Opportunities in plant breeding: from the integration of genomics to the participation of farmers

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- California Dry Bean Advisory Board and California Crop Improvement Association
- UC MEXUS

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Outline

- 1. The contributions of Benjamin Morrison
- 2. 21st century: the new biology and the role of plant breeding
- 3. Currrent challenges for plant breeding
- 4. Opportunities for plant breeding
  - 4.1 Analytical advance: genomics
  - 4.2 Analytical advance: GIS
  - 4.3 Analytical advance: Phenomics
  - 4.4 Availability of large collections of wild relatives and landraces
  - 4.5 Domestication studies
  - 4.6 Distributed plant breeding
- 5. Conclusion: Integrating multiple threads into one strong strand

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Plant Introduction Activities

J Hered (1941) 32 (7): 211-214

- *"It is believed by many that the most suitable species to use in **replanting** an eroded area are those which grew there formerly and still are found in the **neighboring region**, for certainly what plant would be better fitted than one found growing in the same climate? "*
- *"Erosion has changed the environment to stark desert conditions as far as the plant is concerned, and it can not regain a foothold. **Much hardier** kinds of plants must be the pioneers."*
- *"They represent essentially plants that will survive **under particularly difficult conditions** and will serve to reestablish the green cover that once was everywhere. …. there is the knowledge that there must be more seed and more seedlings than would be needed under favorable conditions; and hardier and tougher strains, for nature is no longer helpful ."*

Morrison BY (1935) Painting the hills green. The Scientific Monthly 40:173-177

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21st Century: The New Biology

NRC: A New Biology for the 21st Century (2009)

- *"the essence of the New Biology is **integration** -– re-integration of the many subdisciplines of biology, and the integration into biology of physicists, chemists, computer scientists, engineers, and mathematicians to create a research community with the capacity to tackle a broad range of scientific and societal problems."*
- *"… solving problems in the areas of **food, environment, energy and health** …"*

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NRC: A New Biology for the 21st Century

- *"A **genome sequence** provides both a list of parts and a resource for **plant breeding** methods, but does not give the information needed to understand how each gene contributes to the formation and behavior of individual plant cells, how the cells collaborate and communicate to form tissues (such as the vascular system or the epidermis), and how the tissues function together to form the entire plant."*
- *"Such **predictive** models, combined with a comprehensive approach to cataloguing and appreciating plant biodiversity and the evolutionary relationships among plants, will allow scientific **plant breeding** of a new type, in which genetic changes can be targeted in a way that will predictably result in novel crops and crops adapted to their conditions of growth."*
- *"… recast the principles of **highly successful traditional plant breeding** into a new and accelerated type of plant breeding termed "**genetically informed breeding**."*
- *"…application of novel engineering methods **to automatically record the relevant traits of growing plants**, …"*
- *"Molecular and cellular biologists, ecologists, evolutionary biologists, and computational and physical scientists will all be needed."*

http://www.nap.edu/catalog/12764.html

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Multidisciplinarity in plant breeding:
Example of the processing tomato harvest at UC Davis

- Plant breeding and agricultural engineering
  - Tomato variety (cv. VF-145) + mechanical tomato harvester
- Tomato: Gordie "Jack" Hanna (1903-1993):
  - suitable for mechanical harvesting; less than round ("square")
- Harvester: Coby Lorenzen & Steven Sluka, commercialized by Blackwelder, Rio Vista, CA; American Society of Agricultural and Biological Engineers' 45th historic landmark http://www.youtube.com/watch?v=Xg1UfcJqTss
- Large increase in acreage and productivity; increase in labor offsetting initial reduction in menial manual labor

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Current Challenges for Plant Breeding

Availability and Demand for Food are (and will be) in Disequilibrium

- Increase in population levels and affluence leads to increased and changed demand
- Climate change will lead to higher temperatures and unpredictable rainfall distribution
- Increasing demand for agricultural, non-food products

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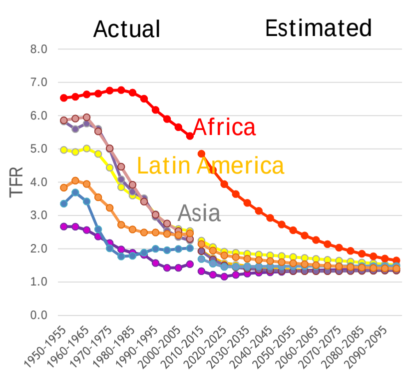
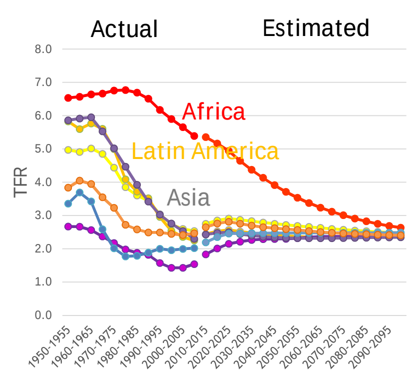
Population parameters

Total Fertility Ratio (Low fertility option)



Total Fertility Ratio (High fertility option)



U.N.: World Population Prospects: The 2012 Revision

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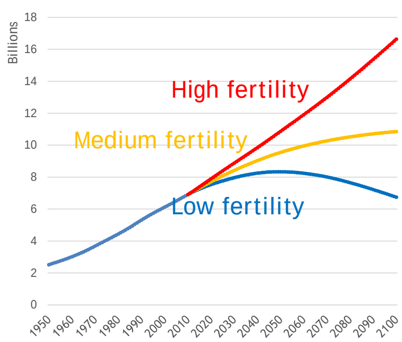
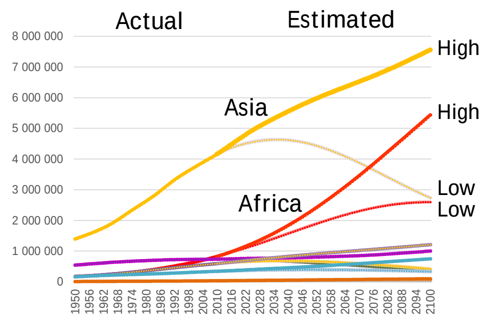
Population parameters

