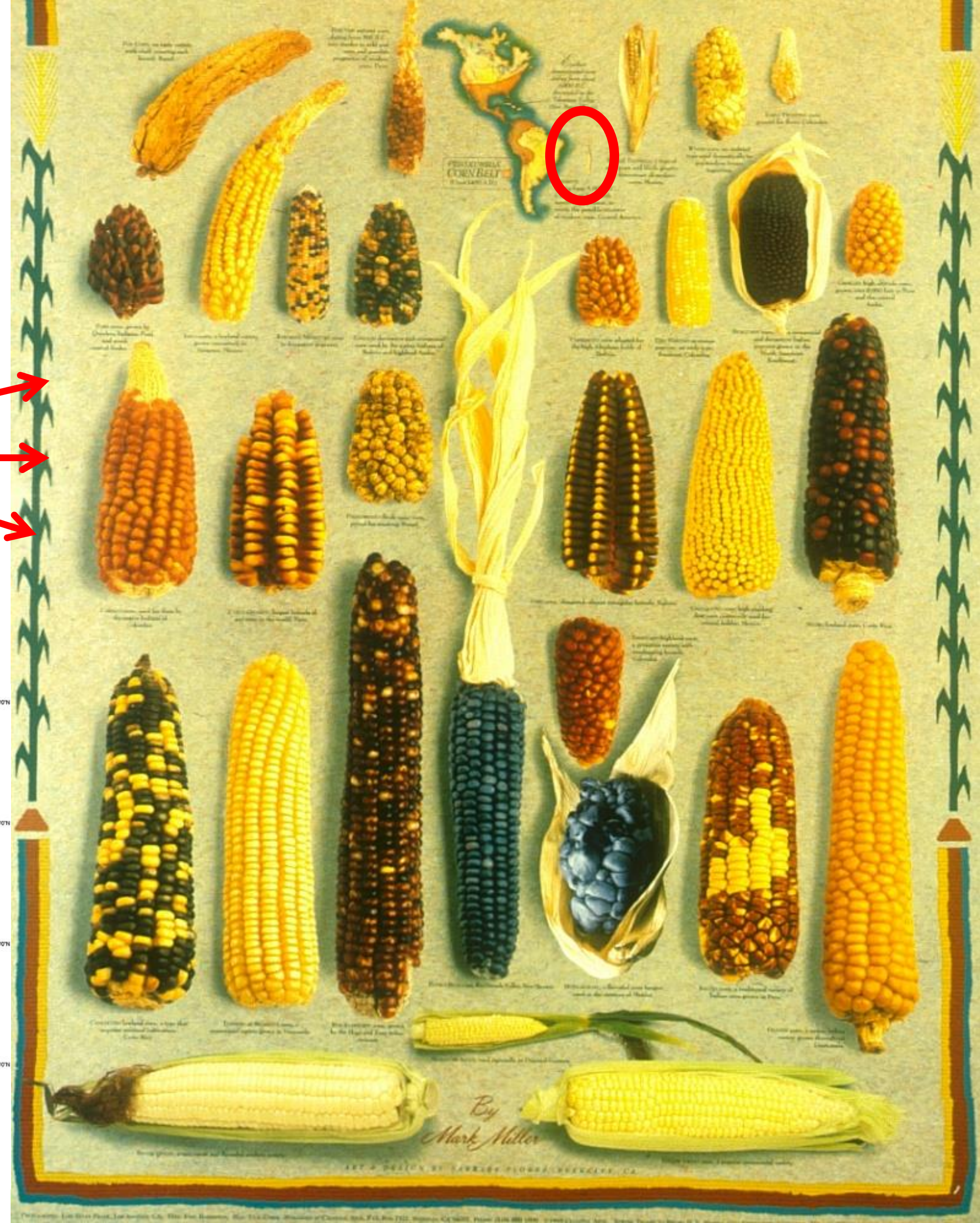
Selection after domestication / crop diversification



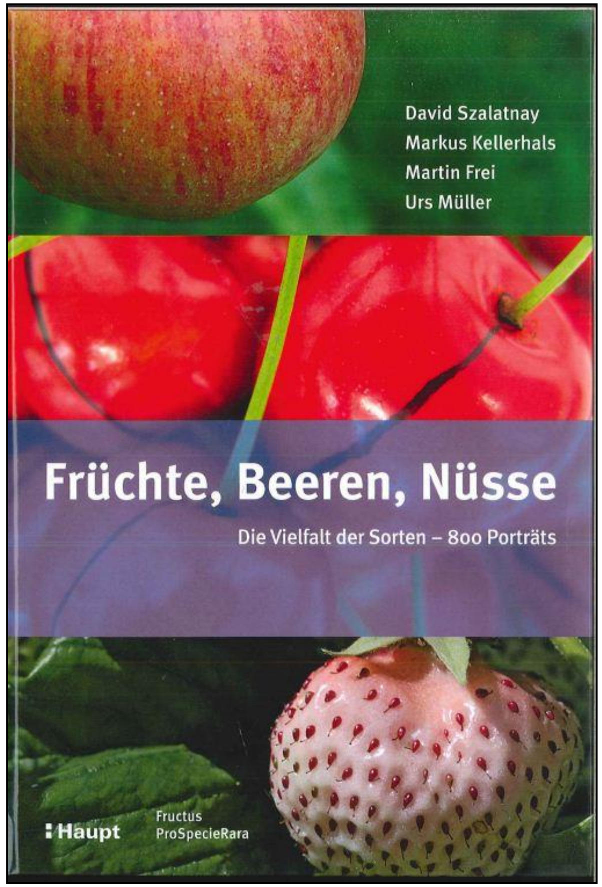
teosinte

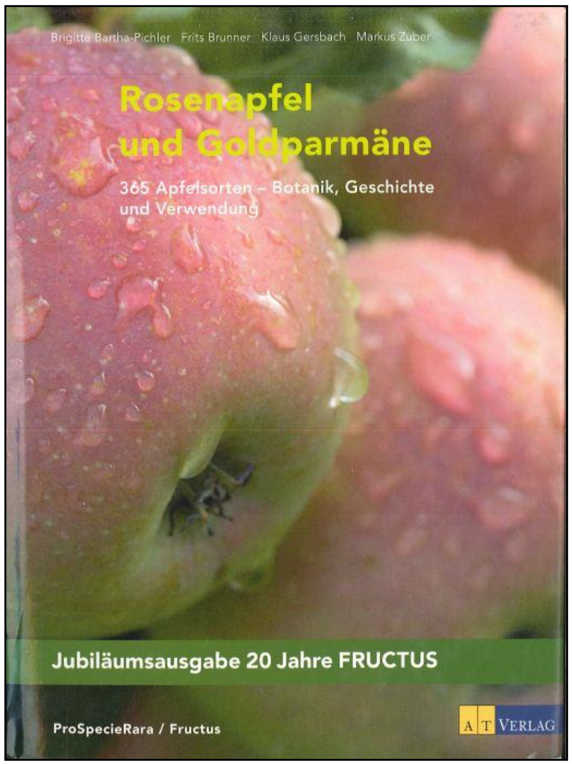
maize



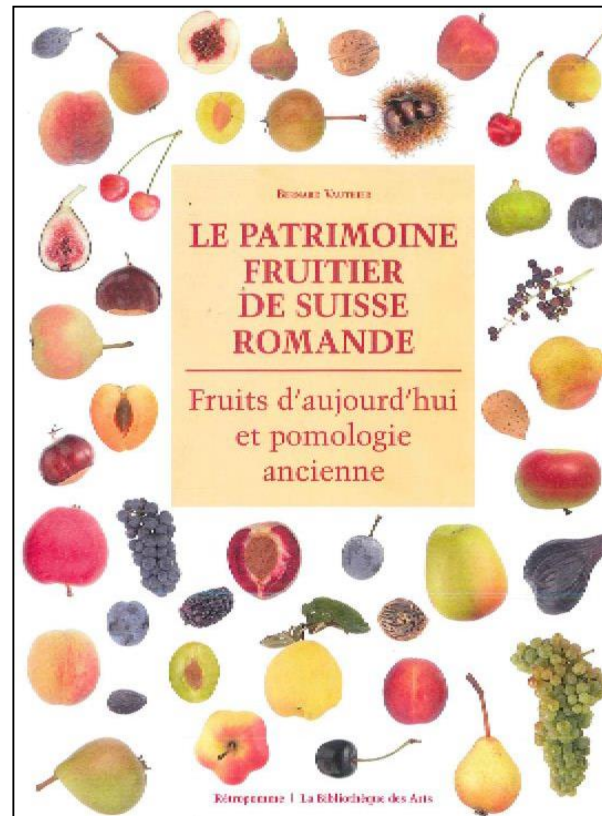


Does Crop diversity matter?





- *Prospecierara*
- *Fructus*
- *Retropomme*



Limits to Food Production - Land, Water & Energy

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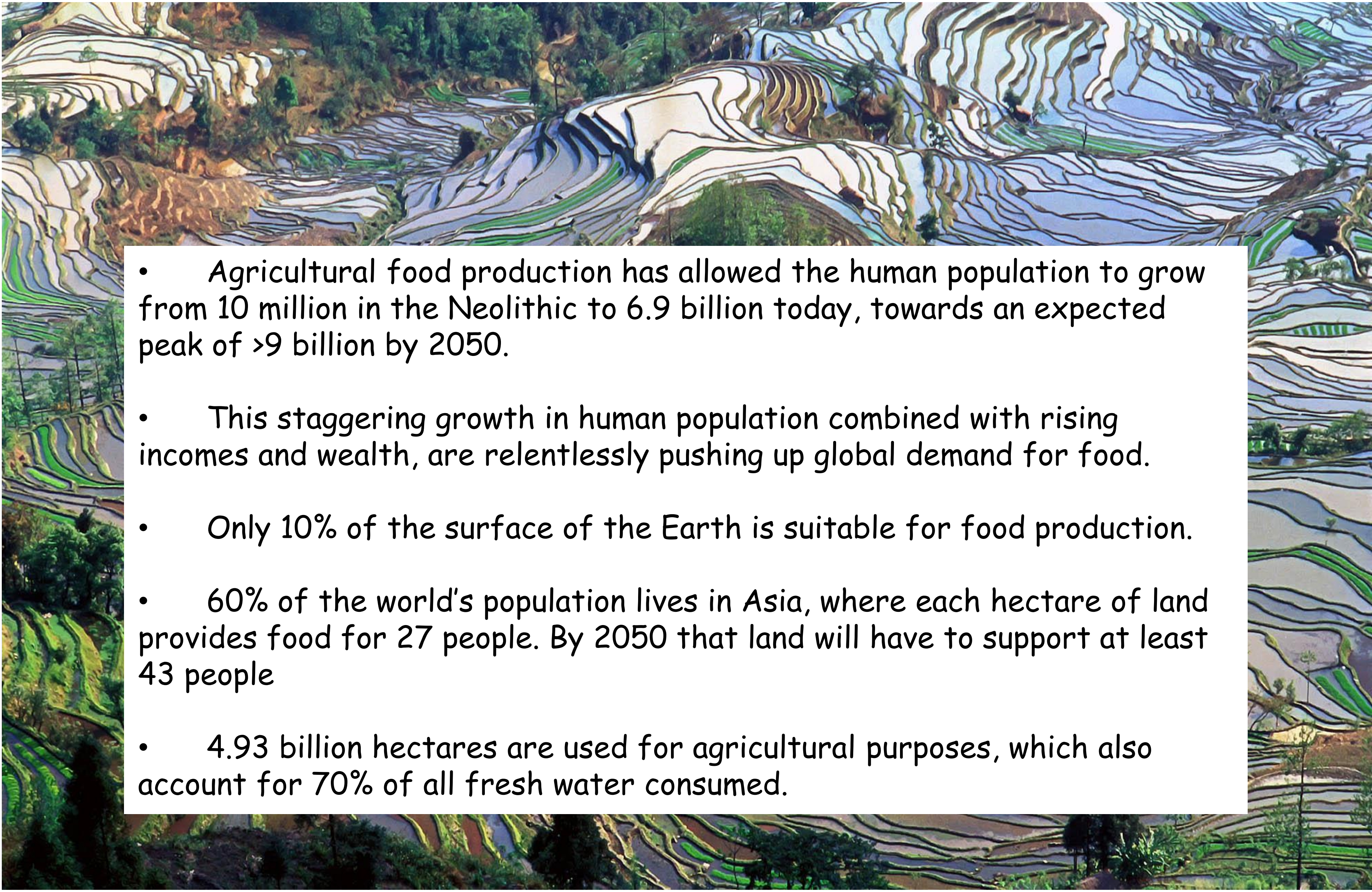


- Agricultural food production has allowed the human population to grow from 10 million in the Neolithic to 6.9 billion today, towards an expected peak of >9 billion by 2050.

- This staggering growth in human population combined with rising incomes and wealth, are relentlessly pushing up global demand for food.

- Only 10% of the surface of the Earth is suitable for food production.

- 60% of the world's population lives in Asia, where each hectare of land provides food for 27 people. By 2050 that land will have to support at least 43 people

- 4.93 billion hectares are used for agricultural purposes, which also account for 70% of all fresh water consumed.

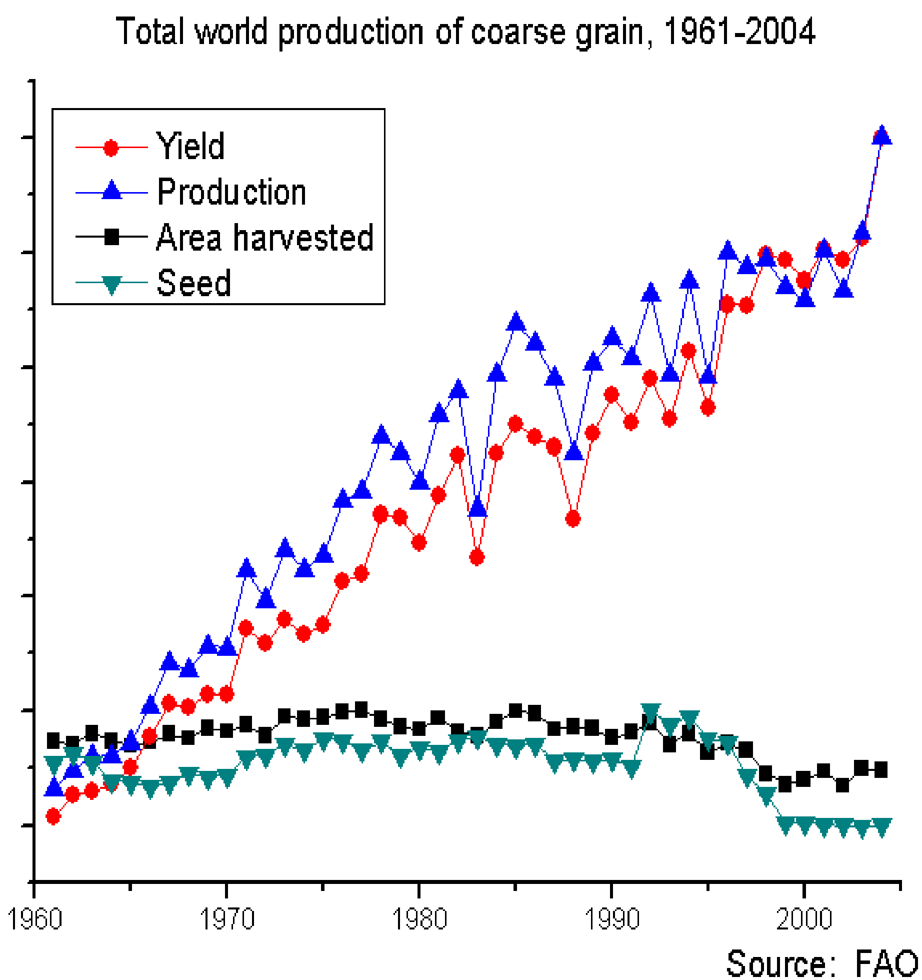
Biofuels

Biofuels are competing for agricultural land and for crops such as maize

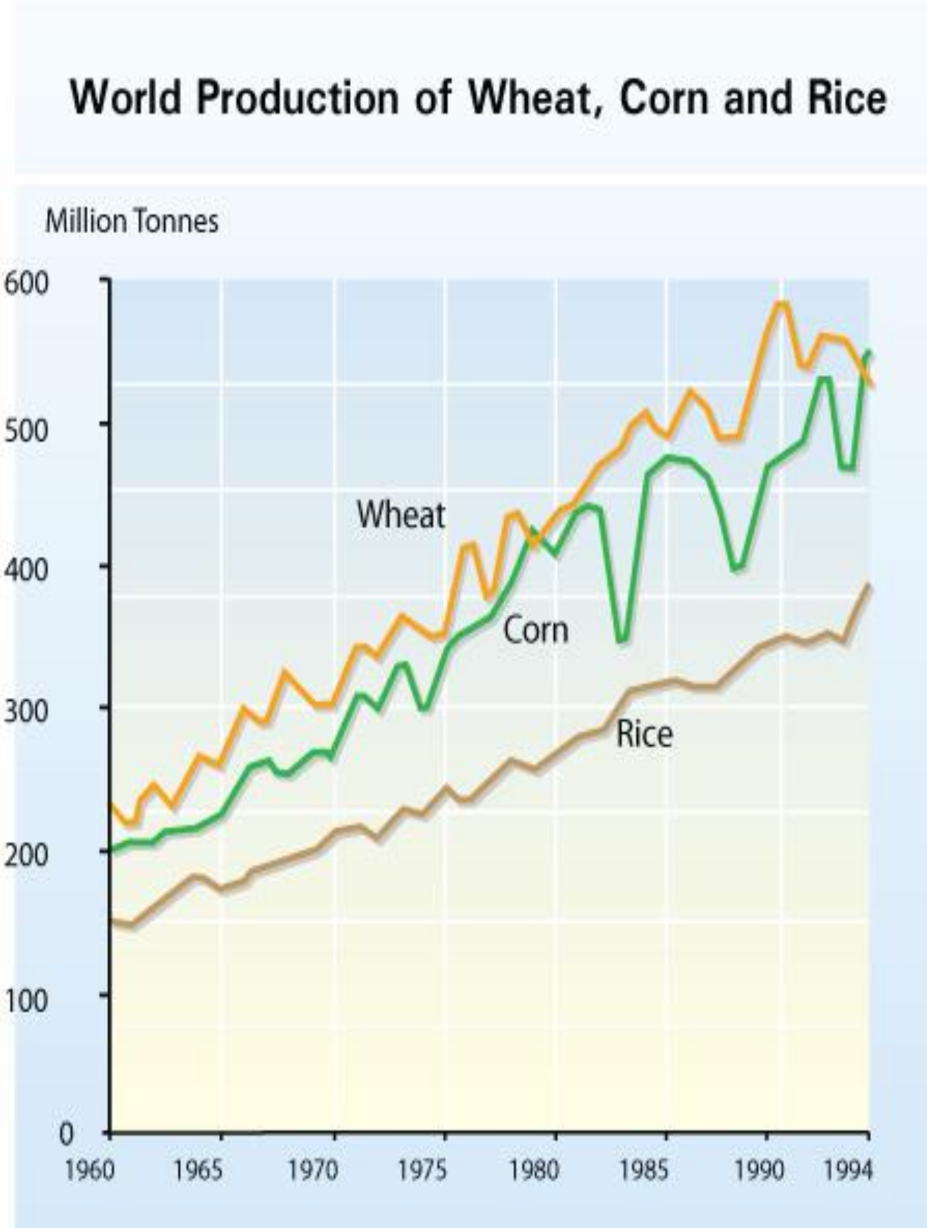
This is pushing the price of maize higher and reducing land available for food production

