Biotechnology in a Changing Climate: Just another technological fix!?

“There will be climate change losers and there will be climate change winners.”

Martina Newell-McGloughlin
Director, International Biotechnology
Adj Professor UC Davis
RNRF October, 2014
"We have recently advanced our knowledge of genetics to the point where we can manipulate life in a way never intended by nature.

We must proceed with the utmost caution in the application of this new found knowledge."

Luther Burbank

1906
Myth: Agricultural technology is new

8,000 BC
19th C
Ea 20th C
Md 20th C
1930s
1940s
1950s
1970s
1980
1990s
21st CC

- Cultivation
- Selective cross breeding
- Cell culture
- Somaclonal variation
- Embryo rescue
- Mutagenesis and selection
- Anther culture
- Recombinant DNA
- Marker assisted selection
- ---omics - Bioinformatics
- Novel Breeding
- RNAi/ GEENs/ Epigenetics
- Network engineering
- Synthetic biology
- Systems biology
Why do we need Biotechnology

Greatest grand challenge of our time!
Population of 9 billion by 2050! 70-100% more food required.

- Need: Affordable, high yielding, high quality food, feed, fuel, fiber, sustainably produced
- Challenges: Changing climate, diminishing resources – degraded land, less water, less fuel, less fertilizer, less pesticides
- Sustainable intensification
Production must double over the next 25 years to feed all these people. "Physiological" optimum using traditional breeding already maximized for many crops.
The Future: Smart Plants Smart Environments

- Smart plants: Systems biology reductive and holistic approaches to identify, modify, introgress and subsequently simultaneously introduce / study / modify/ the expression/interaction of genes and the realtime response of plants to their environment
Projected Impacts of Climate Change

Global temperature change (relative to pre-industrial)

- **0°C**: Possible rising yields in some high latitude regions
- **1°C**: Small mountain glaciers disappear
  - Water supplies threaten in several areas
- **2°C**: Significant decreases in water availability
  - in many areas, including Mediterranean and Southern Africa
- **3°C**: Sea level rise threatens major cities
- **4°C**: Rising number of species face extinction
- **5°C**: Increasing risk of dangerous feedbacks and abrupt, large scale in the climate system

**Source**: Stern Review on the Economics of Climate 2006
Agriculture is a major source of greenhouse gas emissions. Practices - deforestation, cattle feedlots and fertilizer use - currently account for about 25% of greenhouse gas emissions.

Agriculture accounts for 14% of CO$_2$ emission. Agriculture is also a major source of methane (CH$_4$) and nitrous oxide (N$_2$O), with estimates showing that it accounts for 48% of methane emissions and 52% of N$_2$O emissions.
Given the impacts of climate change on agricultural productivity and the part played by agriculture practices in global warming, agricultural techniques must play a substantial part in the fight against climate change. Green biotechnology offers a “toolbox” which can help farmers limiting greenhouse gas emissions as well as adapting their agricultural techniques to shifting climates.

The three major contributions of green biotechnology to the mitigation of the impact of climate change are:

1. Greenhouse gas reduction

2. Crop adaptation (Environmental stress, changing niches)

3. Protection and increase yield in less desirable and marginal soils
Possible benefits and drawbacks of climate change on agriculture, based on an illustration in *Scientific American*. 
Opportunities/challenges for biotech crops

- **Agronomic Traits**
  - Biotic stress: Pests/disease/weeds/
  - Abiotic stress: Drought, heat, salinity, submergence, marginal soils
  - Yield: Nutrient efficiency, fossil genes

- **Quality Traits**
  - Improved post harvest characteristics – Shelf life, processing, taste – waste reduction
  - Improved nutrition – Improved functionality

- **Renewable Resources**
  - Biomass conversion, feedstocks, biofuels, phytoremediation concerns land/water use

- **Plants as Factories**
  - Pharmaceuticals/industrial products
Myth: Biotech only helps “big industrial ag”

- Biotech Crops 2013: **430 million acres**, up 7 million - 3% growth
- 27 countries (19 emerging economies) 18 M farmers 90% (16.5M) resource-poor
- US 70.1Mhas (173Mac), ~90% principal biotech crops
- BT corn. HT Soybean  BT Cotton (27% stacked traits world wide)
Relevant Benefits to date

- $177 million increase in farm productivity
  - 60% reduced costs; 40% increase in yield (377 million tons)
- 1 Billion lb reduction in pesticide active ingredient
- Saved 123 million hectares 1996-2012
- Conservation tillage
  - 93% reduction in erosion
  - 1 billion tons of top soil preserved
  - 70% reduction in herbicide run-off
  - 80% reduction in phosphorus in water
  - >50% reduction in fuel use
  - 59 billion lbs reduction in CO$_2$ emissions
  - ~11.8 million cars off the road
    - (Brookes and Barefoot (2014))
- BT corn 90% reduction in mycotoxin
- Phytase maize (China) decreased pollution
Climate change poses a real challenge in terms of available agricultural land and fresh water use.