Total Population



Population by Continents



U.N.: World Population Prospects: The 2012 Revision

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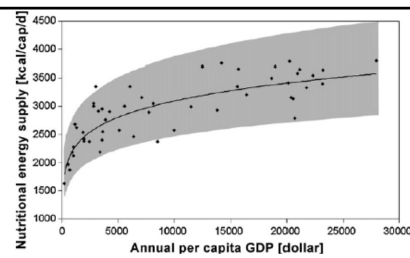
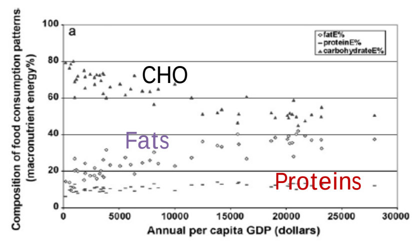
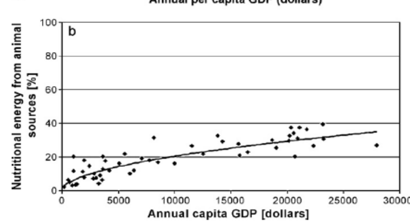
Increase in Population Affluence & Diet Change

(Gerbens-Leenes et al. 2010)

- Transition in low-income countries: low GDP per capita (< $ 5,000)
- Eventually, change in macro-nutrient content:
  - Protein ~
  - Carbohydrates ⇘
  - Fats ⇗
- This represents:
  - Increase in animal consumption
  - Larger use in natural resources
- Higher ratio of supply/actual consumption







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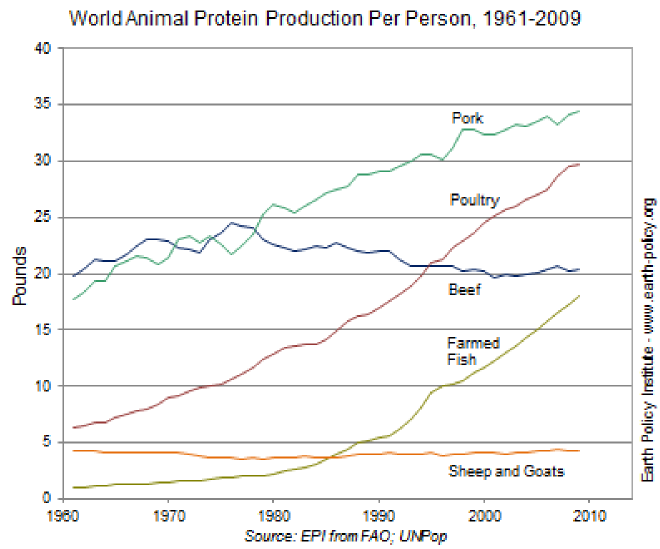
Changing the Demand Side of the Food Equation: Eating less grain-intensive livestock

- Feed conversion efficiency: lbs grain/lb weight gain
  - Beef 7
  - Lamb 5
  - Pork 3.5
  - Poultry > 2
  - Eggs 2
  - Farmed salmon: 1.2-3
  - Tilapia 1.7
- Adopt a Mediterranean diet!
- Eat more legumes!



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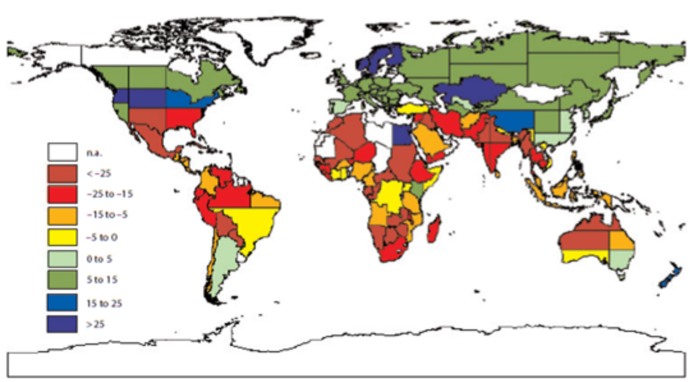
Climate change & agricultural productivity



Cline (2007) (with C fertilization)

Rule of thumb: For each 1°C increase in temperature, the farmer can expect 10% reduction in grain production

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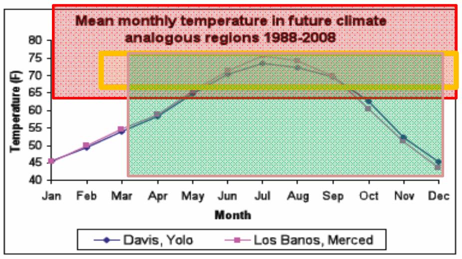
Some numbers…



Optimum temperatures

Hot-season: melon, sweet potato: 64-95°F

Warm-season: tomato, cucumber, peppers, sweet corn: 68-77°F

Cool-season: Lettuce, broccoli, spinach: 41-77°F; legume cover crops

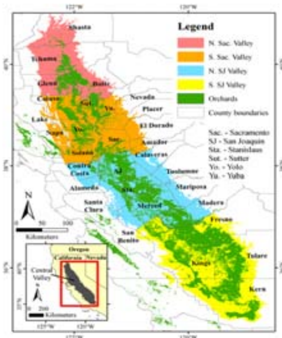
Lesson: Switch crops or crop mixtures

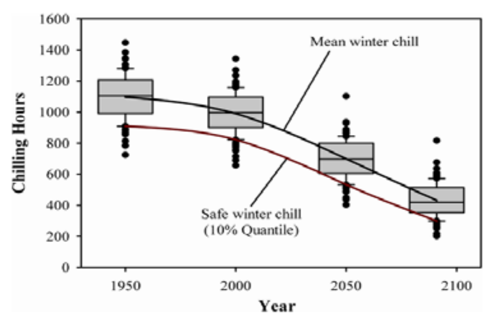
Reproductive development is particularly vulnerable:

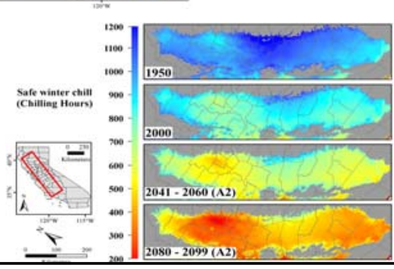
- Pollen viability and production: maize: <77°F; rice: <95°F
- Kernel development: maize: <86°F
- Fruit trees: chilling requirement

Jackson et al. 2009

Perennial Crops: Chilling







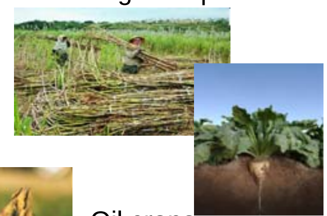
Lesson: Existing variability for adaptation traits; use it!