A maize grain-ethanol biorefinery in Nebraska, USA which uses about 0.6 million tonnes of grain annualy to produce 250 million litres of ethanol

Oil palm plantation used for biodiesel in Sarawak, Malaysia

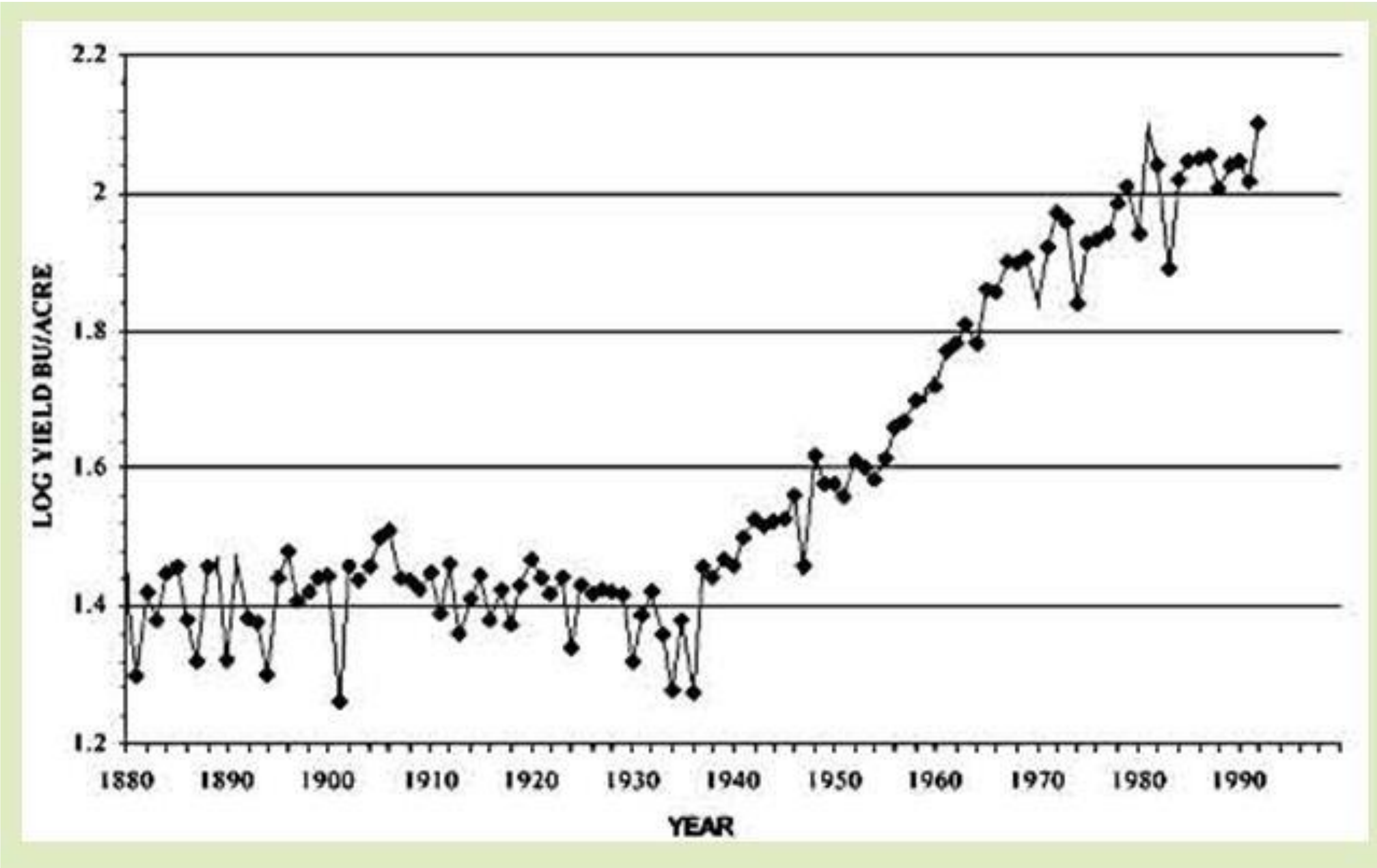


Total world production of coarse grain, 1961-2004
Yield
Production
Area harvested
Seed
1960
1970
1980
1990
2000
Source: FAO

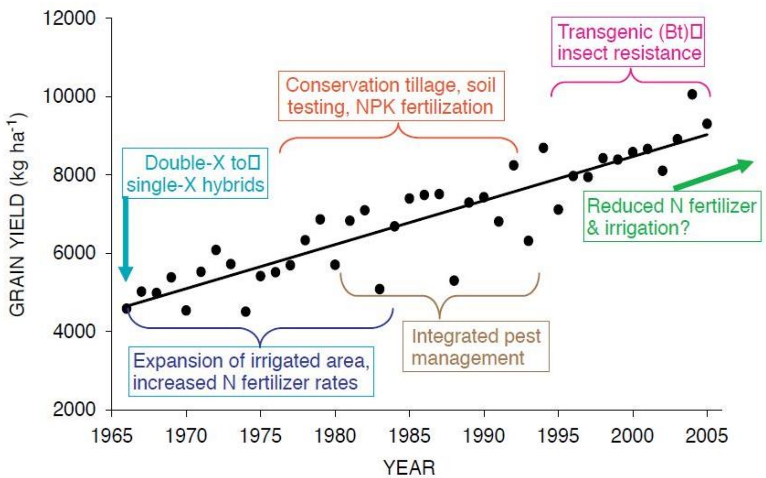


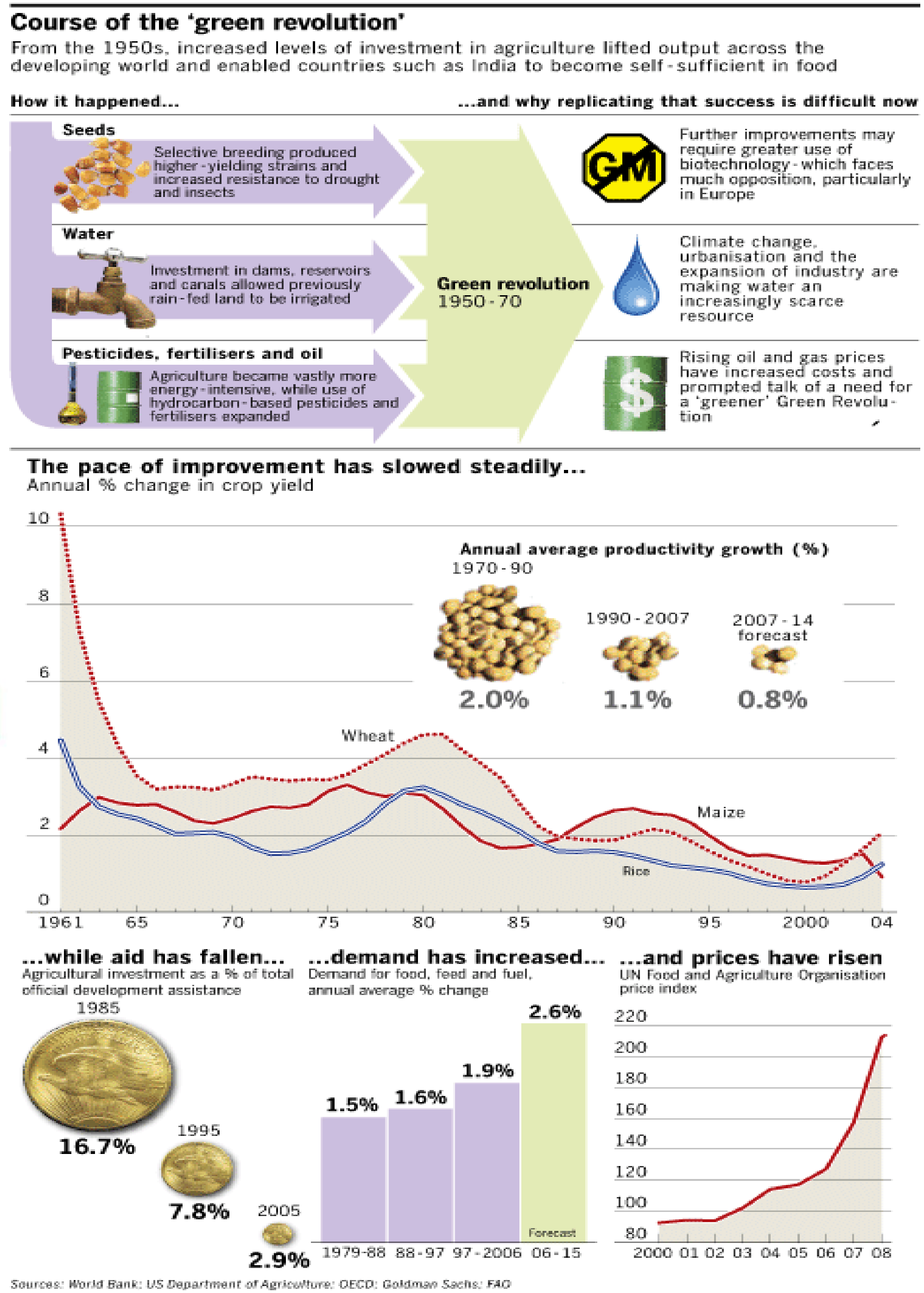
World Production of Wheat, Corn and Rice
Million Tonnes
600
500
400
300
200
100
0
Wheat
Corn
Rice
1960
1965
1970
1975
1980
1985
1990
1994