Solutions must be developed to adapt crops to new conditions, such as marginal soils or harsher conditions such as cold, heat, drought, salinity, submergence.

The agricultural sector uses a huge amount of available fresh water - 70% of the water currently consumed by humans is used in agriculture, and this is likely to increase as temperatures rise.

24.7 million acres of farmland worldwide lost each year due to salinity caused by irrigation. Crops limited by salinity on 40% world's irrigated land (25% US)

In a warmer climate, plants will react to stresses, such as drought, by consuming large quantities of energy which is normally used for growth and seed production.
Abiotic stresses are the primary cause of crop-plants yield losses worldwide.

Decreased land precipitation and increased temperatures are contributing to more regions experiencing drought and heat waves affecting crops.
Abiotic stresses are the primary cause of crop-plants yield losses worldwide.

Global context

Global Drought Total Economic Loss Risk Distribution
“Agriculture in drought”

U.S. Drought Monitor

October 14, 2014
(Released Thursday, Oct. 16, 2014)
Valid 8 a.m. EDT

Drought Impact Types:
- Delineates dominant impacts
- S = Short-Term, typically less than 6 months (e.g., agriculture, grasslands)
- L = Long-Term, typically greater than 6 months (e.g., hydrology, ecology)

Intensity:
- D0 Abnormally Dry
- D1 Moderate Drought
- D2 Severe Drought
- D3 Extreme Drought
- D4 Exceptional Drought

The Drought Monitor focuses on broad-scale conditions. Local conditions may vary. See accompanying text summary for forecast statements.

Author:
Mark Skaboda
National Drought Mitigation Center

http://droughtmonitor.unl.edu/
Numerous genes related to plant response to abiotic stress have been identified and characterized but most efforts to transform genes to crops have failed under field conditions. Reguera et al. 2011

Stresses occurring simultaneously are a common situation for crops that results in a complex system to cope with. More emphasis should be given to study abiotic-stress tolerant crops under field conditions focusing on reproductive stage.
Abiotic stress limiting factor for crops reaching genetic potential

- Improved water conservation —
- Fewer crop losses —
- Higher yields on all acres through improved water utilization —
- Expand in drylands
- BASF Drought-tolerant corn 12 bushels more an acre

Abiotic Stress: Drought, Cold, Heat, Salinity

- Improved water conservation —
- Fewer crop losses —
- Higher yields on all acres through improved water utilization —
- Expand in drylands
- BASF Drought-tolerant corn 12 bushels more an acre

Secondary stresses (Osmotic stress, Oxidative stress)

Disruption of osmotic and ionic homeostasis and damage to structural/functional proteins

Stress Signal Sensors
Kinases, Secondary Messengers

Transcription Factors
AP2/EREBP, Myc, Myb, NAC, bZIP, HB, HSF etc

Stress Gene Activation
Abiotic stress limiting factor for crops reaching genetic potential

- WEM decreased yield loss under drought conditions
- 30% yield advantage compared to conventional hybrids under drought conditions
- Transcription factor (Tf) DREB2A water-stress-responsive /heat-stress-responsive
- Nuclear Factor Y B subunit
- Homeodomain-leucine zipper (HD-Zip) transcription factors respond to H$_2$O & osmotic stress, exogenous abscisic acid
Engineering abiotic stress tolerance

- **Genes associated with osmoregulation.**
  Accumulation of Glycinebetaine, polyamines, proline, trehalose,....

- **Detoxification of reactive oxygen species (ROS).**
  Increasing antioxidant capacity by expressing antioxidant enzymes (i.e. SOD, CAT, APX..)

