CHANGING WHAT'S POSSIBLE

ADVANCED RESEARCH PROJECTS AGENCY – ENERGY
&
BIOLOGICAL AND ENVIRONMENTAL RESEARCH ADVISORY COUNCIL

BRIEFING

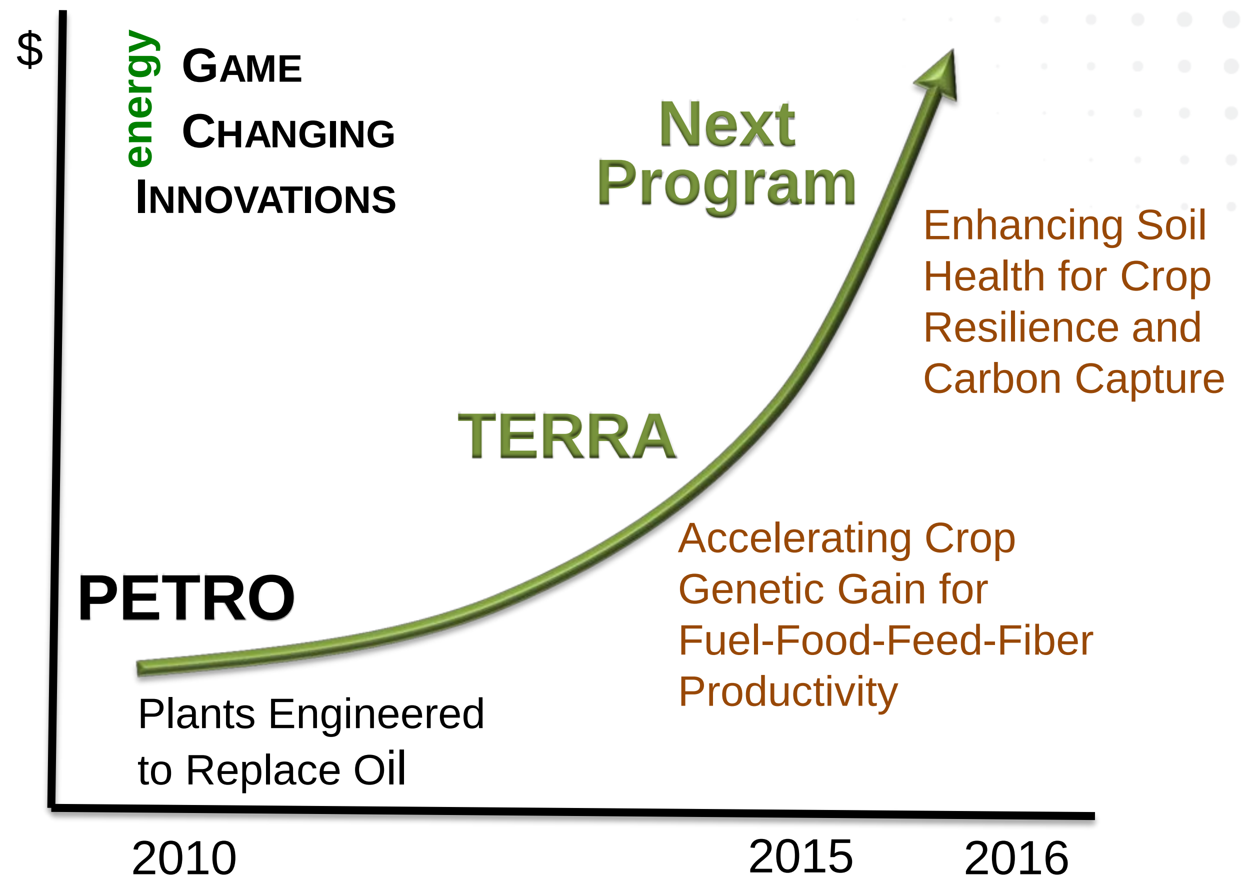
Joe Cornelius
Program Director
25 August 2015

Advanced Research Projects Agency - Energy

Catalyze development of high risk, high-impact, transformational technologies

ENSURE AMERICA'S:

- NATIONAL SECURITY
- ECONOMIC SECURITY
- ENERGY SECURITY
- TECHNOLOGICAL LEADERSHIP



2 New Bio Programs from ARPAE

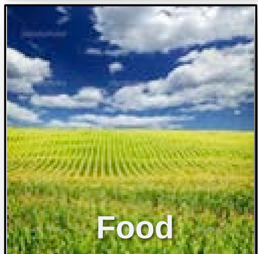
CHANGING WHAT'S POSSIBLE

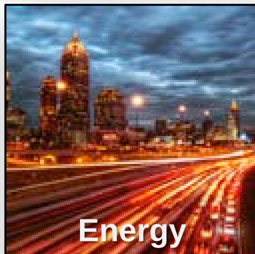
Goal: Sustainable, Economical, Crop Production

FOOD – FUEL – FEED - FIBER

Context:

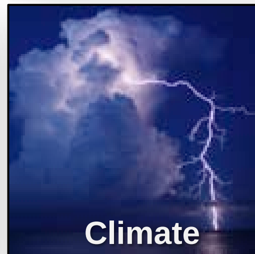
Economic





Demand Doubles

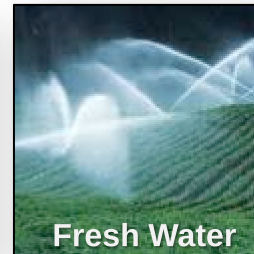
Environment



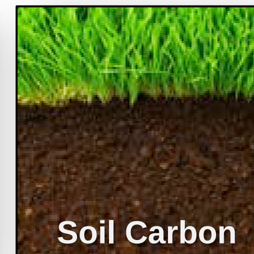
2^{o} C

9.9 GtC

Natural Resources



70% H_20



120 GtC

- ✓ Agriculture has the capacity and scale to deliver significant benefits.
- ✓ However, agriculture is significantly behind its productivity pathway.
- ✓ Increased yield can be achieved through breeding,