Traditional Crop Breeding & Yield Gains for Maize from 1930 onwards

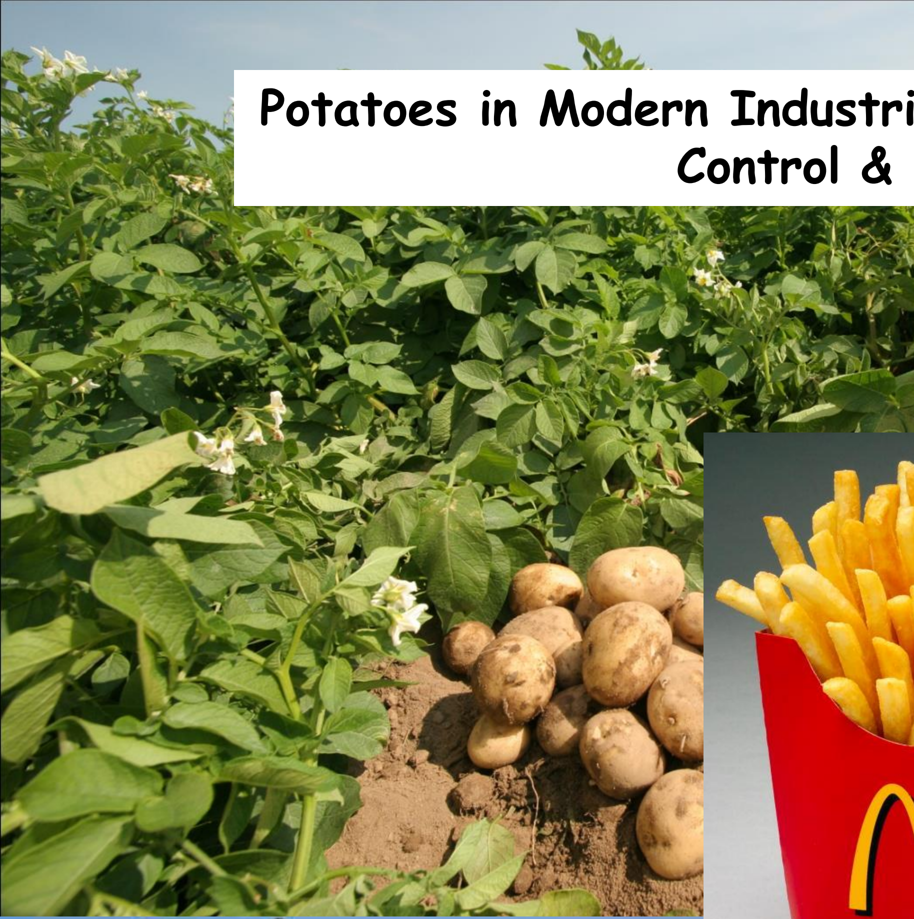


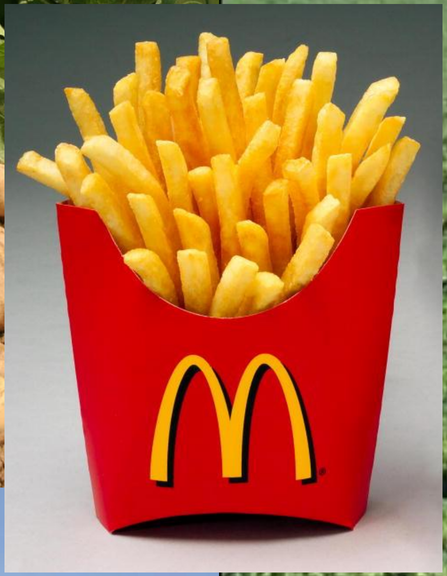
The Green Revolution

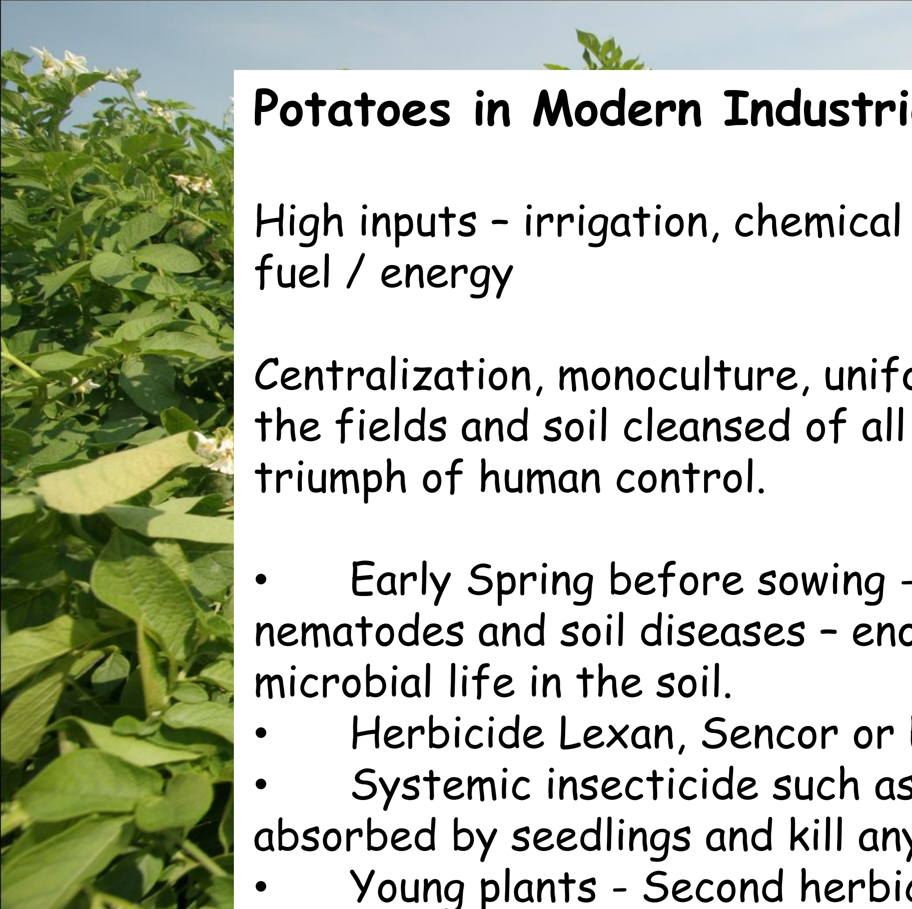


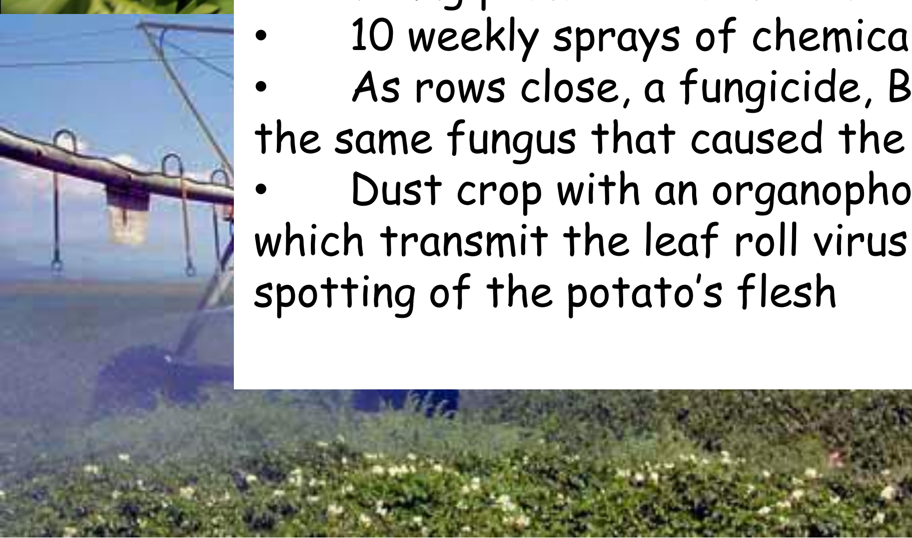


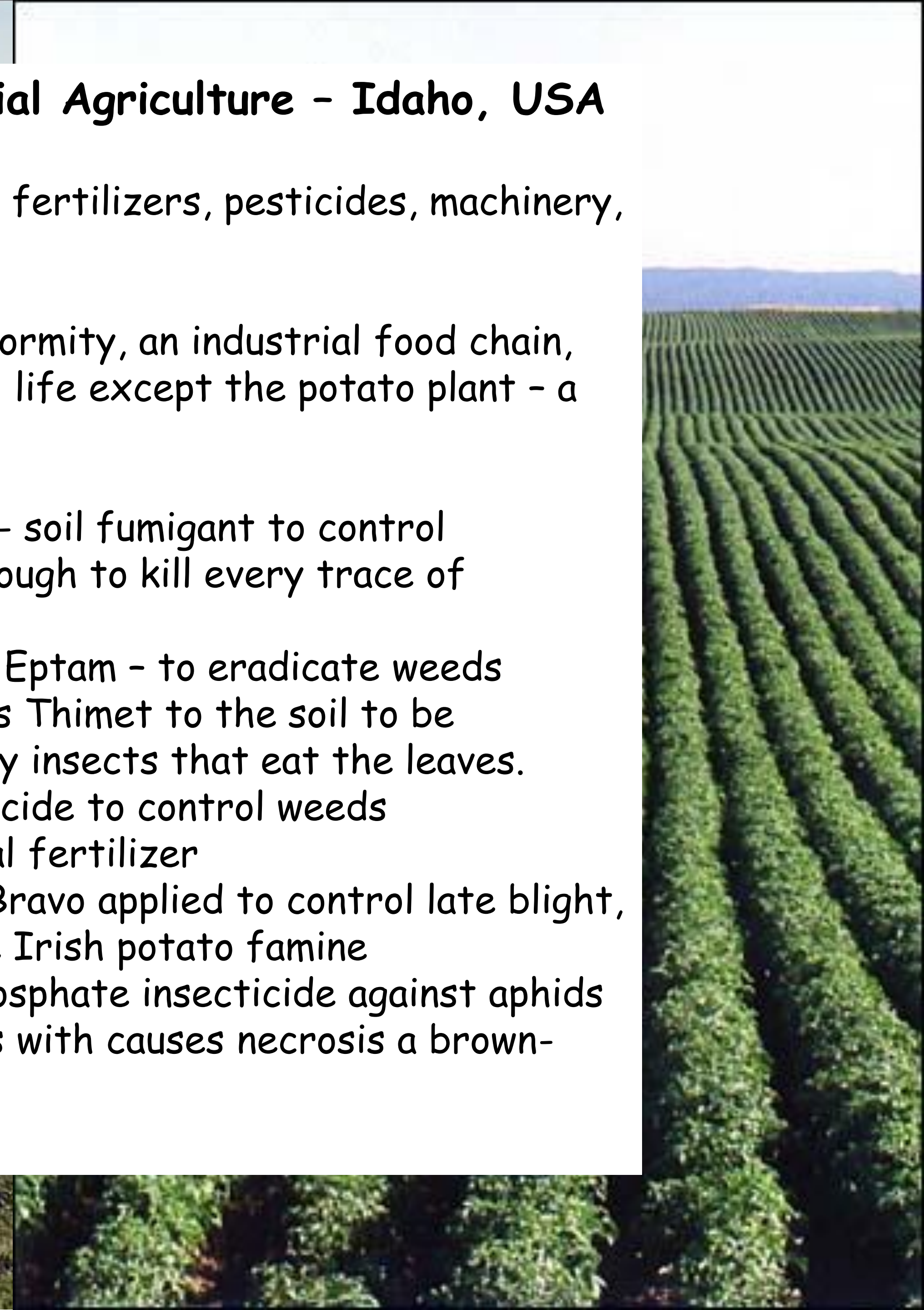
Potatoes in Modern Industrial Agriculture – Idaho, USA
Control & Uniformity









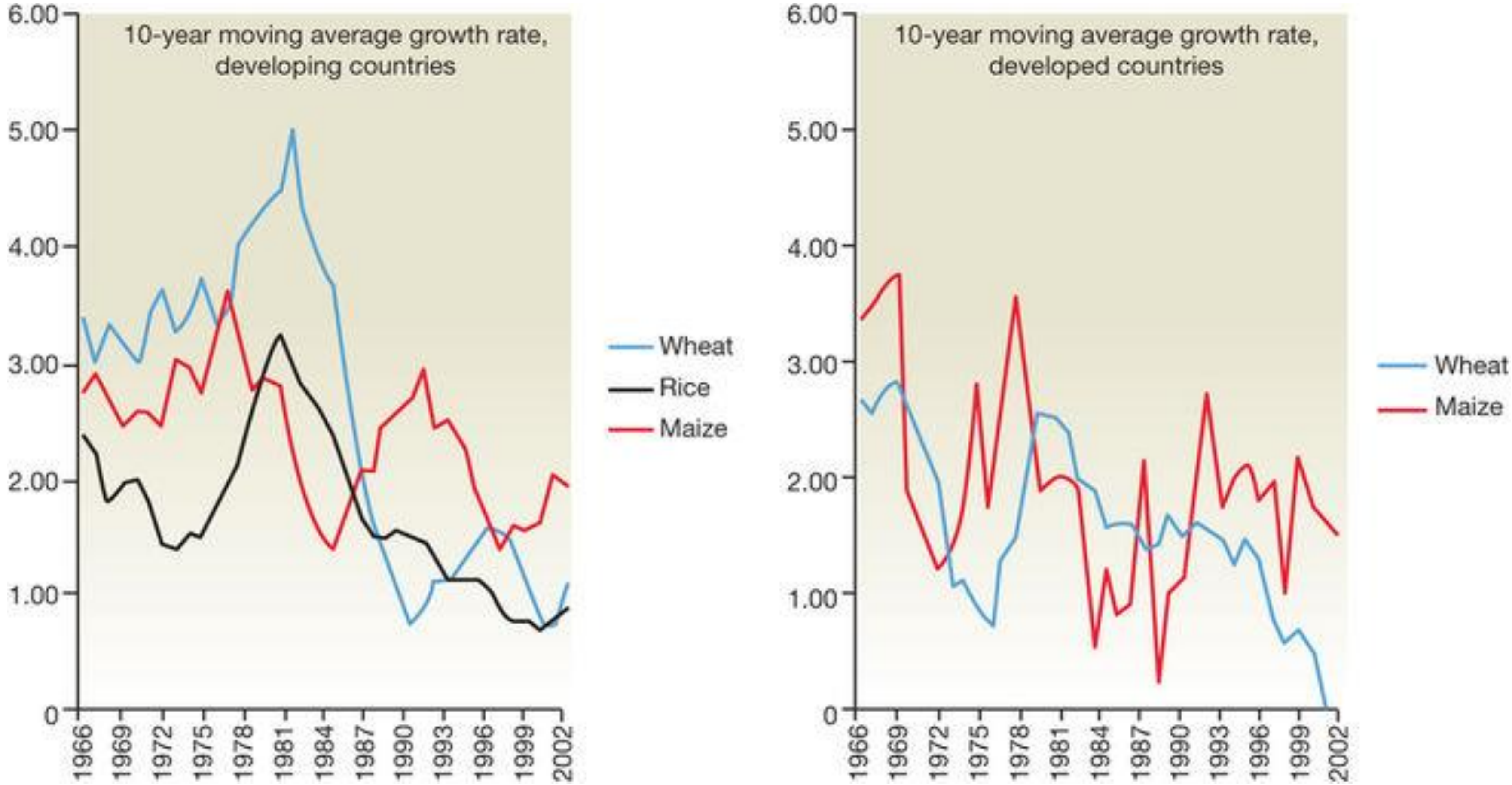


Potatoes in Modern Industrial Agriculture – Idaho, USA

High inputs – irrigation, chemical fertilizers, pesticides, machinery, fuel / energy

Centralization, monoculture, uniformity, an industrial food chain, the fields and soil cleansed of all life except the potato plant – a triumph of human control.

- Early Spring before sowing - soil fumigant to control nematodes and soil diseases – enough to kill every trace of microbial life in the soil.
- Herbicide Lexan, Sencor or Eptam – to eradicate weeds
- Systemic insecticide such as Thimet to the soil to be absorbed by seedlings and kill any insects that eat the leaves.
- Young plants - Second herbicide to control weeds
- 10 weekly sprays of chemical fertilizer
- As rows close, a fungicide, Bravo applied to control late blight, the same fungus that caused the Irish potato famine
- Dust crop with an organophosphate insecticide against aphids which transmit the leaf roll virus with causes necrosis a brown-spotting of the potato's flesh

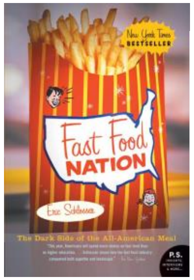


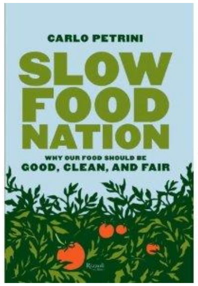
Crop productivity gains due to better plant varieties have slowed down

Flavell (2016)

Organic Food

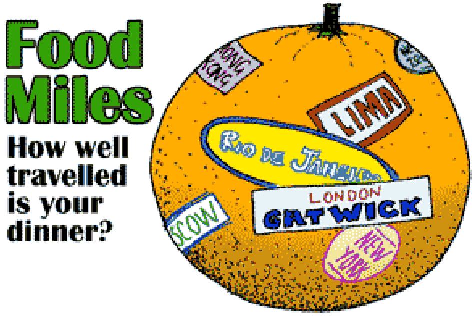
Fast Food & Slow Food





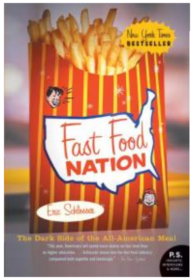
Fair Food

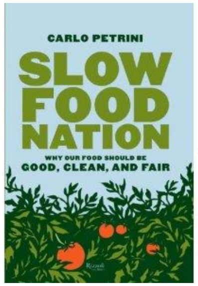
Globalisation, Food Miles & Seasonaility



Organic Food

Fast Food & Slow Food





Slow Food®

Organic Food

Long, complex crop rotations

Strips of flowers on field margins

Biocontrol

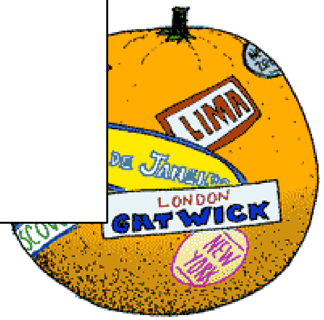
Diversity – mix of crops and varieties

Green manures, manure

> labour; fewer inputs

Globalis
Food Mi
Seasona

dinner?



Will Agriculture Destroy the World Before It Saves It?

Jack A. Bobo, JD, MS
Senior Advisor for Biotechnology
Chief, Biotechnology and Textile Trade Policy Division
United States Department of State

PNAS

PERSPECTIVE

Used planet: A global history

Erle C. Ellis[a,1], Jed O. Kaplan[b], Dorian Q. Fuller[c], Steve Vavrus[d], Kees Klein Goldewijk[e], and Peter H. Verburg[f]

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Feeding 9 billion people

Nearly all new food production in the next 25 years will have to come from existing agricultural land

Only 55% of food crop calories directly nourish people – meat, dairy products and eggs from animals raised on plant food, supply another 4%

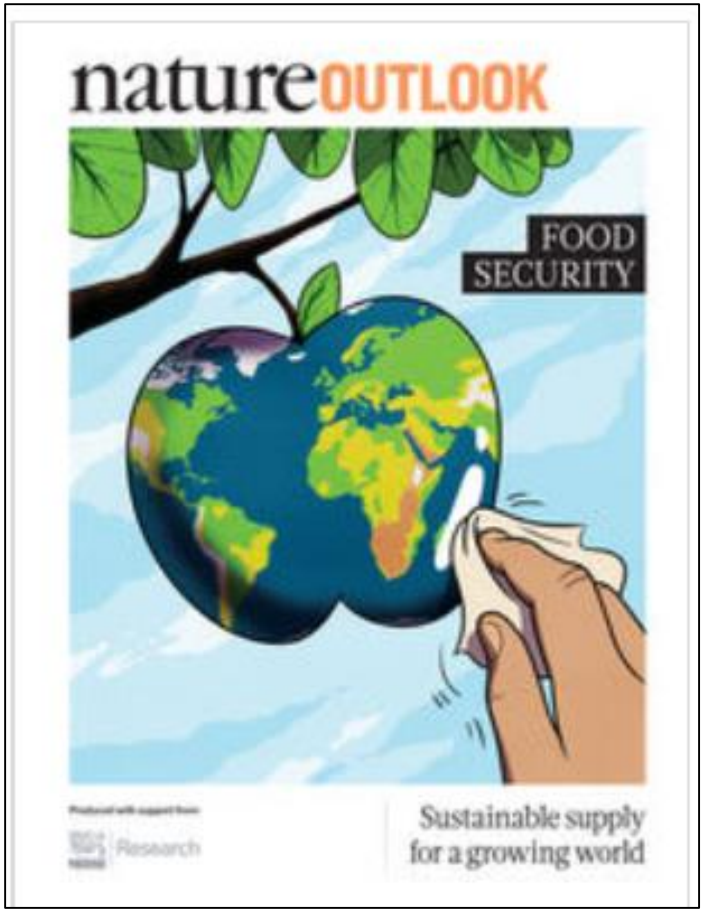
Reducing food waste – 30-40% of food is lost to waste

Closing the yield gap: improving nutrient and water supplies where yields are lowest could result in a 58% increase in global food production

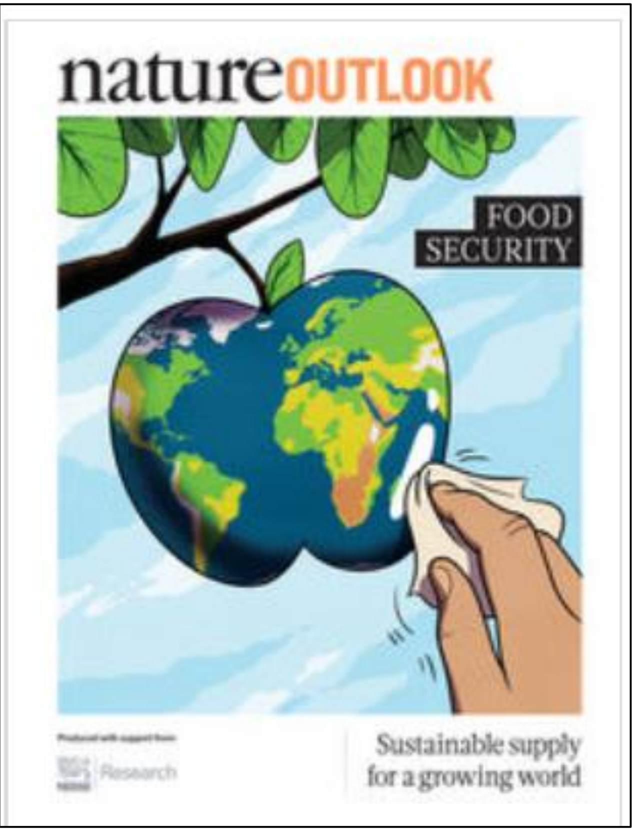
Increasing production limits

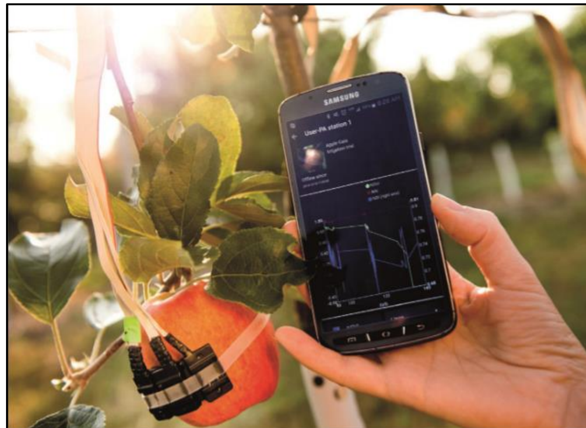
Sustainable intensification

Godfray et al. (2010)



Nature Outlook
Food Security
April 2017





THE FUTURE OF AGRICULTURE

A technological revolution in farming led by advances in robotics and sensing technologies looks set to disrupt modern practice.