Luedeling et al. 2009

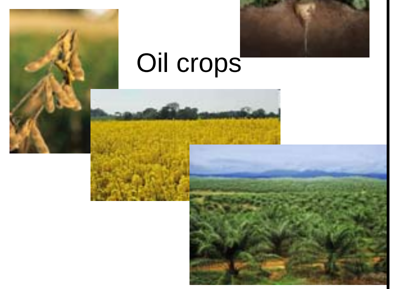
Plants for fuels

- **Biofuels:**
  - **Plant or animal biomass to produce power or heat**
  - **Concerns about:**
    - **Depleting stocks of fossil fuels**
    - **National self-sufficiency and dependence on oil-producing states**
    - **Air pollution from vehicle exhausts**
    - **Greenhouse gas emissions**
- **Alcohol & bio-diesel**

Sugar crops



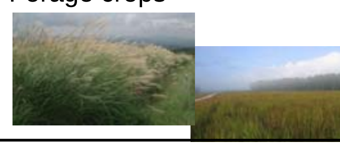
Oil crops



Trees, shrubs

Starch crops

Forage crops



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Plant breeding is fashionable again!

- Plant breeding as a delivery channel for new technologies
- In the U.S.:
  - National Association of Plant Breeders
  - Attracts undergraduate and graduate students
  - Attracted to field experimentation
- Worldwide: e.g., Brazilian Society of Plant Breeding (SBMP)
- IAASTD: International Assessment of Agricultural Science and Technology for Development (http://www.agassessment.org/):
  - Plant breeding and Agroecology
  - Socio-economic and policy factors
  - Agriculture as provider of food security, but also economic security, ecosystem services, and landscape values.
  - Equivalent to IPCC for agriculture and development

National Association of Plant Breeders

NAPB

Improving Plants to Improve Lives

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Opportunities for Plant Breeding

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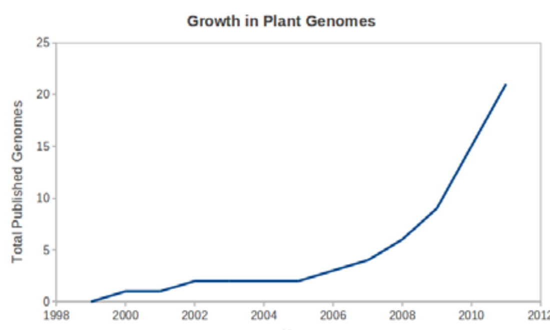
The Future is Here!

1 New analytical tools: Genomics

- Genomics: the study of the "entire" genome sequence and "all" genes, RNA products, protein products and metabolites
- Whole-genome sequencing:
  - Sanger sequencing of BAC clones (Arabidopsis, rice) → whole-genome shotgun sequencing + high-density genetic maps & physical maps; paired-end sequences (e.g., BES); longer Illumina reads; etc.
  - Large increase in sequence information
- Expressed Sequence Tags (EST)
- Proteomics & Metabolomics



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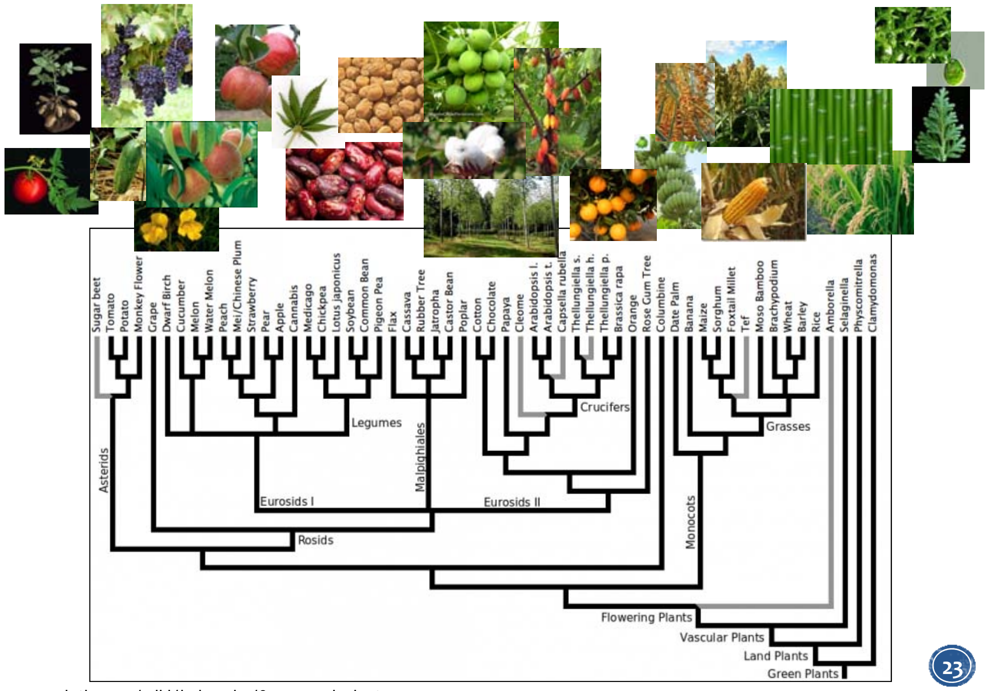