BUT

- Breeding is slow and inefficient

- Investment in crop development is sub-optimal

- Small stakeholders are disadvantaged from the development pipeline

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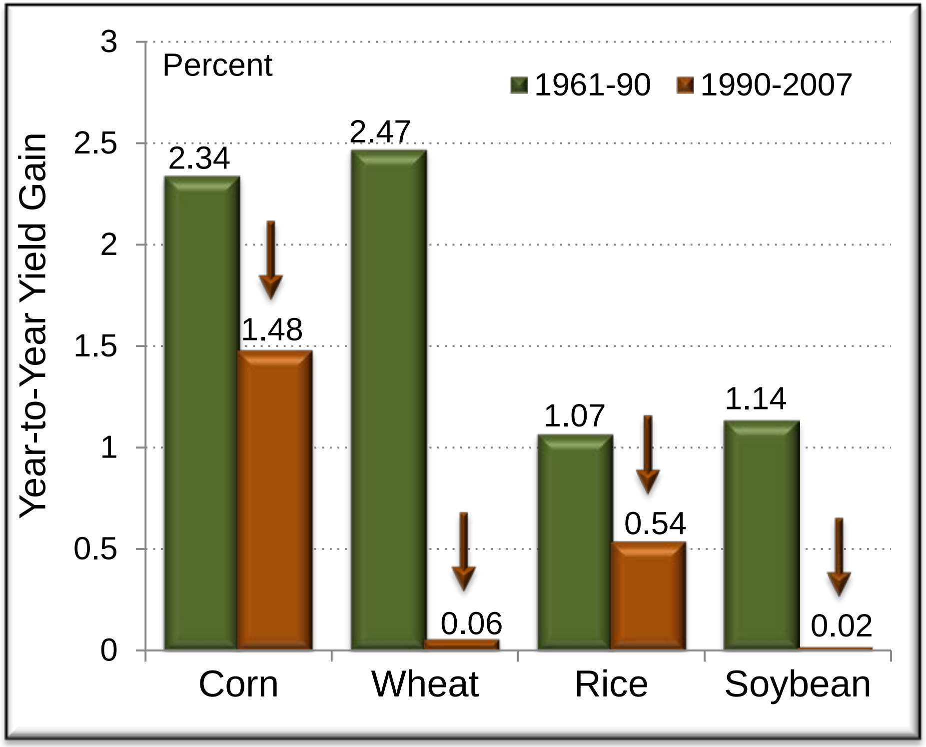
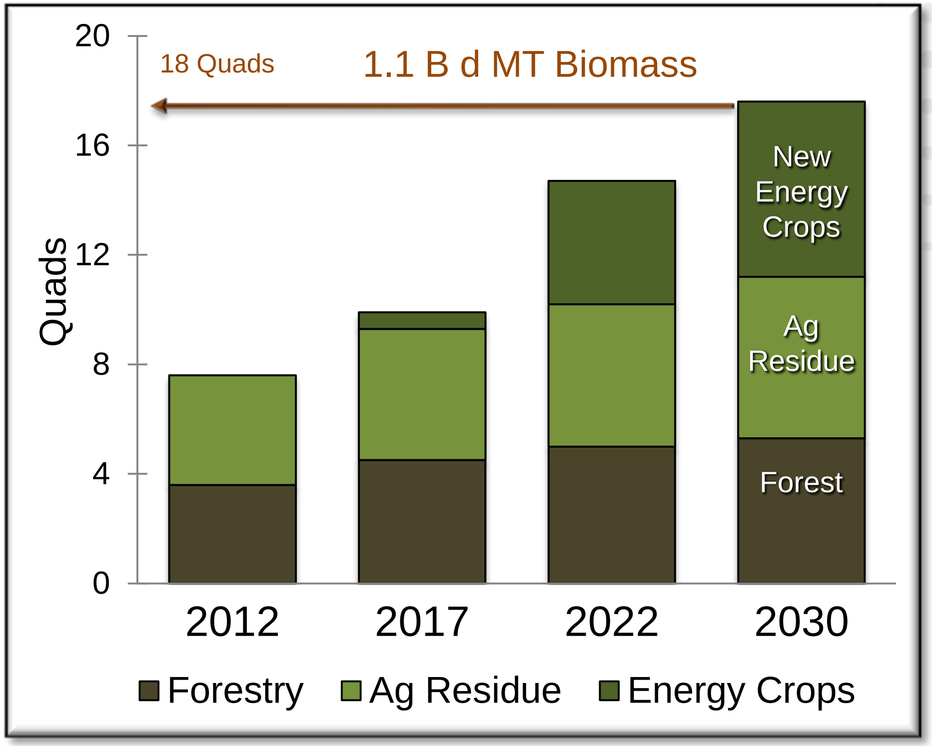
However, We Are Off the Pace to Satisfy Demand

Evidenced by Declining Rate of Genetic Gain in Core Crops



"Improvements in crop yield are below 1.16-1.31 %/y rate required to meet demand in 2050."



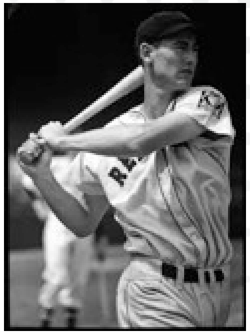
DOE bioenergy plan (Billion Ton Study) requires a 1% /year genetic gain in dedicated energy crops.