Nature Outlook
Food Security
April 2017

A meaty issue

Our insatiable appetite for red meat is bad for our health and for the planet. Sustainable alternatives are in the pipeline, but will they convince us to make the switch?

BY OLIVE HEFFERNAN

Robotic bees
Could this pollinating drone replace bees and butterflies?

http://www.sciencemag.org/news/2017/02/could-pollinating-drone-replace-butterflies-and-bees

https://www.bloomberg.com/news/videos/2018-08-26/scientists-creating-drone-pollinators-video

Robots on the Farm


ARTIFICIAL INTELLIGENCE

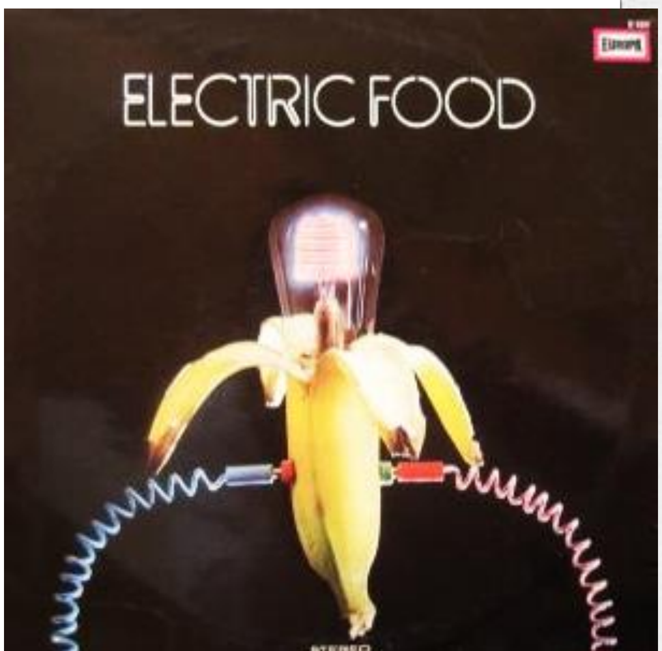
Down on the robot farmstead

A California company has turned to autonomous machines to solve a shortage of agricultural labourers

By Noah Smith LOS ANGELES

Vertical Farming
- verticrop

Electric Food



FOOD

Electric food sounds bizarre. But it might just save our planet

George Monbiot

It's not about "them", it's about us. The horrific rate of biological annihilation reported last week – 60% of the Earth's vertebrate wildlife gone since 1970 – is driven primarily by the food industry. Farming and fishing are the major causes of the collapse of both marine and terrestrial ecosystems. Meat – consumed in greater quantities by the rich than by the poor – is the strongest cause of all. We may shake our heads in horror at the clearance of forests, the drainage of wetlands and the slaughter of predators, but it is done at our behest.

The most important environmental action we can take is to reduce the area of land and sea used by farming and fishing. This means, above all, switching to a plant-based diet: research published in the journal Science shows that cutting out animal products would reduce the global requirement for farmland by 76%. It would also give us a fair chance of feeding the world.

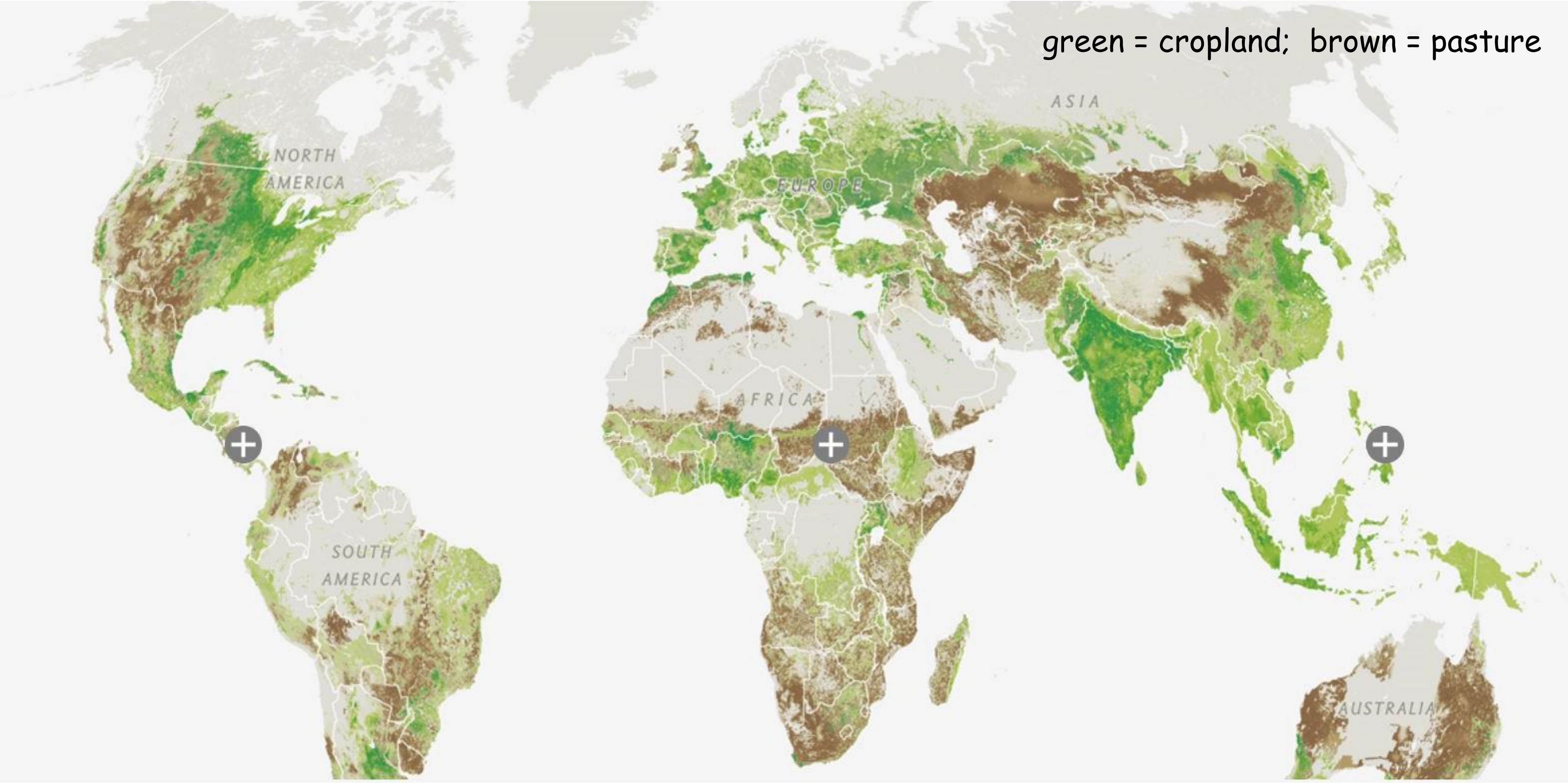
The same action is essential to prevent climate breakdown. Because governments, bowing to the demands of capital, have left it so late, it is almost impossible to see how we can stop more than 1.5C of global warming without drawing carbon dioxide out of the atmosphere. The only way of doing it that has been demonstrated at scale is to allow trees to return to deforested land.

But could we go beyond even a plant-based diet? Could we go beyond agriculture itself? What if, instead of producing food from soil, we were to produce it from air? What if, instead of basing our nutrition on photosynthesis, we were to use electricity to fuel a process whose conversion of sunlight into food is 10 times more efficient?

This sounds like science fiction, but it is already approaching commercialisation. For the past year, a group of Finnish researchers has been producing food without either animals or plants. Their only ingredients are hydrogen-oxidising bacteria, electricity from solar panels, a small amount of water, carbon dioxide drawn

Illustration: Nathalie Lees

Where agriculture exists



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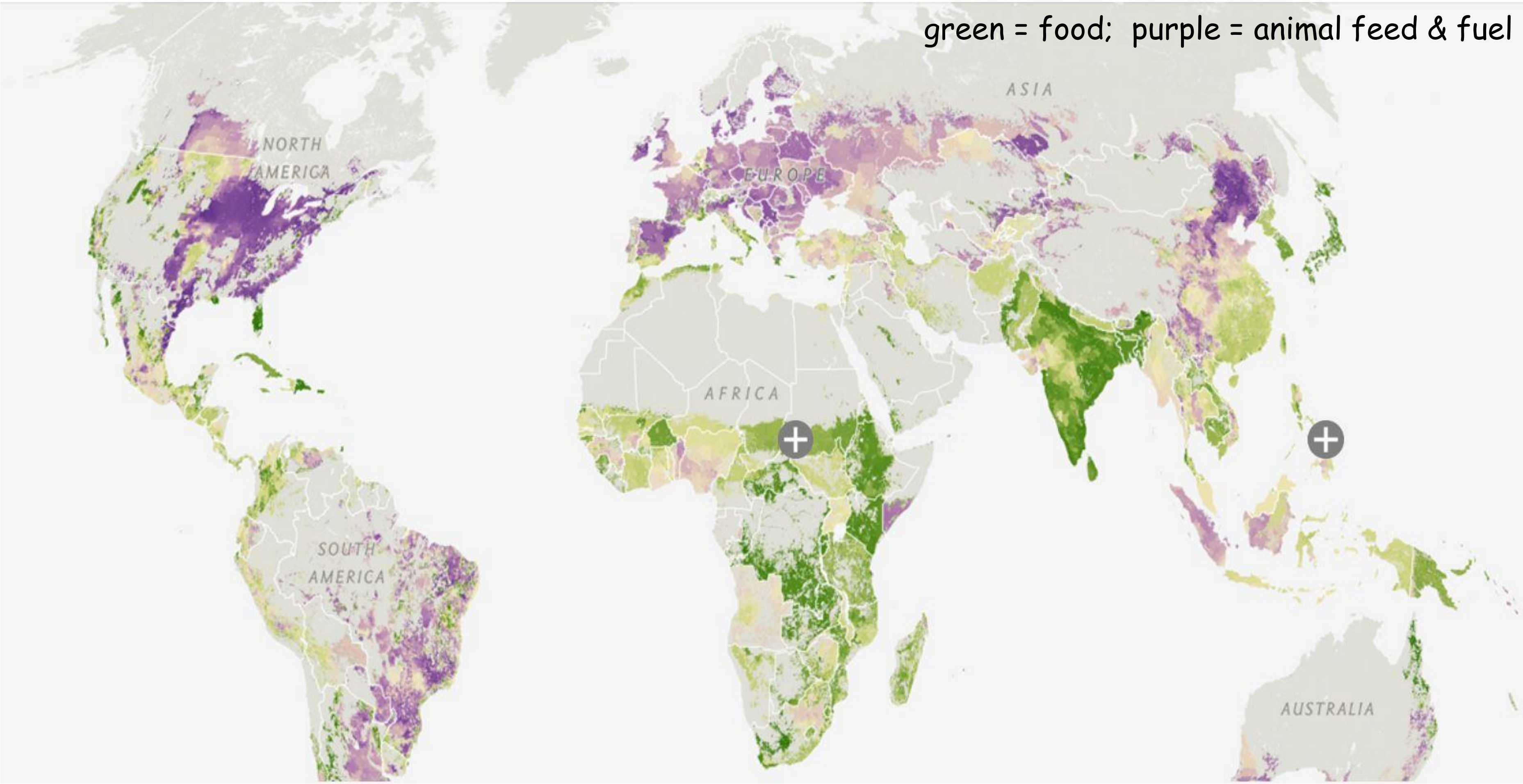
How crops are used



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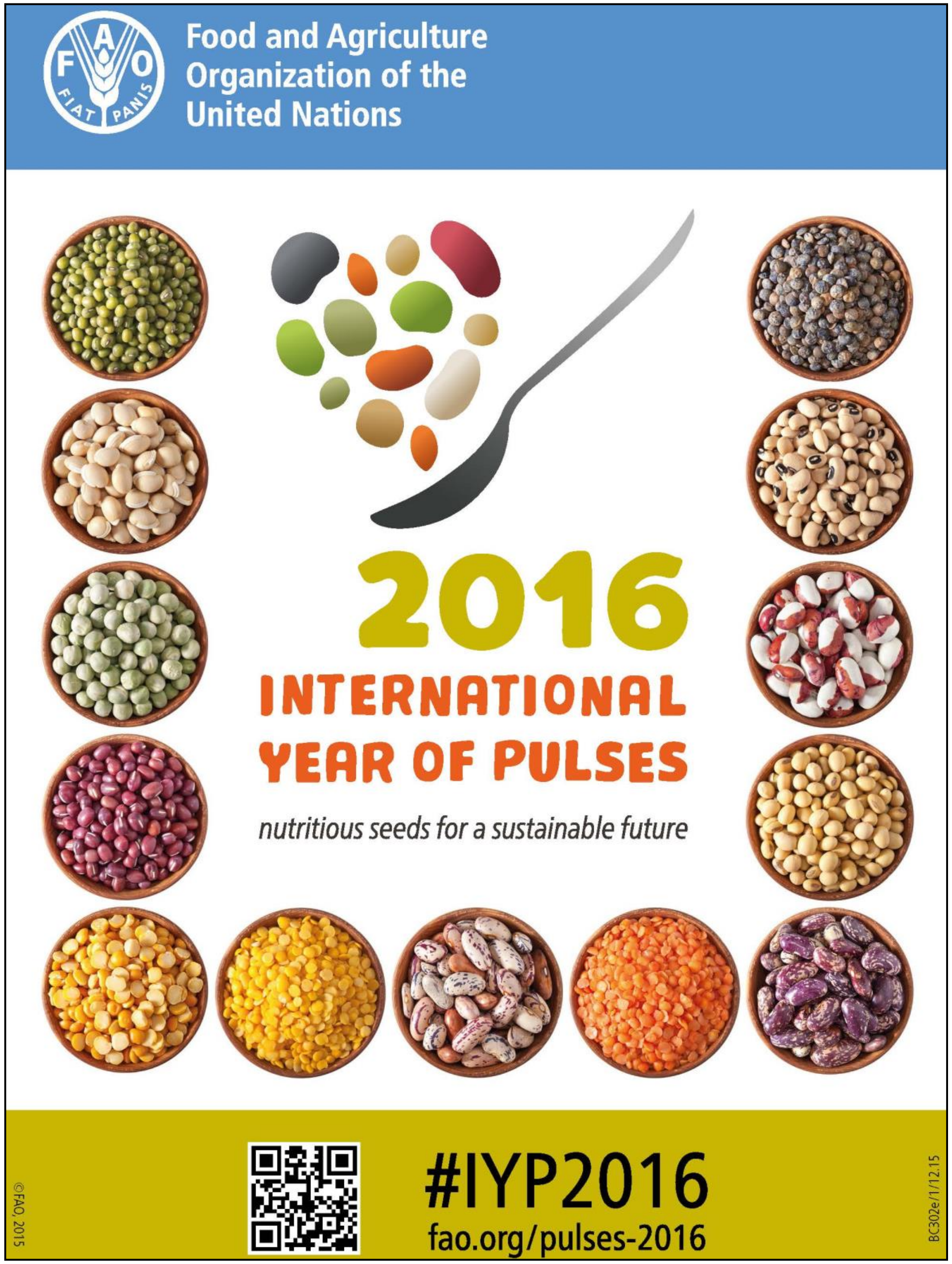
a
b
c
d
e
F
G

Nodulation



nature plants | PERSPECTIVE
PUBLISHED: 2 AUGUST 2016 | ARTICLE NUMBER: 16112 | DOI: 10.1038/NPLANTS.2016.112

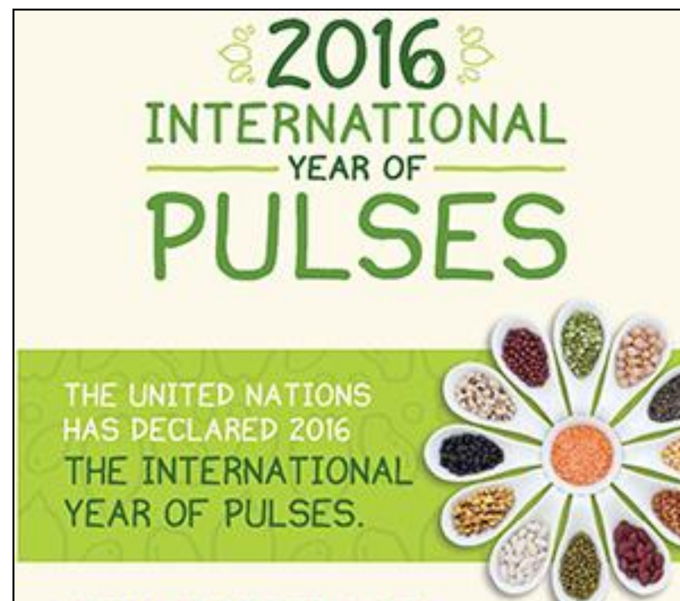
Neglecting legumes has compromised human health and sustainable food production