http://genomevolution.org/wiki/index.php/Sequenced_plant_genomes

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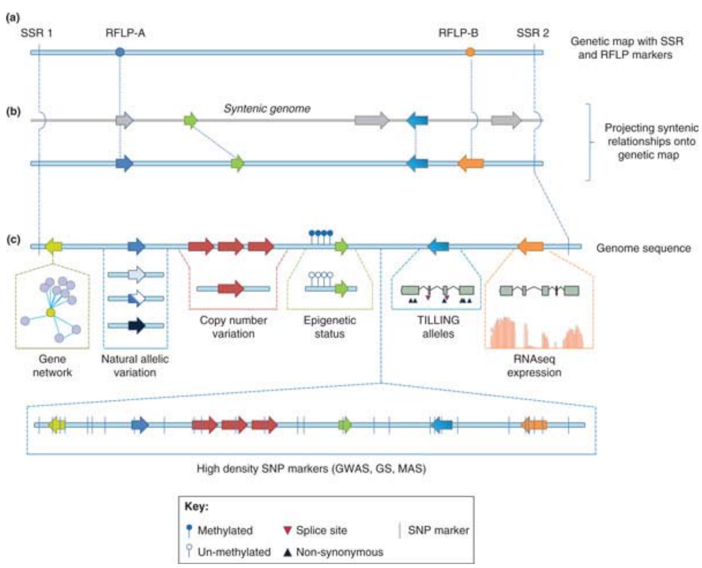
Whole-genome sequencing & marker development



Bevan & Uauy 2013

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What Makes a Good Marker?

- ➢Simple
- ➢Fast
- ➢Robust
- ➢Cheap

- ➢Specific
- ➢Co-dominant
- ➢Proximity to gene
- ➢Coupling
- ➢Polymorphic

➢BOTTOM LINE: Markers (DNA sequence) are the limiting factor for Marker-Assisted Selection because of attrition in developing new markers

Contrasting Gene Pools in Common Bean (*P. vulgaris*):
Andean vs. Mesoamerican
Co-evolution with Pathogens

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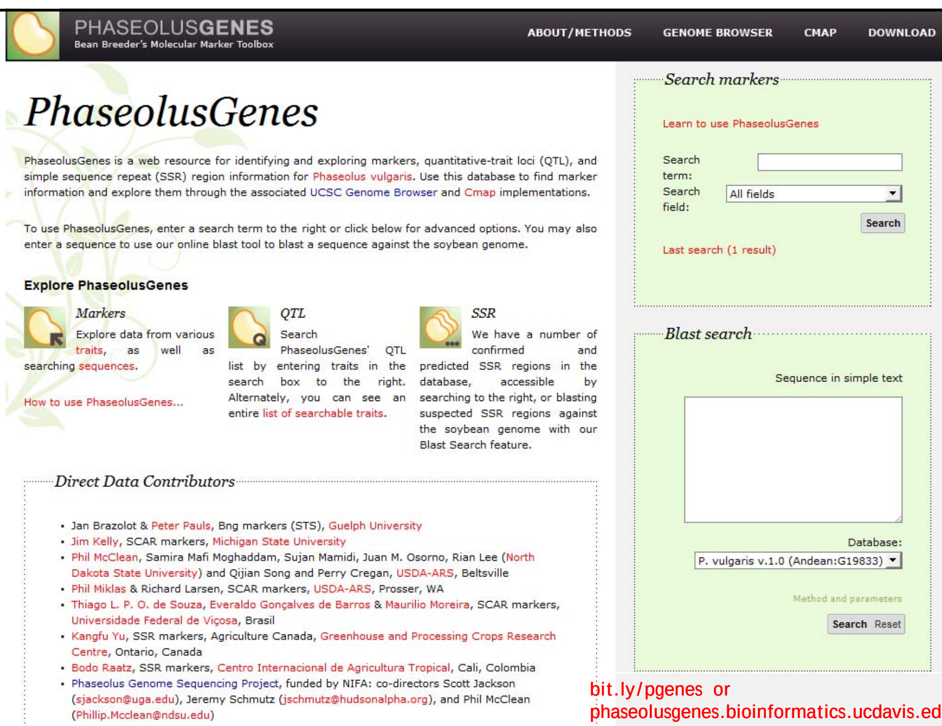

bit.ly/pgenes or
phaseolusgenes.bioinformatics.ucdavis.edu

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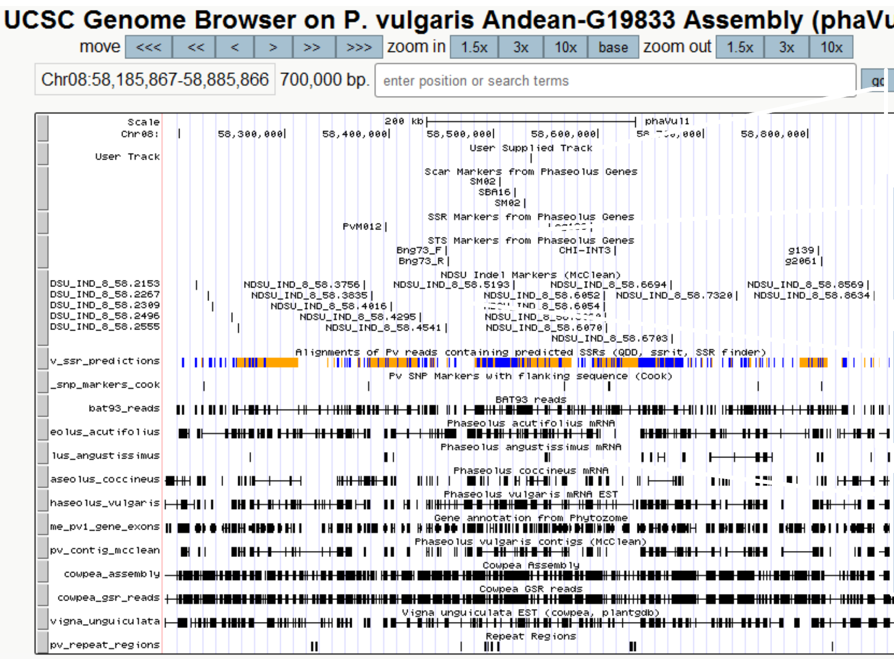