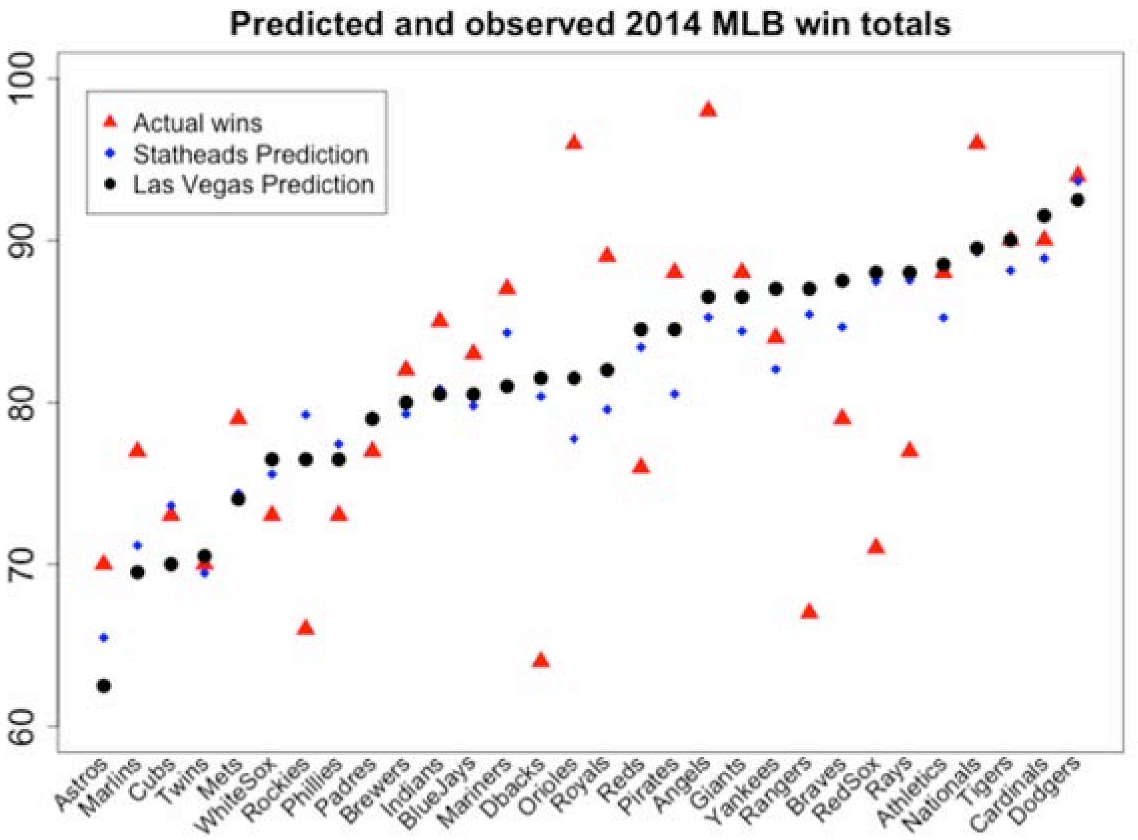
- *Prognosis for genetic improvement of yield potential of major grain crops*. A. J. Hall, R. A. Richards, Field Crops Research, 143 (2013) 18-33.
- DOE Billion Ton Biomass Study Update, 2011

Breeding is like Baseball

Selecting the best players to win games

- What are the drivers for ‘winning’ crop varieties?
- What data should the breeder collect?
- Which genes should the breeder try to discover and utilize?





Ted Williams stat sheet (1939–1960)

	H	HR	RBI	BB	BA	OBP	SLG
1939	185	31	145	107	0.327	0.436	0.609
1940	193	23	113	96	0.344	0.442	0.594
1941	185	37	120	147	0.406	0.553	0.735
1942	186	36	137	145	0.356	0.499	0.648
1946	176	38	123	156	0.342	0.497	0.667
1947	181	32	114	162	0.343	0.499	0.634
1948	188	25	127	126	0.369	0.497	0.615
1949	194	43	159	162	0.343	0.49	0.65
1950	106	28	97	82	0.317	0.452	0.647
1951	169	30	126	144	0.318	0.464	0.556
1952	4	1	3	2	0.4	0.5	0.9
1953	37	13	34	19	0.407	0.509	0.901
1954	133	29	89	136	0.345	0.513	0.635
1955	114	28	83	91	0.356	0.496	0.703
1956	138	24	82	102	0.345	0.479	0.605
1957	163	38	87	119	0.388	0.526	0.731
1958	135	26	85	98	0.328	0.458	0.584
1959	69	10	43	52	0.254	0.372	0.419
1960	98	29	72	75	0.316	0.451	0.645