Lower carbon footprint

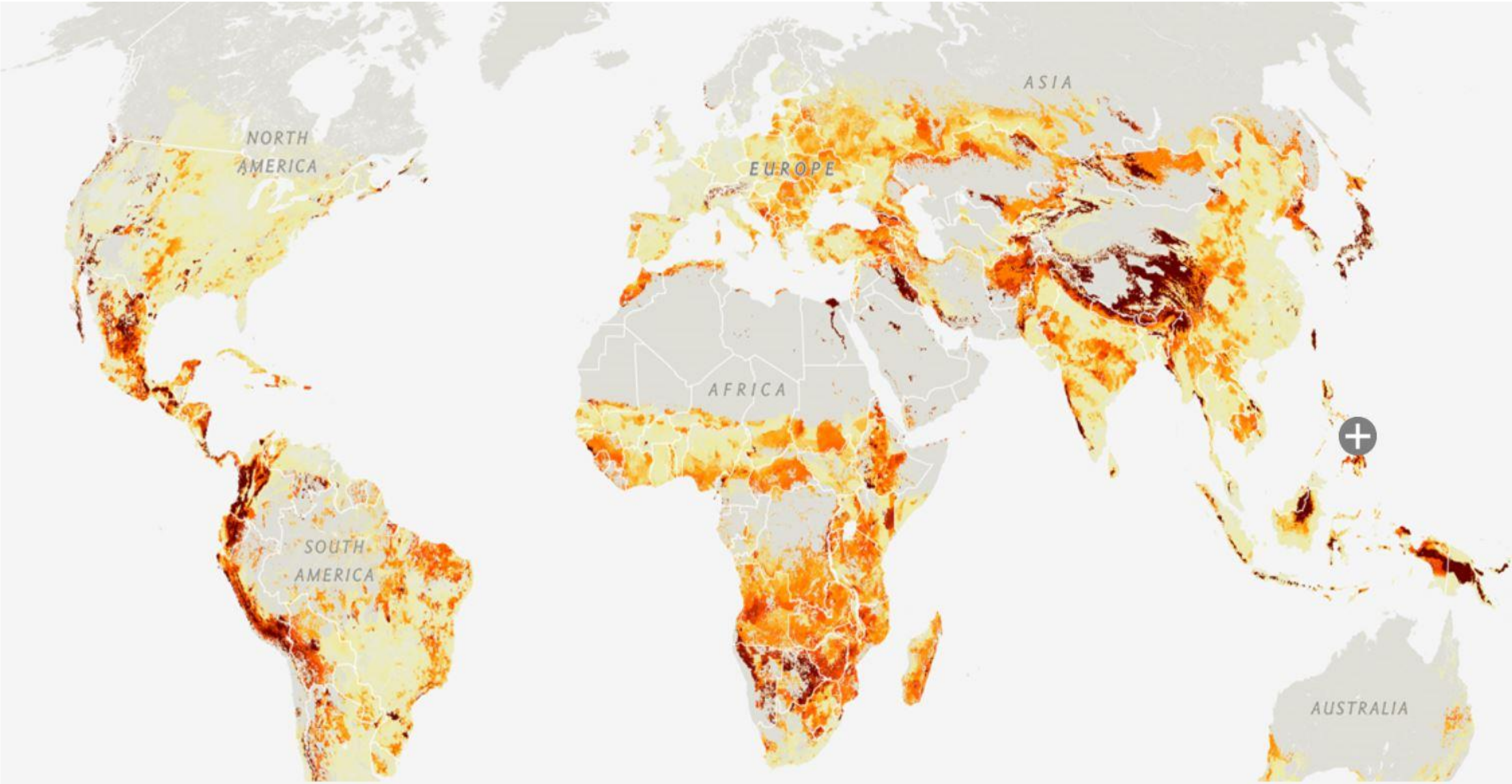
Health & nutrition

Symbiotic Nitrogen fixation

Sustainable cropping systems



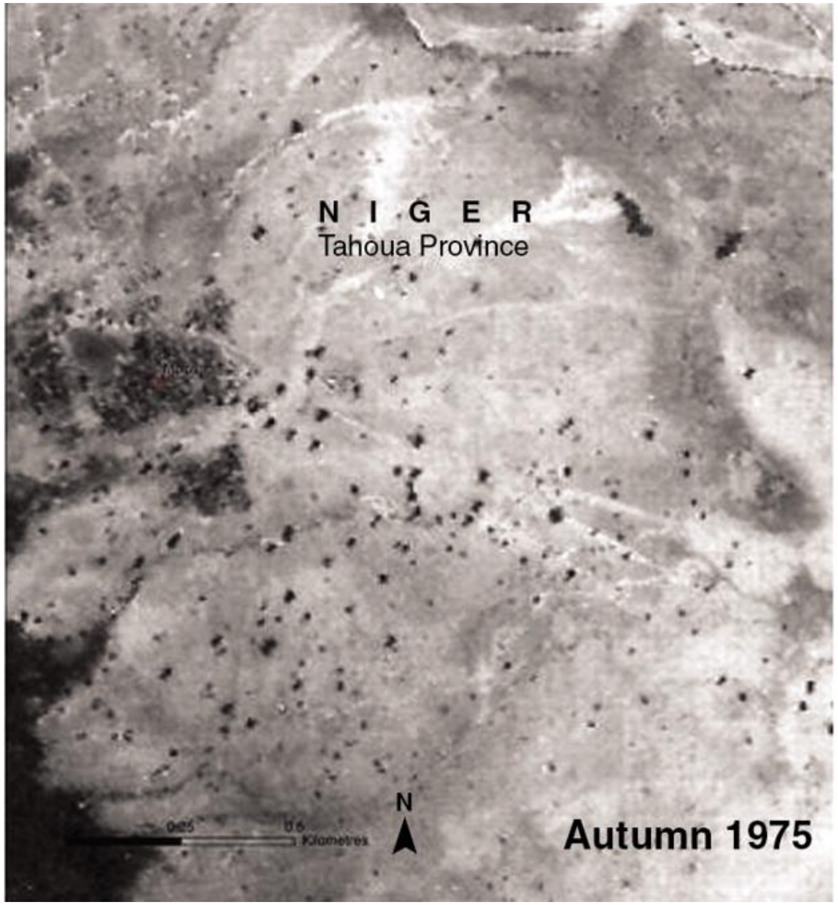
Where yields can be improved on existing agricultural land



Closing the yield gap: improving nutrient and water supplies where yields are lowest could result in a 58% increase in global food production

Urban Agriculture
Agritecture

Sustainable intensification



A major sustainable agriculture project in Niger across 300,000ha involving rehabilitation of degraded land and simple water-harvesting techniques

System of crop intensification

Green Revolution 2

Finger millet, tef, oil seeds, vegetables

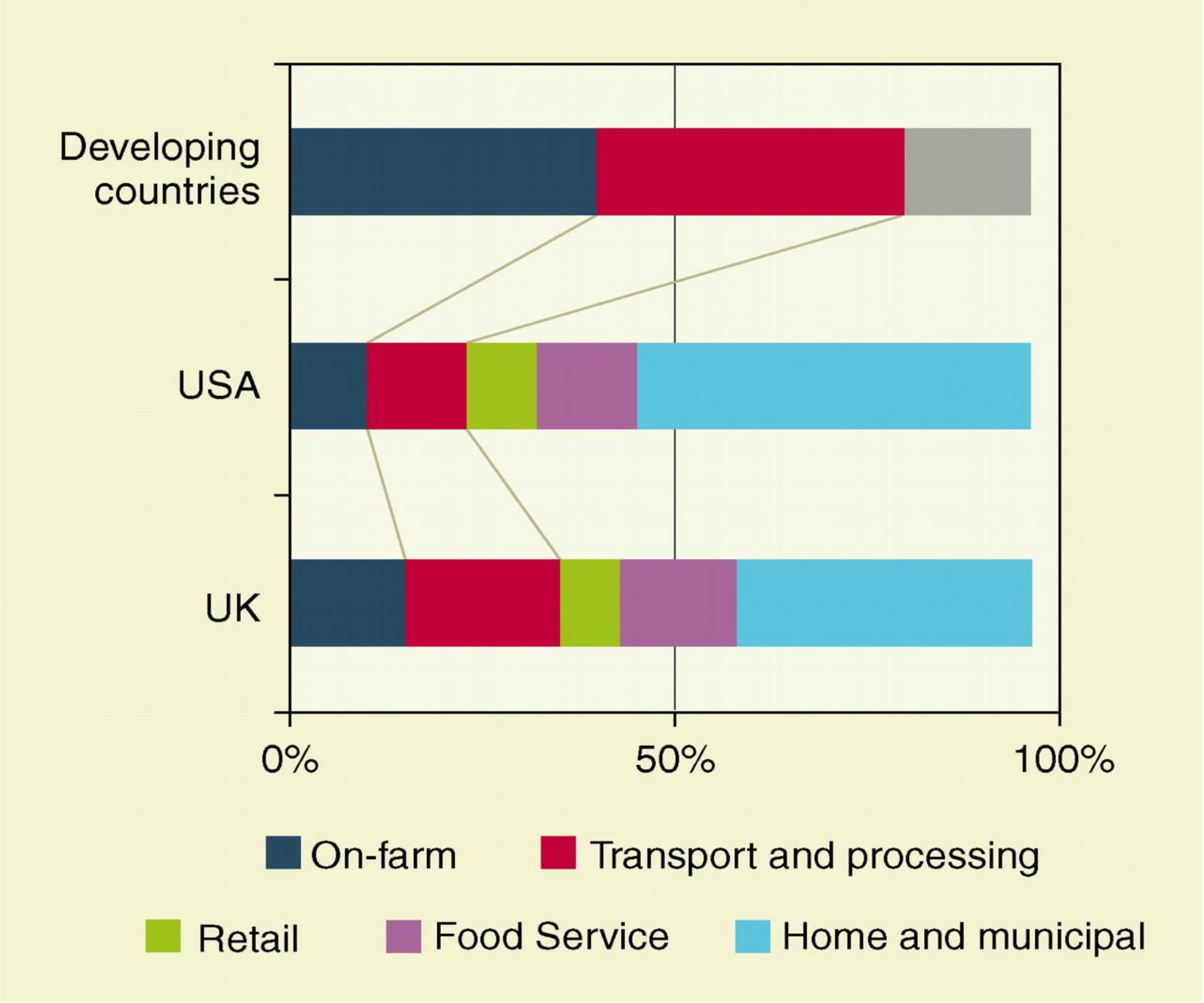
<u>Tef – *Eragrostis tef*</u>
Preferred cereal in Ethiopia, a large food-deficit country

Agronomic research and outreach to increase yields from 1.2 to 2.1 tonnes/ha

Changes in crop management can increase yields 3-fold or more

Abraham et al (2014)

Food waste



Reducing food waste – 30-40% of food is lost to waste

Feeding 9 billion people

Nearly all new food production in the next 25 years will have to come from existing agricultural land

Only 55% of food crop calories directly nourish people – meat, dairy products and eggs from animals raised on plant food, supply another 4%

Reducing food waste – 30-40% of food is lost to waste

Closing the yield gap: improving nutrient and water supplies where yields are lowest could result in a 58% increase in global food production

Increasing production limits

Sustainable intensification = Green Revolution 2

Godfray et al. (2010)

Domesticating New Crops

- Domestication of new crops as a novel way to enhance food security. Few people have tried domesticating wild species from scratch (almost all our crops were domesticated several millennia ago and subsequently further improved), but the technology to do so rapidly is now there.

- Re-visit the origins of existing crops in terms of where, when, how many times and from what progenitors they were first domesticated (this remains incompletely known for many crops still...).

- Identify key domestication genes by comparing existing crop legumes with their progenitors (e.g. non-shattering, 'sweet' seeds, large seeds).

- Quantify bioclimatic niches of wild crop relatives and assess candidate species for domesticating new crops.

- Transform a set of candidate wild species into proto-crops using domestication genes.

- Evaluate proto-crops for food quality and agronomic value

Super-Domestication

- A new era in human understanding of genetics of crop domestication.

- Future advances in crop improvement will come via understanding the genome and its genes.

- This new era of 'super-domestication' uses new ways to enhance yields that go beyond selection from naturally occurring genetic variation, using techniques not available to traditional plant breeders.

- Genome manipulation technologies are providing new ways to overcome barriers to gene exchange and to generate super domesticates with increased yields, resistance to biotic and abiotic stress and new traits for new markets.

- The extent to which plant development can be modified to meet human needs has certainly not reached its limits.

New phase of exponential discovery and innovation

New genes with large beneficial effects

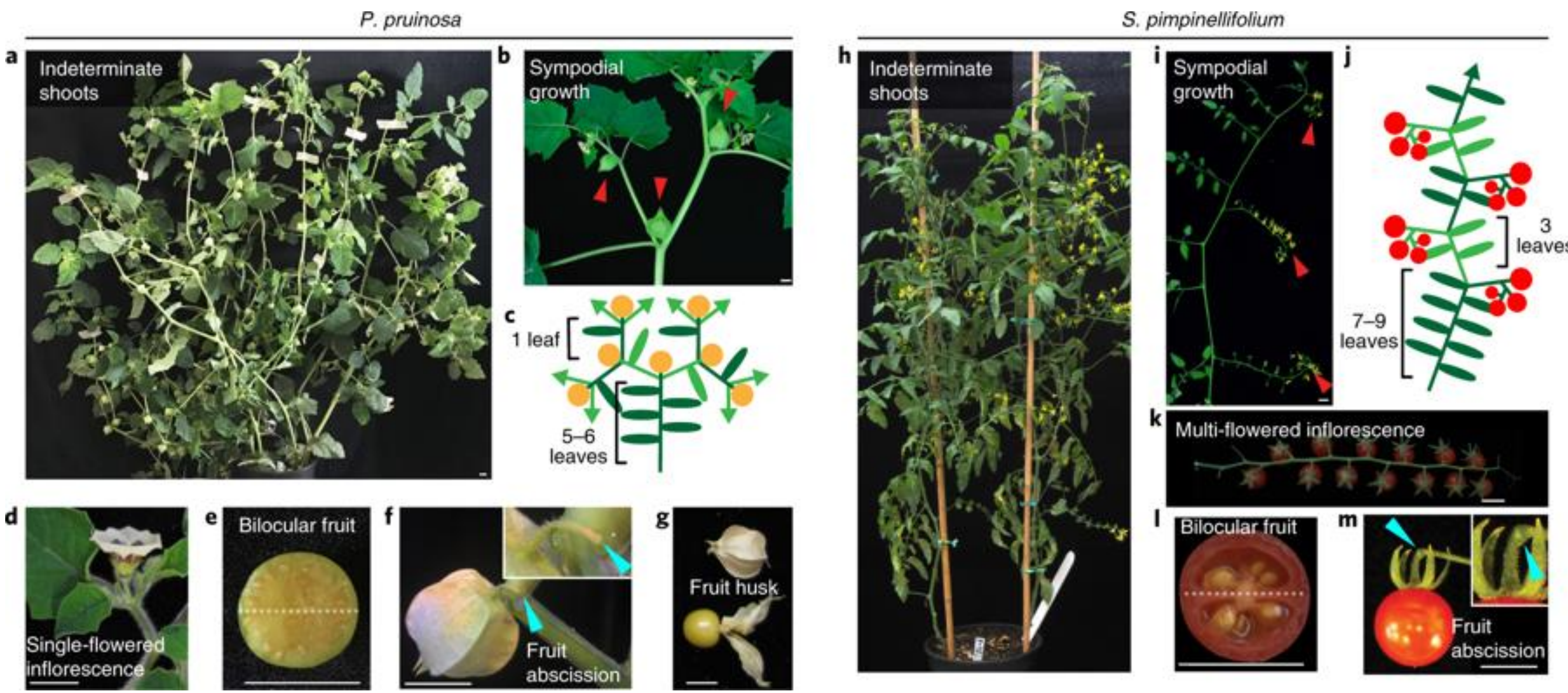
Construction and deployment of complex blocks of useful genes

which can be easily inserted into elite germplasm

New Breeding techniques:
- Genome editing
- Oligonucleotide directed mutagenesis
- Cisgenesis & transgenesis

Rapid improvement of domestication traits in an orphan crop by genome editing

CRISPR gene editing technology



Lemmon et al. (2018)

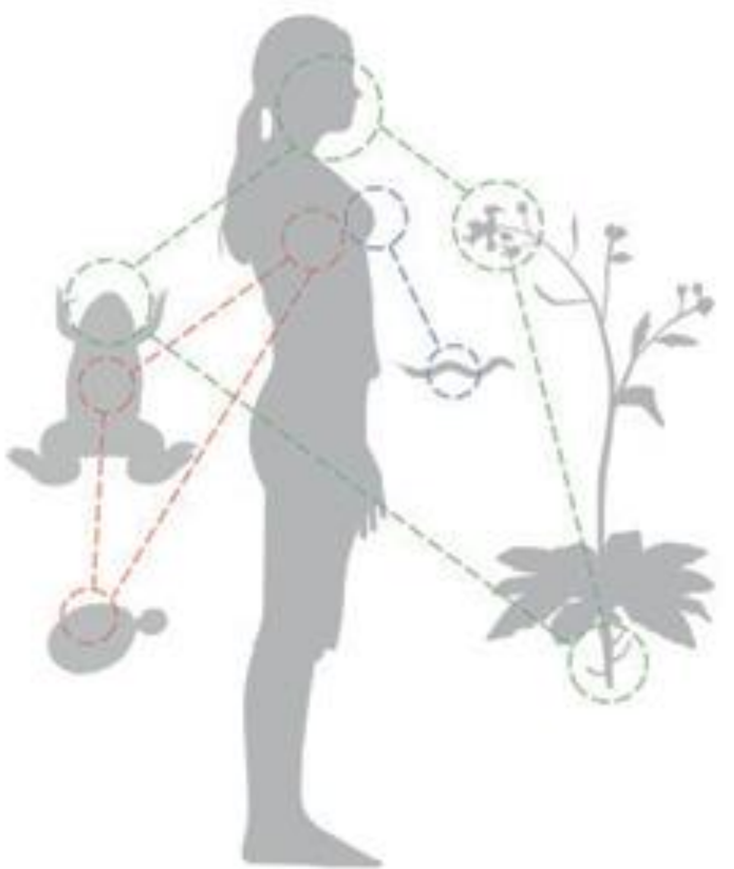
Questions for this week:

What are the benefits and risks associated with genetically modified crops?