Query sequence

Legacy markers: SCAR, SSR, STS

WGS-based markers: indels, SSRs, SNPs

Other Phaseolus sp. & cowpea (Vigna)

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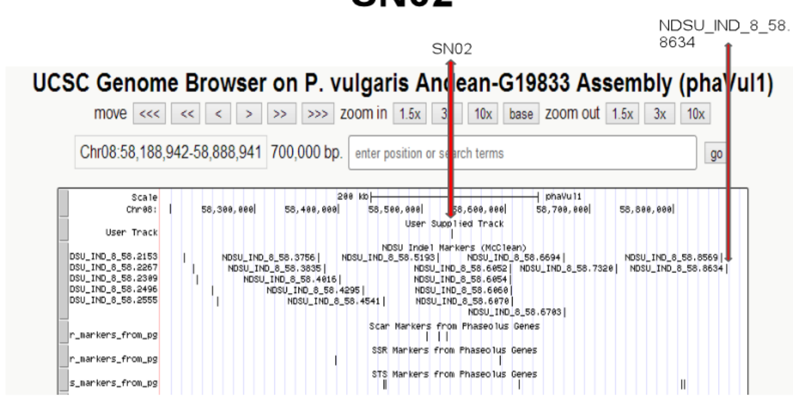
Alternative to SN02 (ALS *Phg-2*) Tamara Miller

- Polymorphism is crucial:
  - Four-parent cross: need to distinguish source of resistance from all three other parents
  - High level of attrition of markers → the more markers, the better

NDSU_IND_8_58.8634 relative to SN02



Distance between SN02 and NDSU_IND_8_58.8634 = 327,226 bp

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Examples of Synteny Utilization & Marker Discovery

Theor Appl Genet
DOI 10.1007/s00122-010-1496-1

ORIGINAL PAPER

Linkage mapping of the *Phg-1* and *Co-1*[4] genes for resistance to angular leaf spot and anthracnose in the common bean cultivar AND 277

Maria Celeste Gonçalves-Vidigal · Anelise S. Cruz · Alexandre Garcia · J. Kami · Pedro S. Vidigal Filho · Lorenna L. Sousa · P. McClean · P. Gepts · M. A. Pastor-Corrales

Theor Appl Genet
DOI 10.1007/s00122-013-2131-8

ORIGINAL PAPER

Co-segregation analysis and mapping of the anthracnose *Co-10* and angular leaf spot *Phg-ON* disease-resistance genes in the common bean cultivar Ouro Negro

M. C. Gonçalves-Vidigal · A. S. Cruz · G. F. Lacanallo · P. S. Vidigal Filho · L. L. Sousa · C. M. N. A. Pacheco · P. McClean · P. Gepts · M. A. Pastor-Corrales

Genetic Characterization and Molecular Mapping *Pse-2* Gene for Resistance to Halo Blight in Common Bean

Phillip N. Miklas,* Deidré Fourie, Jennifer Trapp, Richard C. Larsen, Carolina Chavarro, Matthew W. Blair, and Paul Gepts

Journal of Heredity 2013:104(2):273–286
doi:10.1093/jhered/ess102
Advance Access publication December 12, 2012

Identification and Characterization of a Homologue to the *Arabidopsis* *INDEHISCENT* Gene in Common Bean

Tania Gioia, Giuseppina Logozzo, James Kami, Pierluigi Spagnoletti Zeuli, and Paul Gepts

Theor Appl Genet (2011) 123:1341–1357
DOI 10.1007/s00122-011-1671-z

ORIGINAL PAPER

Nucleotide diversity of a genomic sequence similar to *SHATTERPROOF* (*PvSHP1*) in domesticated and wild common bean (*Phaseolus vulgaris* L.)

L. Nanni · E. Bitocchi · E. Bellucci · M. Rossi · D. Rau · G. Attene · P. Gepts · R. Papa

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Population-specific Genomics in Plant Breeding & Genotyping by Sequencing: Developing genomic resources for lima bean

Sarah Dohle

UC Haskell
Indeterminate,
Small seeds
Resistant to Lygus

P1

UC92
Determinate,
Large seeds
Nematode R

P2

x

F1

Re-Sequencing of P1, P2
BLAST onto bean and soybean genomes --> physical map
Use RI population for genetic map and QTL analysis
Identify polymorphisms --> potential markers

Recombinant Inbred population
Genetic experiment

Inbred Backcross population
Other breeding populations
Breeding experiments (multiple crosses)

Field Breeding
Marker-assisted breeding

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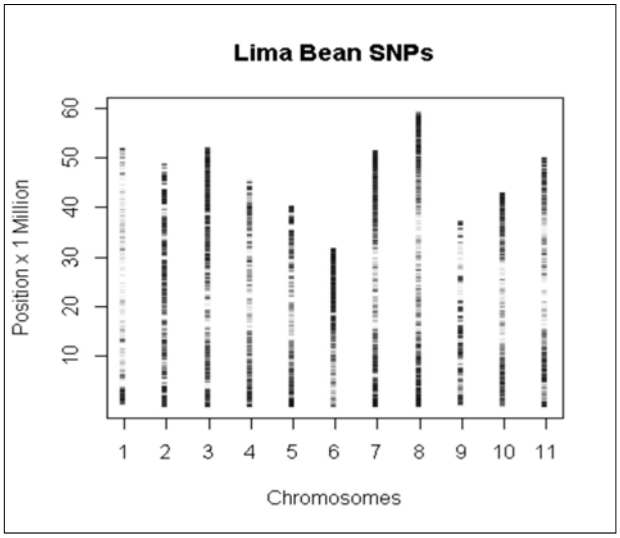
Mapping of lima bean SNPs through synteny with common bean

Sarah Dohle



Distribution of ~ 50,000 lima bean single-base-pair (SNP) markers on the common bean chromosomes. Each horizontal line represents an individual SNP.

Such markers will be used to determine where genes for resistance to Lygus and nematodes are located.