- **Manipulation of the expression of chaperones, heat-shock (HSP) proteins and late embryogenesis abundant (LEA) proteins.**
  ROB5, a stress inducible gene isolated from bromegrass that encodes for a heat stable LEA group 3-like protein express in potato conferred heat stress (Molecular Breeding, 2010, 25(3) pp 527-540)
Engineering abiotic stress tolerance

- Regulation of water and ion homeostasis

  Silencing or overexpression of aquaporins, uniporters, ion channels or antiporters (i.e. NHXs) ...

- Manipulation of regulatory genes (Transcription Factors, TFs).

  Several families of TFs are involved in the regulation of stress responsive genes (ERF/AP2, bZIP, MYB, MADSbox,...)

- Modifications of hormone homeostasis

  Phytohormones regulate every aspect of plant growth, development and plant responses to environmental changes.

Drought stress accelerate senescence of plants, modifying sink/source relationships

Hormones are key regulators of source/sink relationships

Environmental factors (abiotic stress)

- Brassinosteroids
- Gibberellins
- Abscisic Acid
- Jasmonic acid
- Salicylic acid
- Cytokinin
- Nitric oxide
- Auxins
- Ethylene
It is possible to enhance the tolerance of plants to abiotic stress by delaying stress-induced senescence, increasing source fitness and improving source/sink relationships.
**Nicotiana tabacum** as a model plant

Wild-type and transgenic plants expressing Isopentenyltransferase (IPT) under the control of SARK promoter after 15 days Drought followed by 7 days Re-watering.
-Expression of *IPT* during drought alters **hormone homeostasis** and improves **source/sink relationships**.

-Induction of **CK** results in higher leaf starch and sucrose contents, and an **inhibition of sucrose degradation** that prevents the increase of glucose and fructose contents.

-Metabolite, enzyme and transcriptomic profiling revealed a **delay in stress associated degradation processes**, including **protein stability and chloroplast function**.

-The cytokinin dependent **coordination of C and N metabolism** ensured an adequate supply of energy, reducing power and organic compounds that ultimately **enhanced survival of** *P_{SARK::IPT}* plants under water stress.
Regulated Expression of an Isopentenyltransferase Gene (IPT) in Peanut Significantly Improves Drought Tolerance and Increases Yield Under Field Conditions

Wild-type and transgenic peanut plants in the field and phenotype of pods from these peanut plants.

Overall, the specific inhibition of either GA, BR or Auxins, negatively affected GY and plant biomass while the inhibition of ABA or Ethylene resulted in the improvement of GY and plant Biomass though the strengthening of source fitness in rice.

These results will help identifying hormone related pathways that can be manipulated to improve rice productivity.
Drought Tolerant Oilseed Rape engineered to reduce the levels PARP [poly(ADP-ribose) polymerase], a key stress-related protein in plants. Relative yield increases of up to +44% compared to non-drought tolerant varieties.


Pioneer Hi-Bred International is developing hybrids and varieties that use water sources more efficiently and therefore perform better during water deficits.

Maintaining yields during water stress will help preserve grower incomes and yield more grain for the food and energy value chain as well as reducing the need for irrigation.
Climate change can prevent crops from reaching their potential

- Submergence sub -1 gene produces 6X grain - save 3 million tons rice

- Arabidopsis antiporter gene used to create plants that can grow and yield fruit in irrigation water that is more than 50 times saltier than normal (1/3 as salty as sea water).

- Cold: Engineering with COR15a Tf, role in freezing tolerance.

- Plants engineered with Choline oxidase (codA) tolerated saline and cold
Nutrient access implications

- Arcadia has produced plants with increased Nitrogen Use Efficiency (NUE). These plants yield the same as conventional plants, but use 30% less nitrogen and are licensed to China.

- Phosphite rather than phosphate also control weeds

- Plant Microbiome- Engineering plants for natural Nitrogen fixation
**Biological Nitrogen Fixation** – bacteria harness the sun

\[ \text{N}_2 + 8\text{H}^+ + 8\text{e}^- + 16 \text{ATP} \rightarrow 2\text{NH}_3 + \text{H}_2 + 16 \text{ADP} + 16 \text{Pi} \]

**N\textsubscript{2} Fixation an energy “expensive” reaction**

N\textsubscript{2} and Plant-associated bacteria in a novel glycan

**Hypothesis:** indigenous landraces of corn grown in isolated regions of Mexico co-evolved diazotrophic microbiomes that contribute to plant performance due to nitrogen deficiency in the soil.
Biotic Stresses also changing in response to Climate change