Is genetic modification changing the relationship between plants and people in fundamental ways?

What will we be eating in 30 years from now?

Genetically-Modified (GM) Crops



- Herbicide Tolerance – e.g. 'Roundup-Ready' Soya.

- Pest Resistance – e.g. Monsanto's 'Newleaf' Potato – genetically engineered to produce its own insecticide via a gene borrowed from one strain of the common soil bacterium *Bacillus thuringiensis*, or Bt.

- Cold tolerance – e.g. by introducing antifreeze genes from cold water fish into crops such as tobacco and potato.

- Nutritionally-enhanced crops - e.g. 'Golden Rice'

Grafting

The tomatato

Artificial Hybrids

Plum

X

Peach

= Genetic Modification??

Time scale	Target crop trait	Target crop
Current	Herbicide tolerance	Maize, soybean, oilseed rape
	Insect resistance	Maize, cotton, oilseed rape
5-10 yrs	Nutritional biofortification	Staple cereals
	Resistance to fungus and virus pathogens & insects	Potato, wheat, rice, banana, fruits, vegetables
	Improved processing & storage	Wheat, potato, fruits, vegetables
10-20 yrs	Drought tolerance	Staple cereal and tuber crops
	Salinity tolerance	Staple cereal and tuber crops
	Increased nitrogen use efficiency	Staple cereal and tuber crops
>20 yrs	Nitrogen fixation	Staple cereal and tuber crops
	Increased photosynthetic efficiency & C4 photosynthesis	Staple cereal and tuber crops
	Conversion to perennial habit	Staple cereal and tuber crops

Godfray et al. (2010)

•potatoes that that absorb less fat when fried

•maize that can withstand drought

•grass lawns that don’t need to be mowed

•bananas that deliver vaccines

•tomatoes enhanced with fish genes to withstand frost

•wheat, barley and rye ‘on the cob’ using the maize tga1 gene which regulates cob development

•cotton that grows in every colour of the rainbow

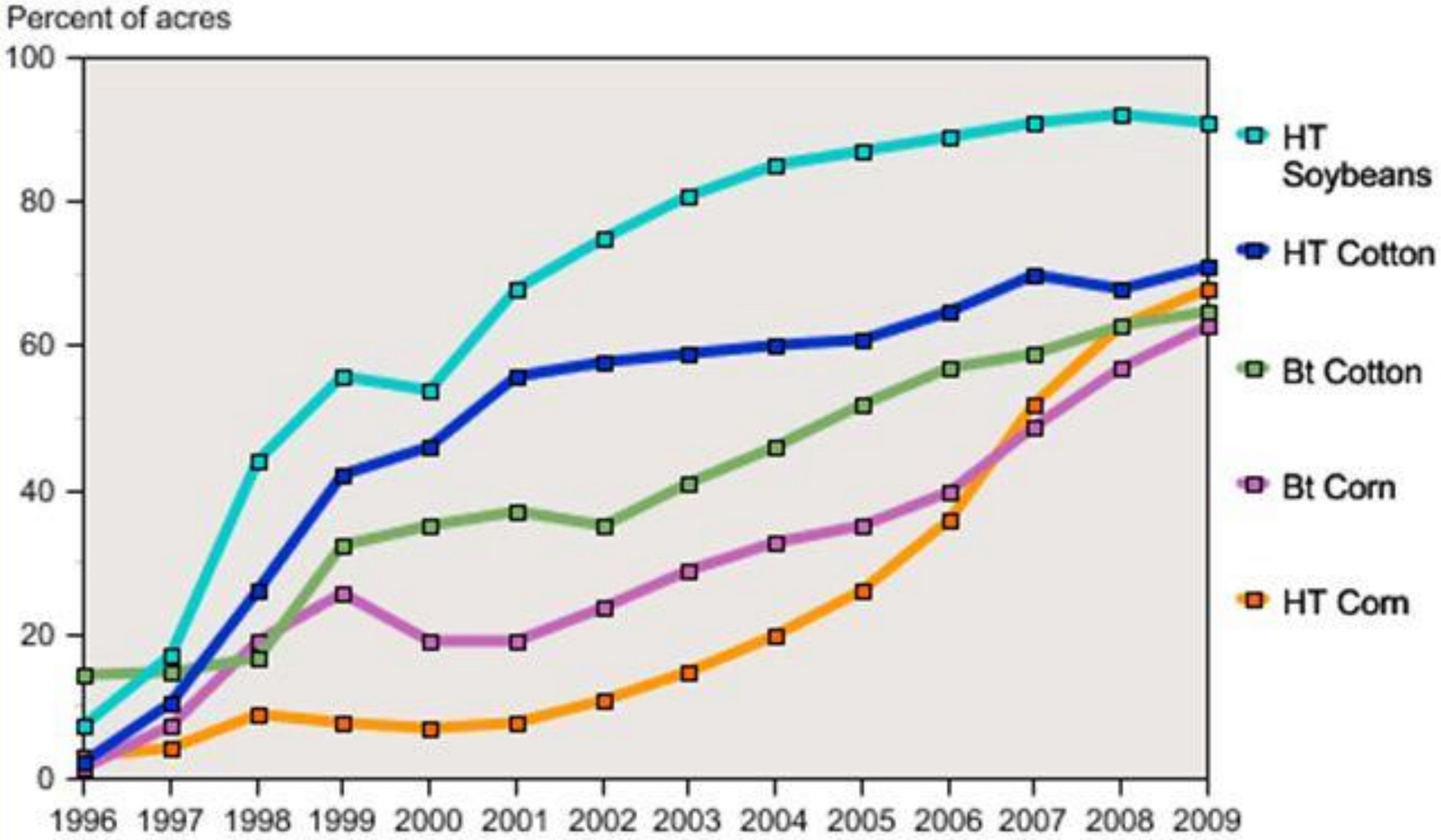
•hay-fever free grass

•a no-tears onion

•caffeine-free coffee plants

•rice with the C4 photosynthetic pathway.

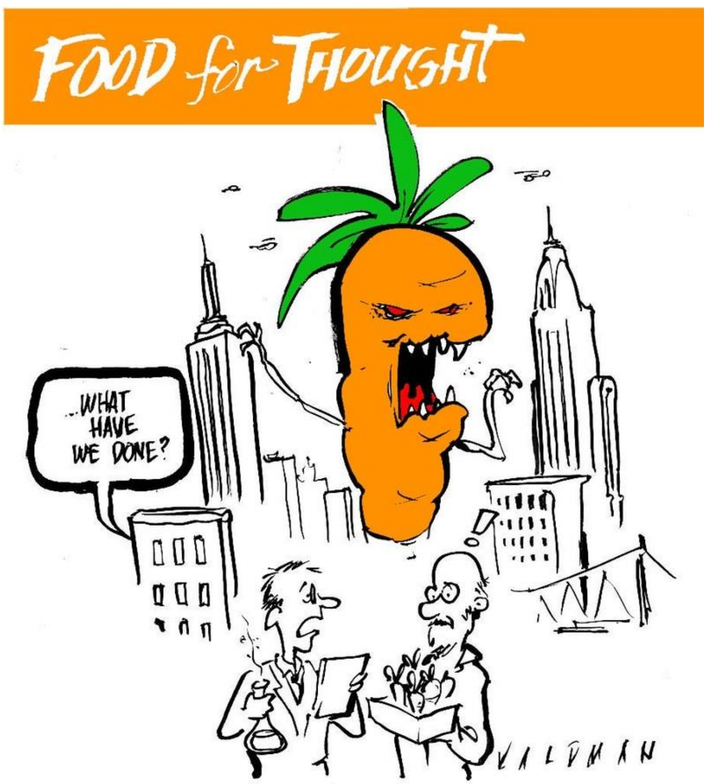
Rapid growth in adoption of genetically engineered crops continues in the U.S.



Data for each crop category include varieties with both HT and Bt (stacked) traits.
Sources: 1996-1999 data are from Fernandez-Cornejo and McBride (2002). Data for 2000-09 are available in tables 1-3.

Frankenstein Food, Jumping Genes & Superweeds

- Environmental hazards
- Human health risks
- Economic concerns



It's perfectly safe

Frankenfood: *noun.* Derogatory term for genetically modified produce. Used by consumers who won't eat food made by a "pharmer," namely a scientist who modifies plants or animals by incorporating altered DNA into their cells.

Environmental hazards

•Unintended harm to other, non-target organisms, e.g. Monarch butterflies and pollen from Bt corn

•Reduced effectiveness of pesticides – i.e. that insects will become resistant to B.t.

•Gene transfer to non-target species, e.g. of herbicide tolerance genes into weeds, that will become 'superweeds'.

•Gene transfer of ecologically relevant traits to traditional crop varieties and land races and other crop wild relatives with potential impacts on the genetic diversity and crop genetic resources, e.g. transgenic constructs – the 35S promoter – used in Yieldguard Bt maize and Roundup-Ready maize GM varieties - was detected in 'criollo' land races in Mexico.

Human health risks

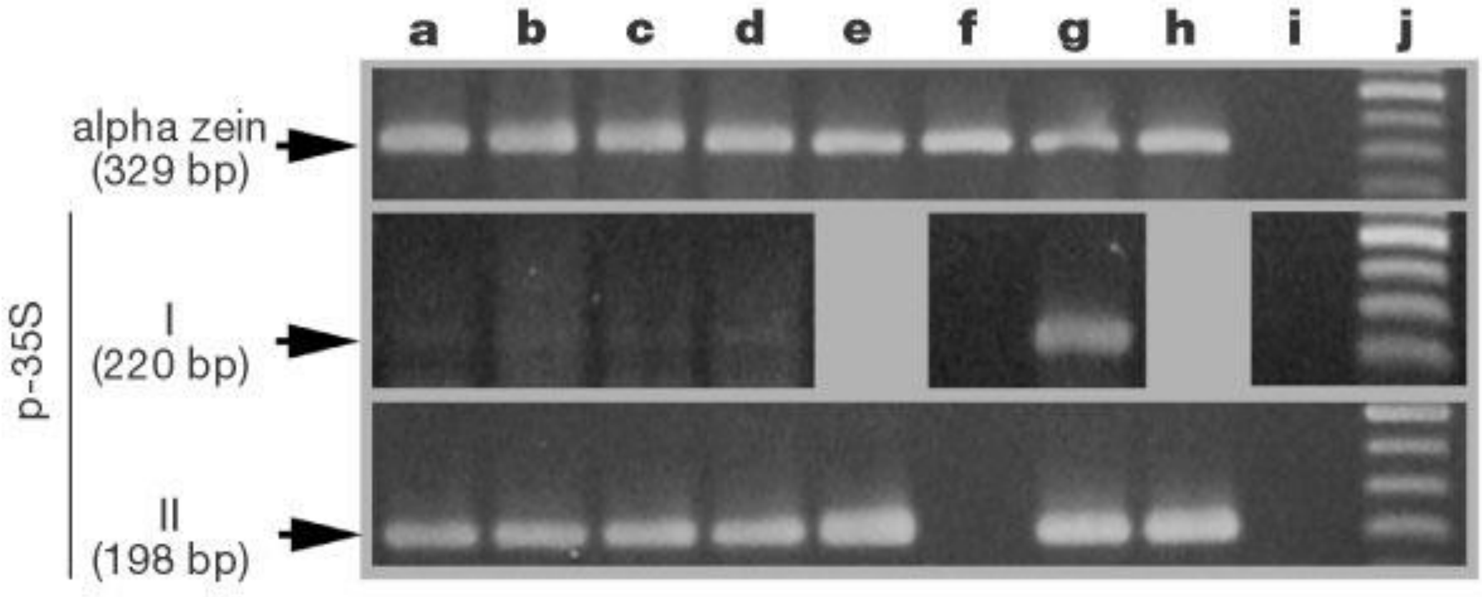
Allergenicity – new allergins.

Frankenstein Foods prompted by controversial studies.

Economic concerns

bringing GM varieties to commercial use is long and costly and Agri-Biotech companies want to protect these investments via patents.

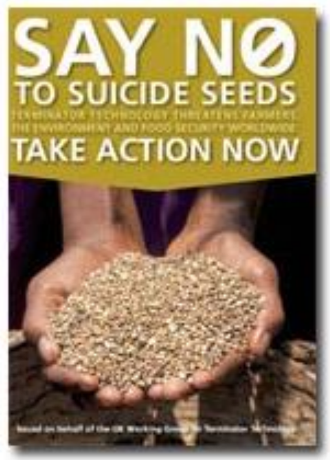
Transgenic DNA introgressed into traditional maize land races in Oaxaca, Mexico

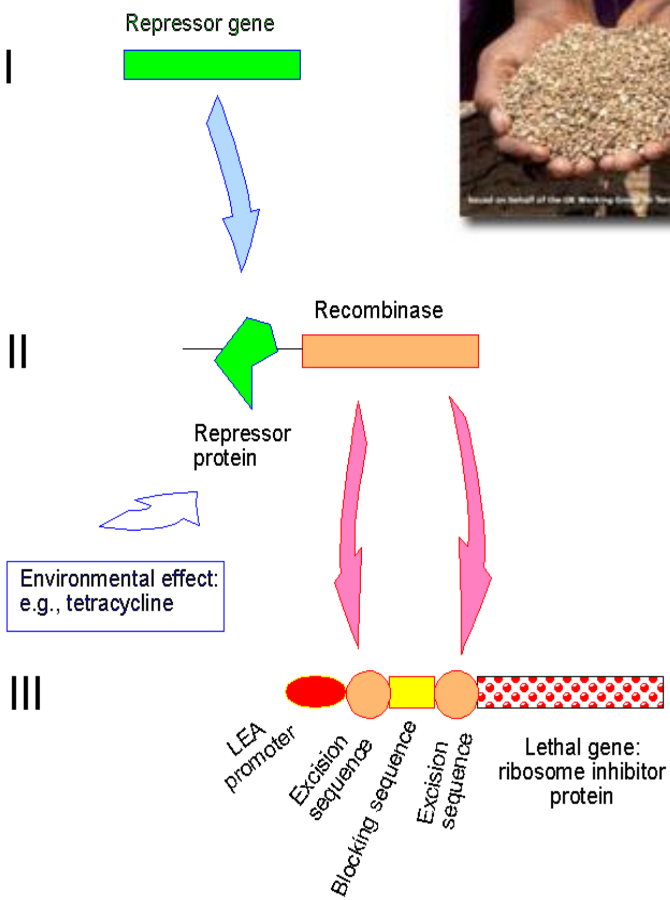


Demonstrated that there have been numerous introgressions of transgenic elements from Yieldguard Bt maize and Roundup-Ready maize GM varieties into 'criollo' land races of maize in the remote mountains of Oaxaca, the centre of origin and diversification of maize. It is thought that this occurred via pollination and that they are probably maintained in land race populations from one generation to the next. The diversity of introgressed DNA in land races is particularly striking given the existence in Mexico, of a moratorium on the planting of transgenic maize since 1998.

Quist & Chapela (2001)

Ownership of Crop Genetic Resources & theTerminator Technology





In March 1998, patent number 5,723,765, describing a novel method for the 'control of plant gene expression' was granted jointly to USDA and a cottonseed company Delta and Pine Land, a radical new genetic technology that causes the seeds that a plant makes to become sterile – hence the terms terminator technology & suicide seeds, designed to ensure that seed can only come from companies. It is only in the last few decades that farmers began to buy their seeds from big companies. Even today 1.4 billion people depend on saved seed for growing food. This has allowed farmers to select strains adapted to local conditions. It is this process that has produced most of our major crops over the millennia. Terminator technology spawned an international barrage of criticism and companies such as Monsanto have given up such approaches, but there are other 'genetic use restriction technologies' that are used to protect crop variety patents.

Rice (again……)

• The world's most important staple food crop

• Feeds >50% of the world's population, 700 million people in Asia alone depend on rice, and > people than any other crop since the time of its domestication

•The world's population is expected to reach 10 billion by 2050.