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New analytical tools: Geographic Information System (GIS)

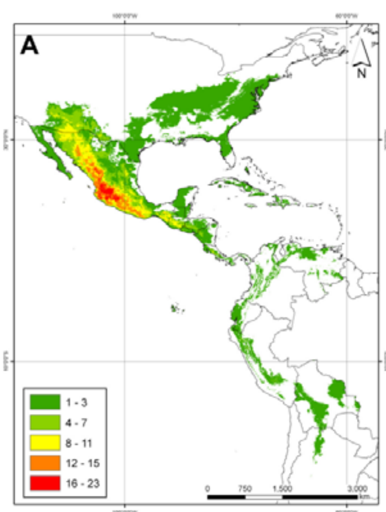
- Wikipedia: *"integrates, stores, edits, analyzes, shares, and displays geographic information for informing decision making."*
- Applications to germplasm conservation?

OPEN ACCESS Freely available online PLoS one

A Gap Analysis Methodology for Collecting Crop Genepools: A Case Study with *Phaseolus* Beans

Julián Ramírez-Villegas[1*], Colin Khoury[2], Andy Jarvis[1,3,4], Daniel Gabriel Debouck[5], Luigi Guarino[2]

  - Spatial and temporal analyses
- Applications to breeding?
  - High-throughput phenotypic evaluations



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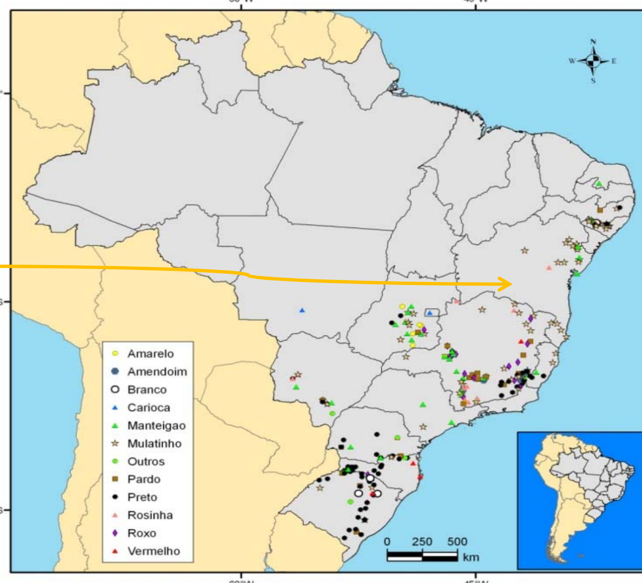
Eco-geographic variation of common bean in Brazil Marilia Burle

'Mulatinho' market class:

lower altitudes, precipitation; higher temperature



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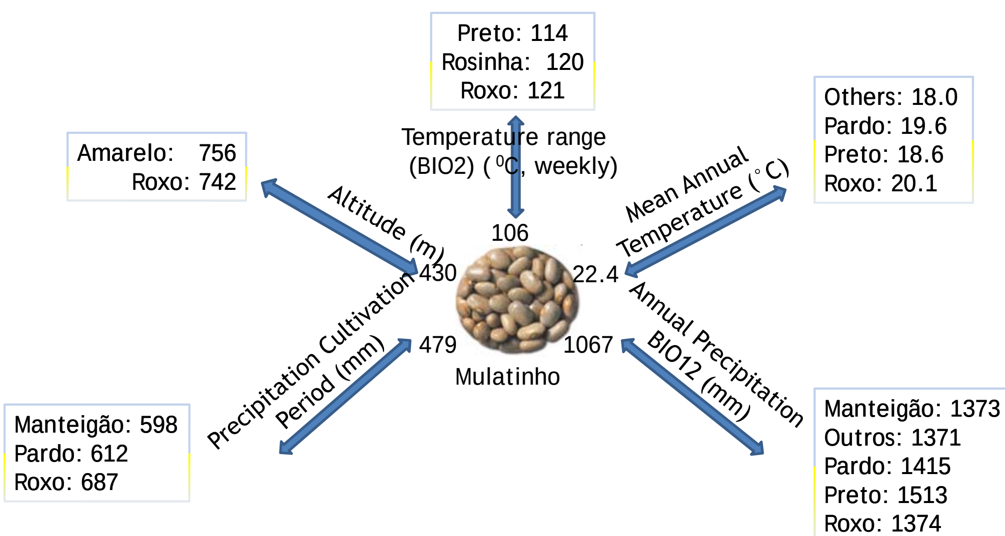
Significant* Contrasts between Mulatinhos and Other Commercial Types



* Tukey test (α = 0.05)

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New analytical tools: Phenomics

- **High-throughput** evaluations of phenotypes in **field conditions**
- **Match precision** obtained by DNA sequencing (SNP level) by similar precision at the phenotypic level
- **Limitations** of greenhouse and growth chamber evaluations:
  - Limited air volume precludes flowering & maturation: cannot assess stress tolerance during reproductive growth
  - Limited soil volume: different growth & development, nutrient and water regimes
  - Different solar radiation, wind strength, evaporation rates
- **Field-based phenotyping**:
  - More **accurate** description of trait expression
  - Needs to be **high-throughput**: large populations (100s plots), diurnal cycles (recovery from stresses), multiple traits and tissues simultaneously
  - **Non-destructive**
  - **Close-range sensing**
  - Combine with **wireless sensor network** to monitor environmental conditions
- **Correlate** individual traits with overall performance: yield, phenology

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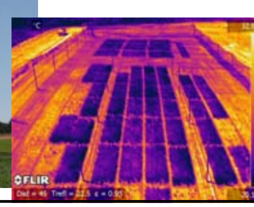
Examples of Types of Analyses

- Direct measures:
  - Visible light
  - Near-infrared: water status
  - Infrared: heat/temperature status
  - Multispectral imaging: composition, disease status, etc.
  - Fluorescence: chlorophyll
  - Height profiling (top, sideways)
- Processed data:
  - Image analyses
  - Mathematical models of growth and development