Crop Improvement Process… 8 -10 years / new hybrid

Phenotyping is the Bottleneck for Trait Discovery and Cultivar Development

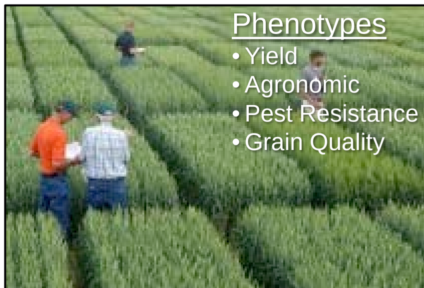
Manual - <u>Expensive</u>
Low Throughput
Unreliable

Automated - Economical
High Throughput
Precise

Harvest

Genetic Gain

Field Evaluations



PHENOTYPES

Seed Chipper

GENOTYPES

Crop Breeding Cycle

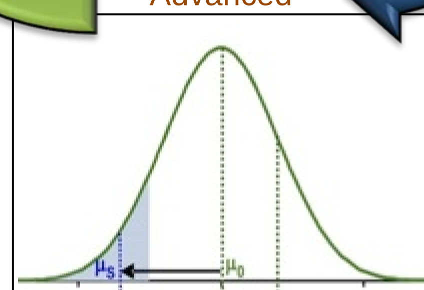
Phenotype = Genotype × Environment × Management

(P = G × E × M)

Parent Crossing

Cultivar Advanced

Genetic Markers



Select

Major breeding objectives: yield, composition, disease and insect resistance and tolerance to abiotic stresses.

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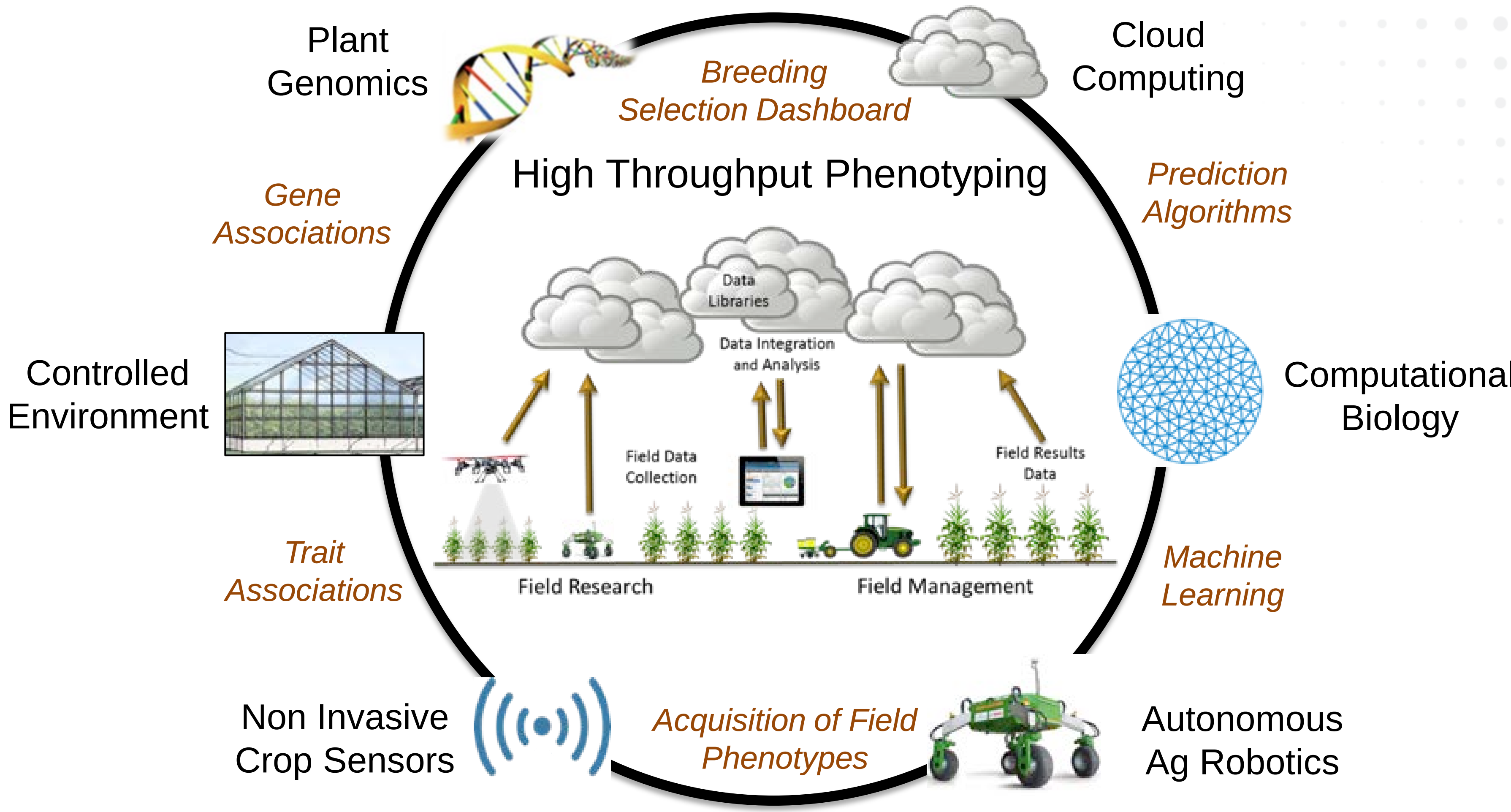
TERRA: Program Vision