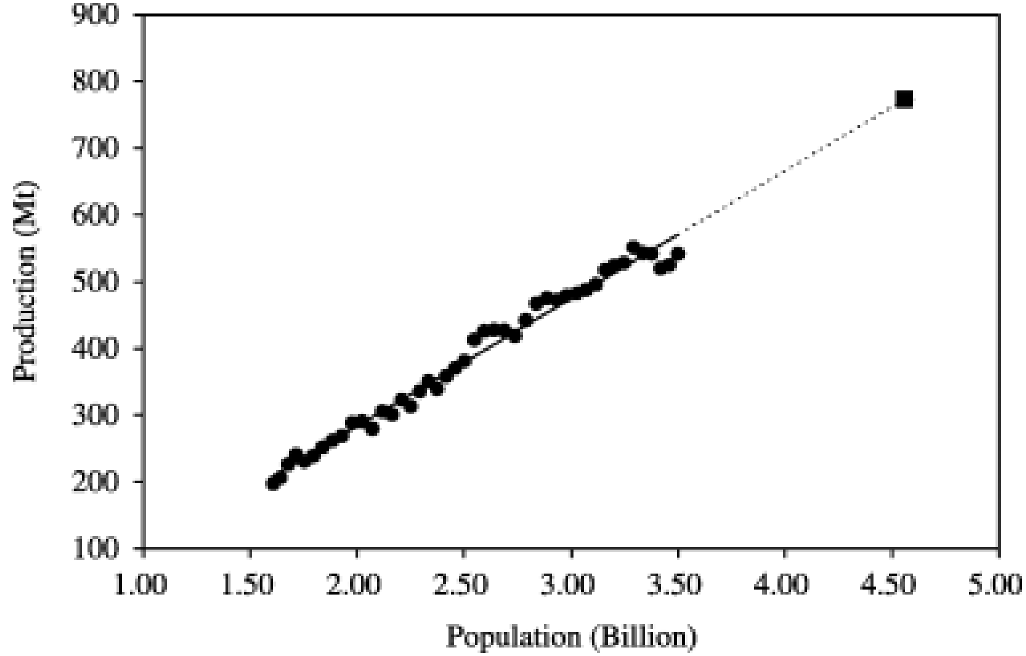
• 20% of all calories consumed by humans

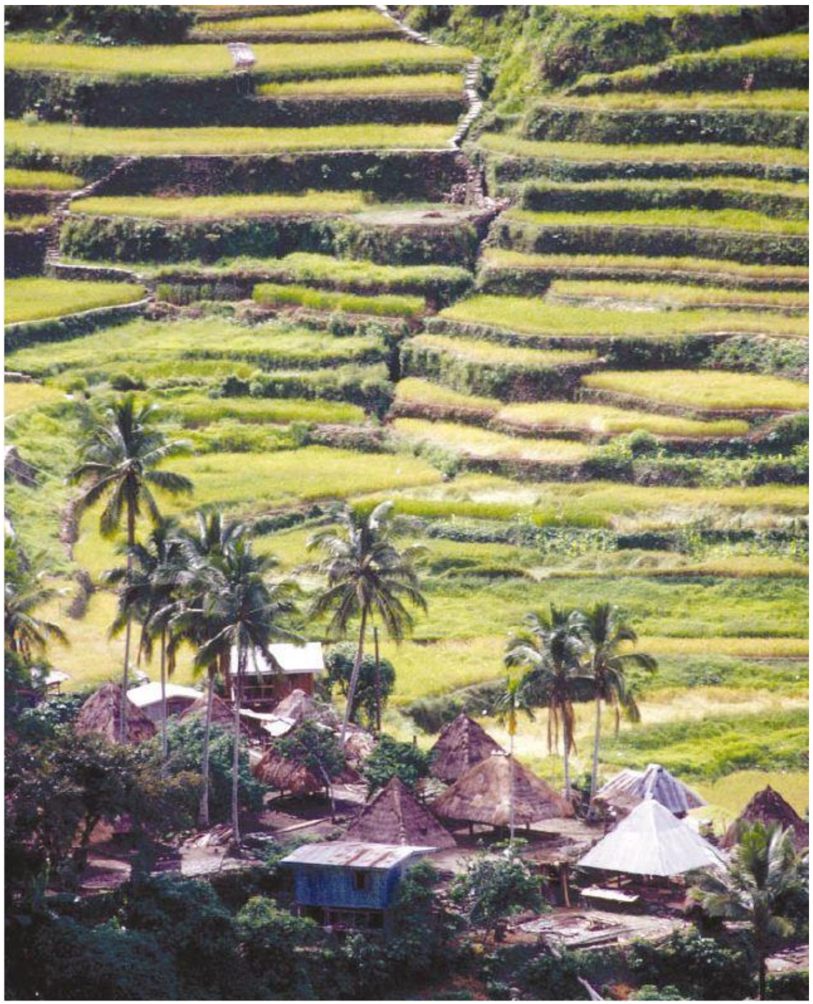
• 408,661 million metric tonnes produced per year

• During the next 40 years, rice production needs to increase by 50%, whilst adapting to adverse changes in climate and water availability

• Rice yields are approaching a theoretical limit set by the crop's efficiency to harvest sunlight and using its energy to make carbohydrates

How to keep on increasing rice production in line with human population growth?



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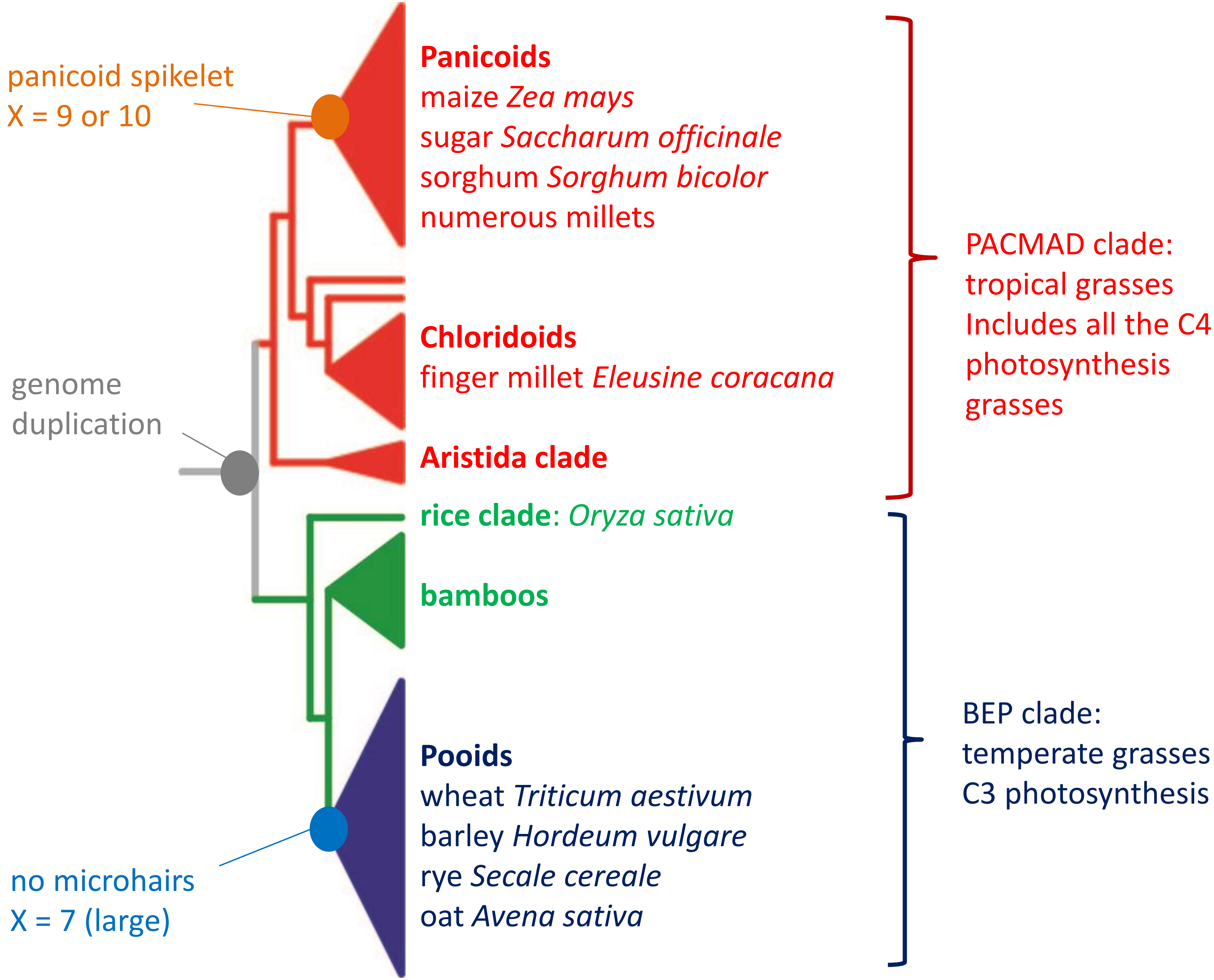
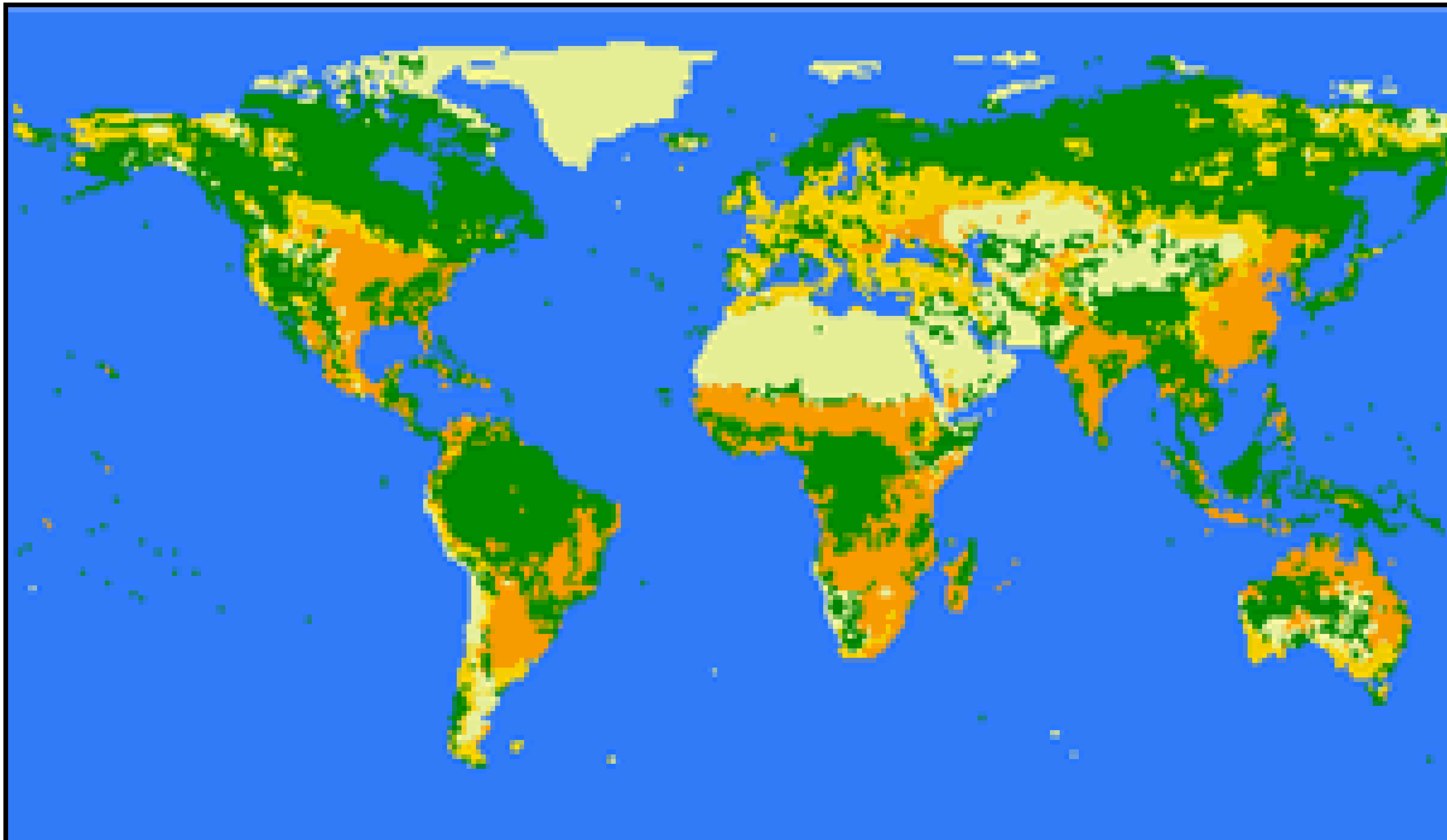
Efficiency of C3 vs C4 Photosynthesis

Attribute and source	Rice (C_3)	Maize (C_4)	C_4 to C_3 advantage
Water (transpiration) use efficiency, WUE; adjusted for relative humidity of the atmosphere (g DW kg^{-1} water) (Loomis & Connor, 1992)	76	144	1.9
Photosynthetic nitrogen use efficiency, PNUE (μmole CO_2 s^{-1} $mmole^{-1}$ N) (Evans & von Caemmerer, 2000)	0.26	0.74	2.8
Radiation (PAR) use efficiency, RUE (g DW MJ^{-1} intercepted PAR) (Kiniry *et al.*, 1989)	2.2	3.3	1.5

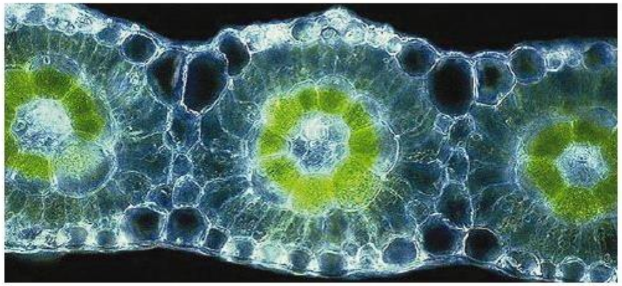

panicoid spikelet
X = 9 or 10
genome
duplication
no microhairs
X = 7 (large)
Panicoids
maize Zea mays
sugar Saccharum officinale
sorghum Sorghum bicolor
numerous millets
Chloridoids
finger millet Eleusine coracana
Aristida clade
rice clade: Oryza sativa
bamboos
Pooids
wheat Triticum aestivum
barley Hordeum vulgare
rye Secale cereale
oat Avena sativa
PACMAD clade:
tropical grasses
Includes all the C4
photosynthesis
grasses
BEP clade:
temperate grasses
C3 photosynthesis

C4 distribution

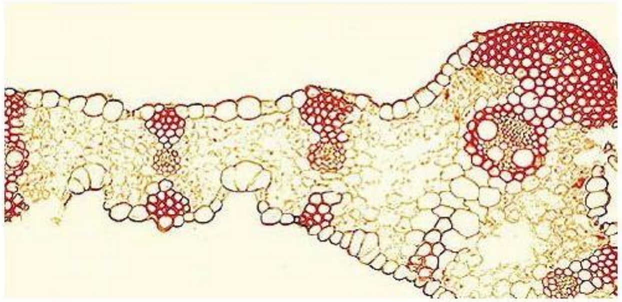


C4 Photosynthesis

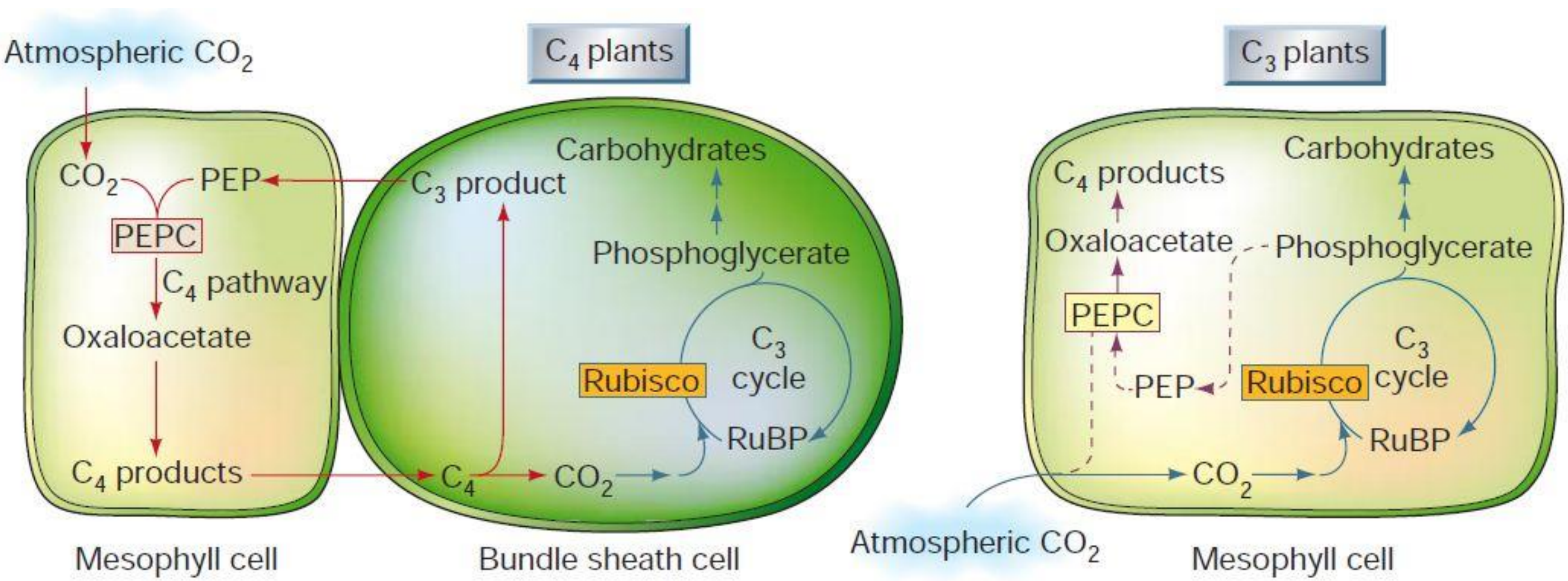
Series of anatomical (Kranz anatomy) and biochemical modifications that have exploited the PEPc enzyme to concentrate CO_2 around the carboxylating enzyme Rubisco, thereby increasing photosynthetic efficiency