Lemnatec

White & Conley 2013

Australian Plant Phenomics Facility

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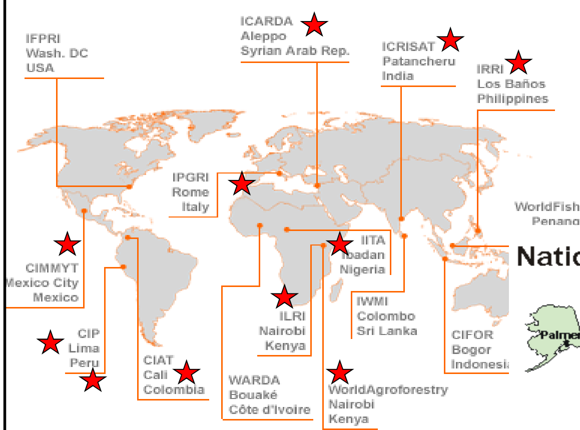
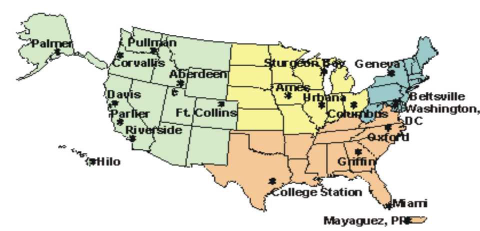
Large collections of crop germplasm: *Ex situ* conservation

- CGIAR system
- USDA-NPGS
- Other national or international banks



National Germplasm Repositories



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McCouch S et al. 2013. Agriculture: feeding the future. Nature 499:23-24

The International Center for Tropical Agriculture in Colombia holds 65,000 crop samples from 141 countries.

Feeding the future

We must mine the biodiversity in seed banks to help to overcome food shortages, urge **Susan McCouch** and colleagues.

- Sample of sequence information of ITPGRFA accessions
- Analyze phenotypes of the same accessions and combine data with sequence, crossing progeny, geographical, and ecological data
- Create an informatics infrastructure to link the different data types

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The role of domestication studies

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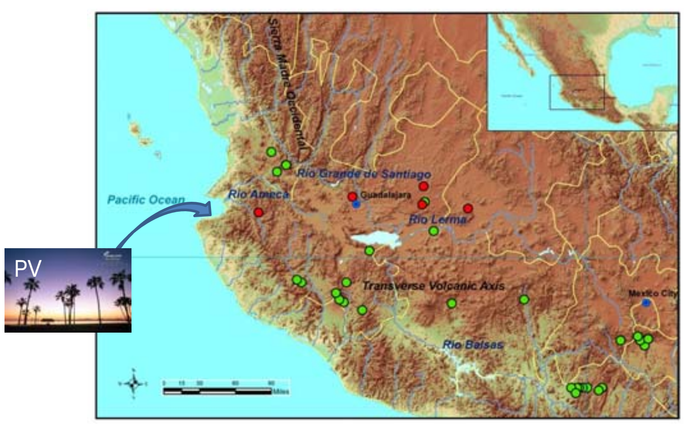
The Putative Domestication Center of Common Bean in Mexico



M. Kwak, J. Kami & P. Gepts, Crop Sci., 2009

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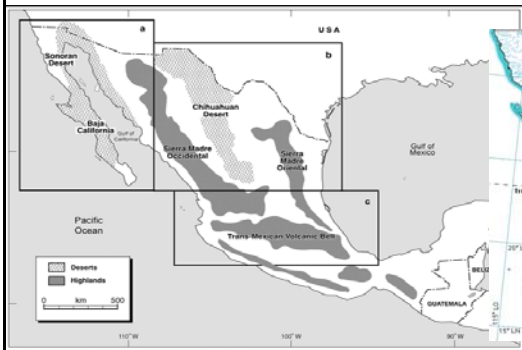
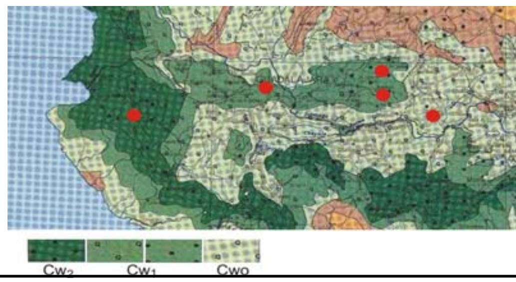
Why the Lerma-Santiago Basin?

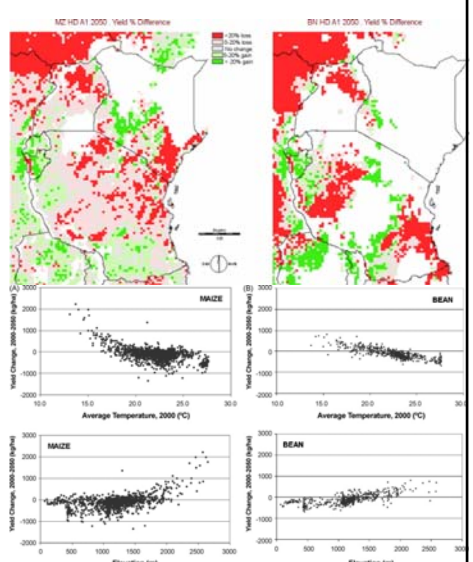




- Climate: Cwa
  - Subtropical: t° coldest month: 5-18 °C
  - Subhumid: 4-6 months of humidity in summer
  - Semi-warm: average annual t°: 18-22 °C
- Vegetation:
  - Dry deciduous forest to drier thorn forest

6 Towards Distributed Breeding: Farmer Participatory Breeding/Selection

- By analogy with distributed computing
- Currently, varietal development is centralized: AES, Seed companies
- Complement with local capabilities?
  - Local adaptation:
    - Broad vs. narrow adaptation
    - Maximize G x E interactions
  - Local consumer needs:
    - Cultural and gender differences
    - Novelties & flexibility
- Deal with future uncertainties of climate change



Thornton et al. 2009

Integration with Human Effects: Are Farmers Agents of Selection and Gene Flow?