- Potato Late Blight – 75% crop loss
  - 2 genes from wild potato - Less spray, less loss = $4.3 billion potential savings
- Hawaiian Papaya
  - Biotechnology saved the industry in Hawaii No natural resistance so traditional breeding will not work Removes viral reservoir thus protects all growers
- Apple
  - Fireblight: Peptide alternative to antibiotic sprays
  - Applescab: Chitinase alternative to fungicides
- Citrus Greening
  - No natural resistance so traditional breeding will not work – biotech the only solution
- Grapes - Pierce's disease
  - Fusion of two genes innate immunity and membrane lysis - Preferable to spraying malathion
Myth: Biotech crops are not regulated

- Most thoroughly regulated of any process in crop breeding – USDA (APHIS), EPA, FDA
  - Commercialization: 7 to 10 years, at least 9 stages
- Biotech crops and foods more thoroughly tested than conventional varieties which have “GRAS” status
- >150 livestock feeding studies
- Substantially equivalent to parent in composition, nutritional content, allergenicity potential, protein digestibility, anti-nutritional effects, toxicity studies
  - Highly sensitive profiling technology shows GM crop more like parent than ANY other breeding technique
- International consensus: OECD, CBD, CODEX
Potential Relative Risks with Biotechnology

• Health/ Food Safety http://www.ilsi.org/AboutILSI/ifbic.htm
  ♦ Novel Toxins
  ♦ Novel Allergens
  ♦ Instability
  ♦ Lack of specificity – pleiotropic effects
  ♦ Antibiotic Resistance
  ♦ Diminished Nutrition Value
  ♦ Lack of knowledge of components
  ♦ Gene Flow- Active Therapeutics
  ♦ Transgenic animals (Mammals, Fowl, Fish, arthropods)

• Environmental Impact
  ♦ Gene Flow – genetic pollution
  ♦ novel pests/weeds
  ♦ Novel Pathogens
  ♦ Effect on non-target species
  ♦ Loss of effectiveness
  ♦ Pest pressure shifts
  ♦ Reduced diversity - Monocultures
  ♦ Coexistence – economic construct
  ♦ Feral animals – interbreeding, displacement, niche disruption
Risk Management

- Antibiotic Resistance (perceived not scientific)
  - Transposon tagging
  - Positive selection – exclusive energy source
- Gene Flow-
  - Space
  - Male sterility
  - “Terminator” technology
  - Chloroplast transformation
- Lack of specificity – pleiotropic effects (expected, unexpected)
  - Site-specific recombination
  - Cre-Lox
- Effect on non-target species
  - Tissue specific expression
  - Chloroplast transformation
- Loss of effectiveness – resistance management
  - Refugia
  - Gene Pyramiding, Gene shuffling
- Reduced diversity
  - More sources of genetic diversity – rescue heritage varieties and landraces
- Novel animals – Food safety, feral potential
  - Physical and Biological containment
Out of the world's total land area of 13 billion hectares (ha), 12% is cultivated but the future expansion of farmland for food production will be slower than in the past. (FAO)

In the next 30 years, developing countries will need an additional 120 million ha for crops according to the FAO, this means, less new land will be opened up than in the past.

Some countries and communities will face problems related to land scarcity. This will strengthen their dependency to food and feed import.

Genetically modified crop varieties are the most cost-effective way to sustain farming in marginal areas and to restore degraded lands to production.

If we want to feed the world without destroying our resources, science and technology should drive the development of modern agriculture.
Professional scientific and/or medical bodies with an opinion on safety of GMOs

**Generally Positive**
- The U.S. National Research Council (NRC)
- U.S. National Academy of Sciences (NAS)
- The American Medical Association (AMA)
- U.S. Department of Agriculture (USDA)
- U.S. Environmental Protection Agency (EPA)
- U.S. Food and Drug Administration (FDA)
- European Food Safety authority (EFSA)
- American Society for Plant Biology (ASPB)
- World Health Organization (WHO)
- Food and Agriculture Organization (FAO)
- Royal Society (London)
- Brazil National Academy of Science
- Chinese National Academy of Science
- Indian National Academy of Science
- Mexican Academy of Science
- Third World Academy of Sciences

**Generally Negative**
Threats that harm and those that upset are often quite different.

Genetically modifying humans to solve climate change...

First, we extract the conspiracy theory gene...

Wilcox
It is all about Adaptation!

Climate change evidence

Climate is changing

Dave Granlund © www.davegranlund.com

handoko.tjung@gmail.com