C4

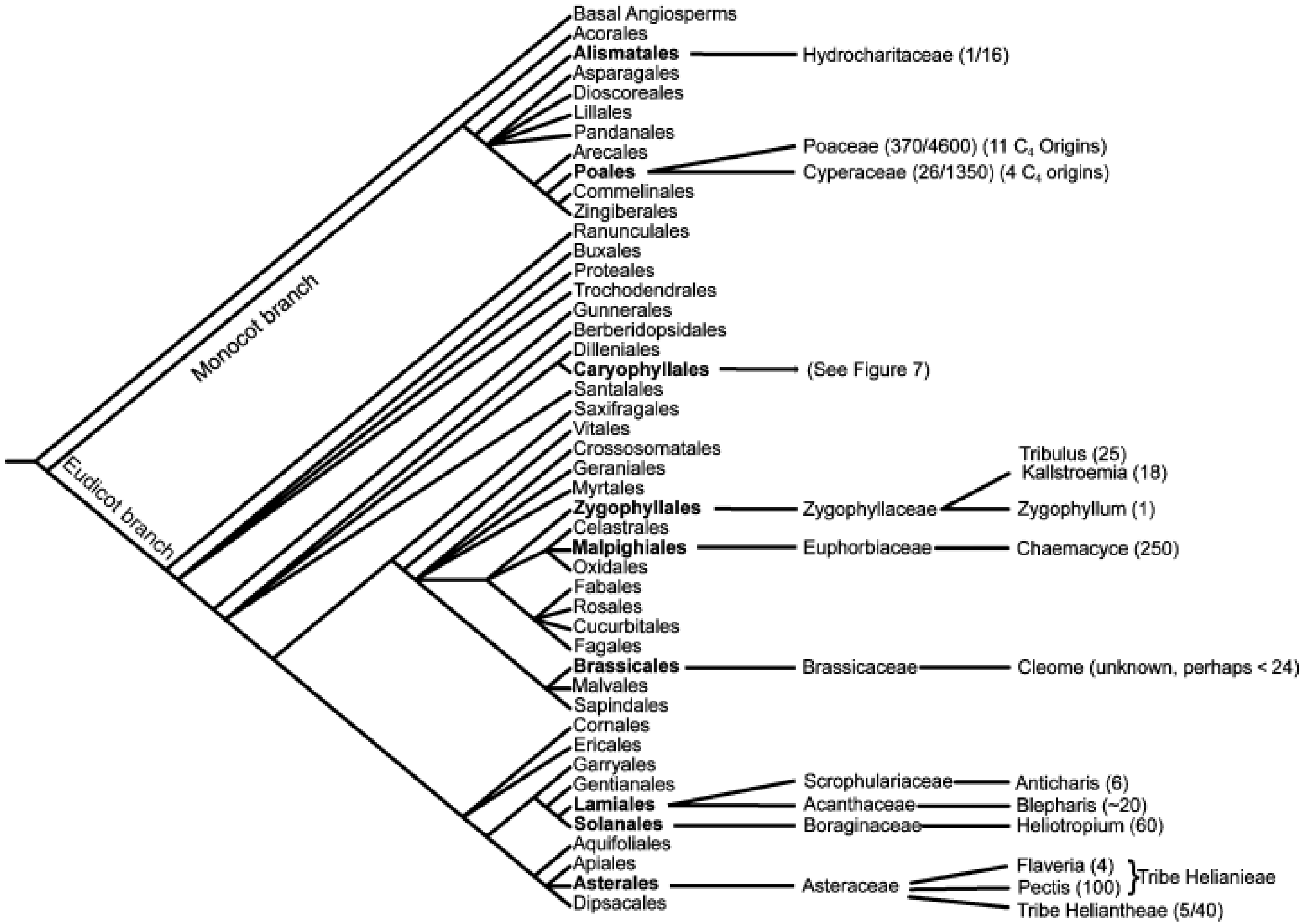


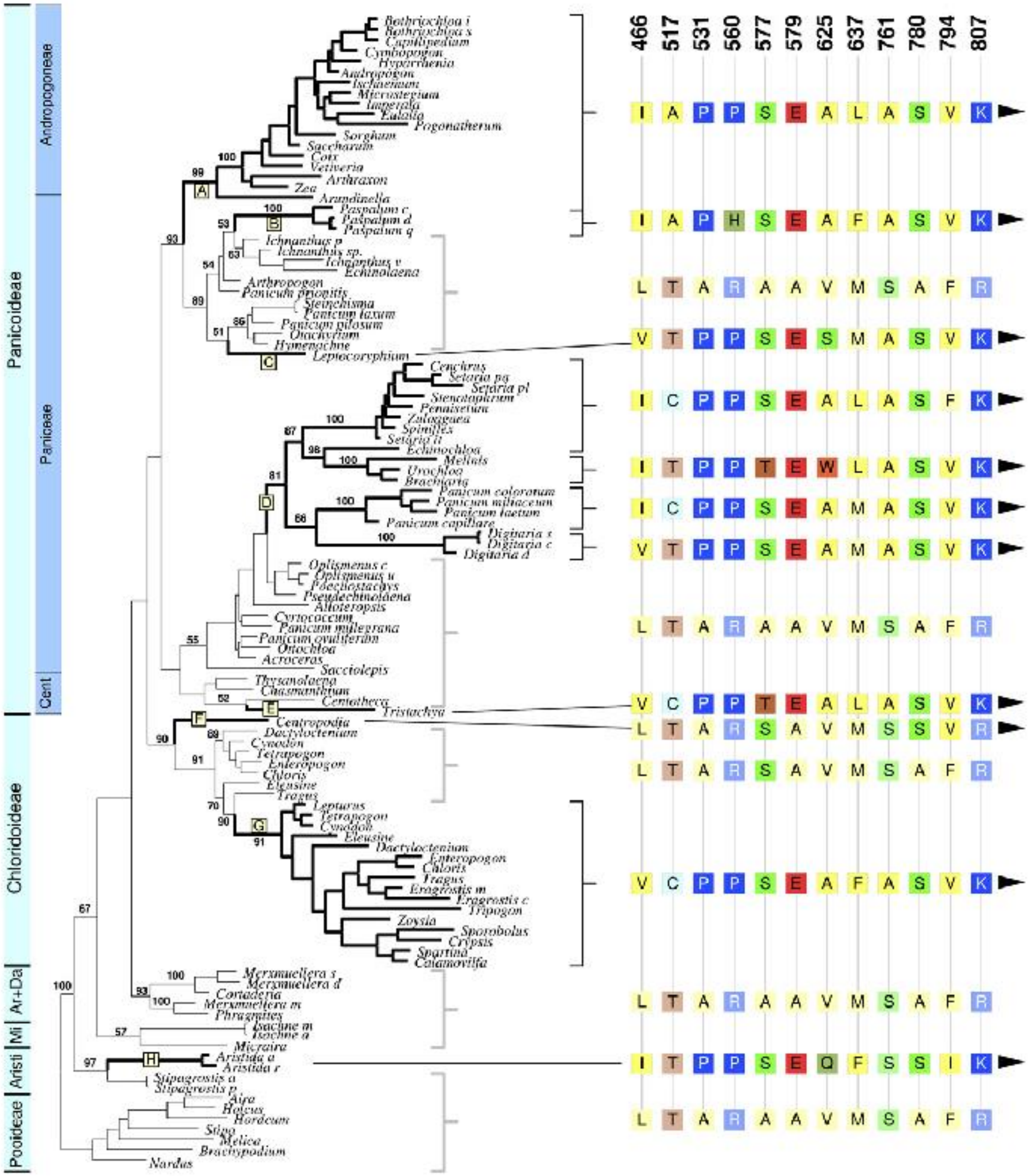
C3



Supercharged: two-stage C_4 photosynthesis is more efficient than the C_3 version found in most plants.

Phylogenetic distribution of C_4: Convergent evolution at least 45 times independently





Evolution of C4 photosynthesis in grasses

- Genetic basis of:

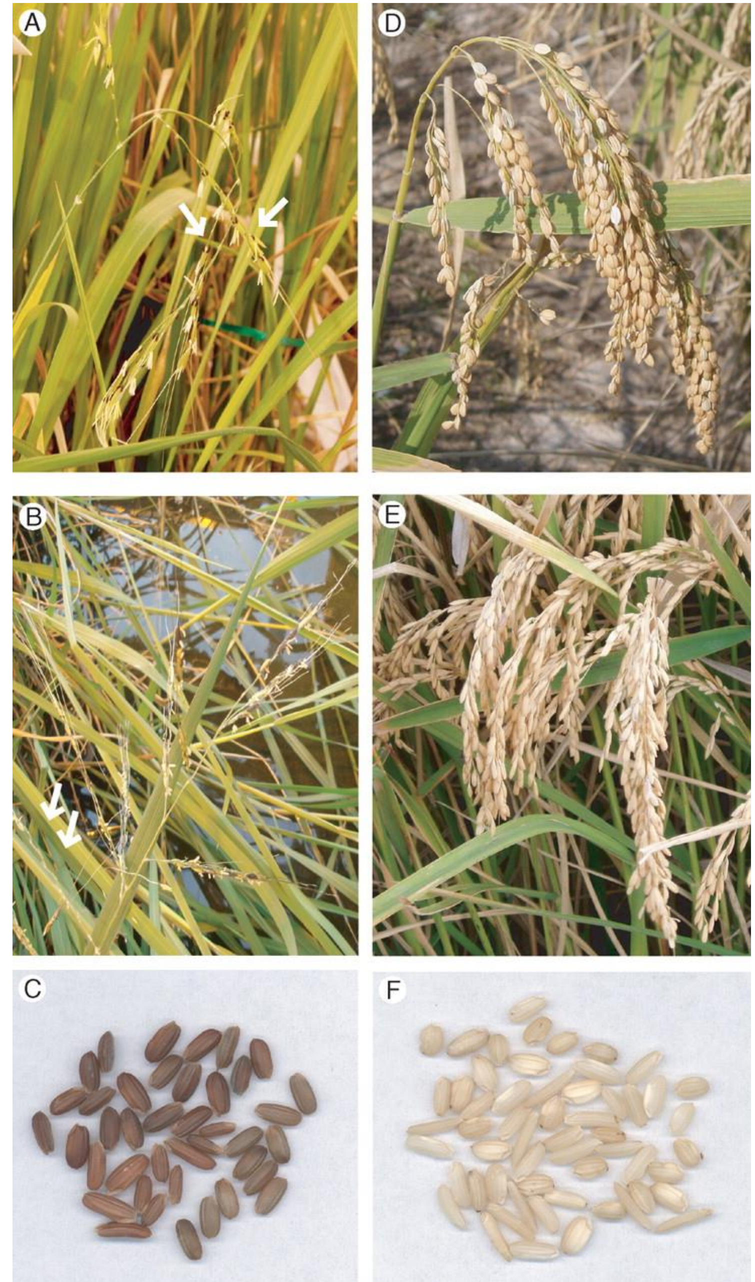
- Convergence
- Parallelism
- Homoplasy

Rice: changes during domestication

- Perennial to annual
- Shattering to non-shattering seeds, critical for effective harvesting, and the hallmark of domestication
- Disparate to synchronized seed maturation
- Awns to lack of awns
- Prostrate habit to erect habit providing improved plant architecture and increased yields
- Many to fewer tillers
- Low yield to high yield
- Seed dormancy to reduced seed dormancy

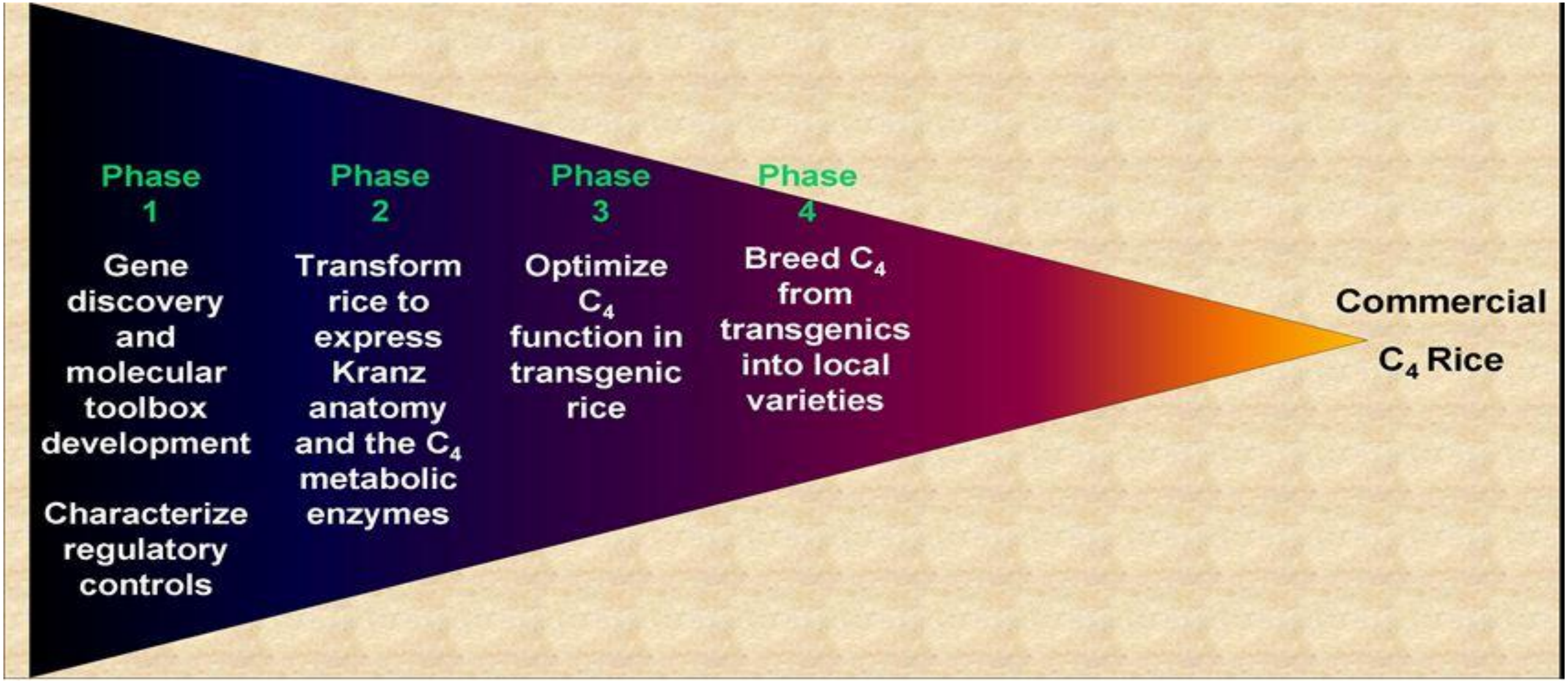
a

b



International Rice Research Institute, Philippines

Bill Gates Foundation



Feeding the Future – the C4 Rice Project

C4 photosynthesis pathway can increase efficiency by 50%

Highly ambitious – involves changes to both leaf anatomy and biochemical pathways

Nitrogen Fixation

Symbiotic association of N-fixing bacteria Rhizobium through formation of root nodules – another 'big' complex trait.

N_2 constitutes 80% of the atmosphere providing a virtually unlimited supply yet very few plants, and no animals can assimilate nitrogen in its free form.

Synthetic nitrogen fertilisers used in agriculture have high economic, energy and environmental costs.

Signalling pathways between bacteria and hosts well characterized

Nitrogen-fixing grasses?

Greener revolutions for all

Richard B Flavell

To ensure global food security for all, the adoption of crop improvement technologies is no longer just an option—it is an imperative.

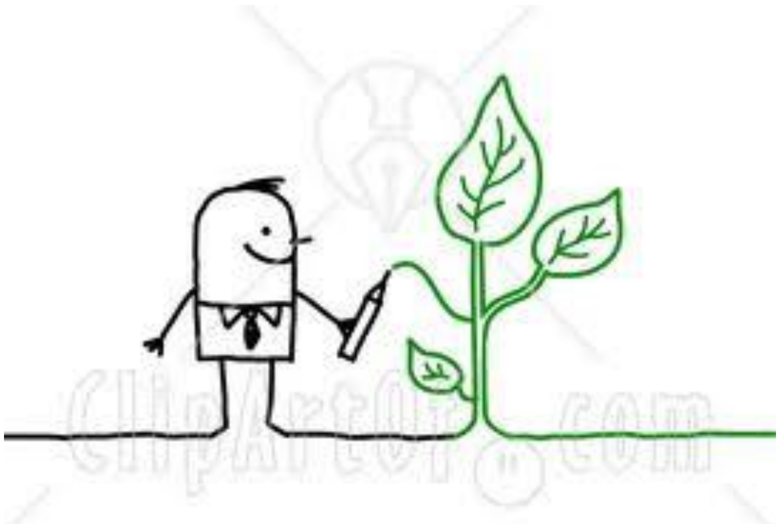
Debate should not be about GMOs vs organic

It should be about inclusive planning to understand how innovative technologies can be safely deployed

To enable enough food to be available to all

A New Green Revolution?

A New Era in the Relationship between Plants & People?

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