Selection During and After Harvest

Photos: D. Zizumbo

Payró de la Cruz et al. 2005

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Different Genetic Structure in W & D

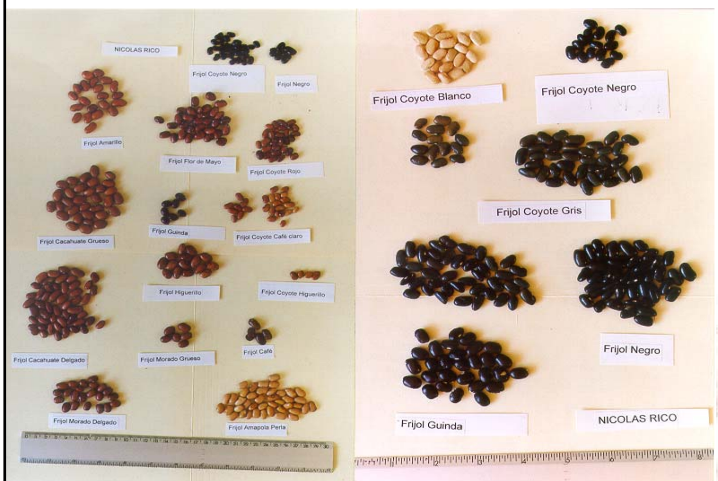
Zizumbo-Villarreal et al. 2005

	H	*h*	G_{ST}	*Nm*
Wild	0.24	0.13-0.18	0.40	0.78
Landraces	0.26	0.22-0.29	0.26	1.40
Breeding lines	--	0.03-0.06	--	--

- Wild: less diversity within populations, more among populations compared to Domesticated
- Higher gene flow in Domesticated:
  - Diversity within landraces: outcrosses
  - Seed exchange among farmers

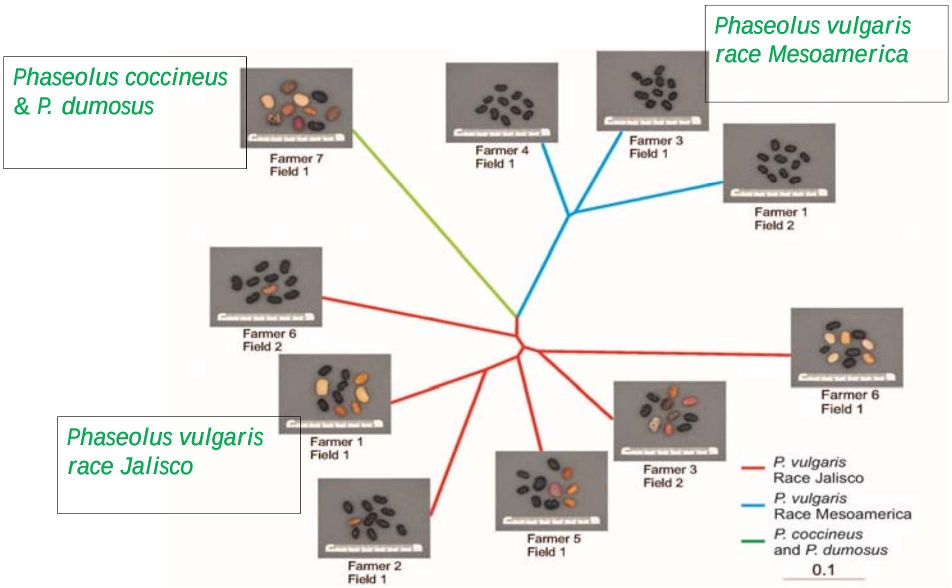
Wide range of diversity including improved cultivars and wild beans

	Average seed weight (g/100)
Wild	6
Weedy	20
Domesticated	45



Environs of Yuriria, Guanajuato-Michoacán, Mexico

Three main taxa



M. Worthington, D. Soleri, & P. Gepts, Crop Sci 2012

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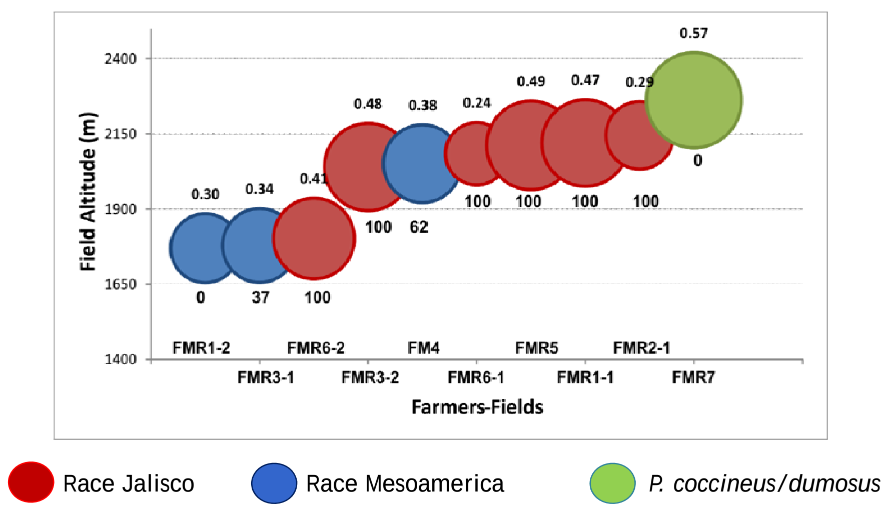
Altitude distribution of different beans



M. Worthington, D. Soleri, & P. Gepts, Crop Sci. 2012

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Social sciences: Socio-cultural preferences, economic circumstances of households, demographic changes

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Conclusion: Integrating multiple threads into one strong strand

- Our food supply is at risk
  - Population
  - Consumption choices
  - Climate change
  - Energy production
- Plant breeding is part of the solution: Multiple threads
  - Adoption of new analytical tools
  - Use of existing collections and domestication studies
  - Different breeding strategies: MAS, distributed breeding
- Modified from B.Y. Morrison: Painting the Hills Green (1935)
  - "… green hills clad with forests or with pastures, but in any case luxuriant and verdant, have become a symbol of happiness and well-being. "

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