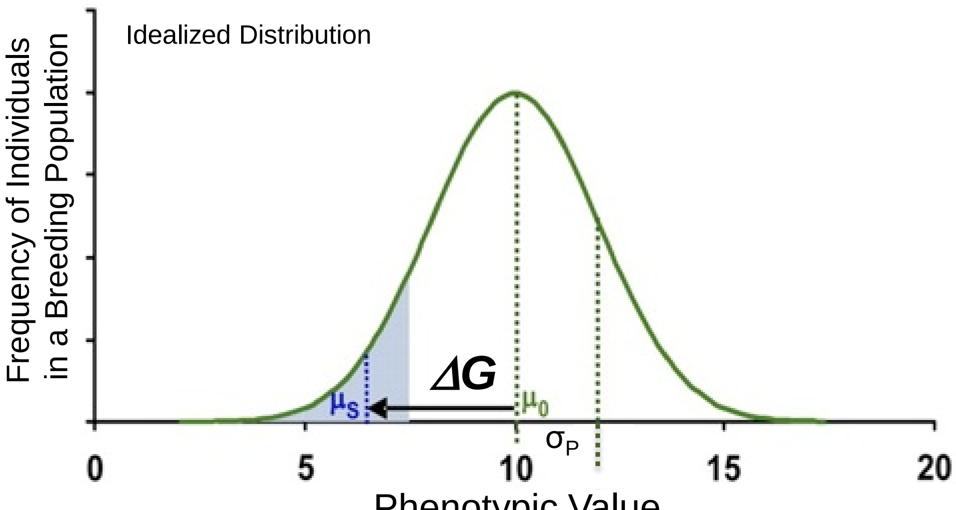
Transportation Energy Resources From Renewable Agriculture



Integrated Technologies Provide Platform for Accelerated Breeding

TERRA enables breeders to accelerate genetic gain

(ΔG) Genetic Gain is the predicted change in the mean value of a trait within a population that occurs with selection.



(In this example, trait improvement is achieved by selecting for a lower phenotypic value, e.g. disease susceptibility)

$$\Delta G \approx h^2 \sigma_p i / L$$

Genetic Gain Equation Component Parts:

- ΔG = Genetic Gain
- μ_0 = mean phenotypic value of the original population
- μ_s = mean phenotypic value of selected individuals
- h^2 = heritability, a measure of the linkage between genotype and phenotype independent of environment
- σ_P = phenotypic variability in population
- i = selection intensity, proportion of population selected to produce the next generation
- L = length of cycle interval (usually 1 generation)

TERRA increases *ΔG by* :

- Estimating *h* by large scale collection of phenotype × genotype association data (*GWAS*)
- Determining environmental effects on traits at multiple field sites (*$h^2 \approx P / (G \times E)$*)
- Introducing new genes (σ_p)
- Increasing number of crosses/population (i)
- Shortening cycles (L)

Stephen P. Moose, and Rita H. Mumm
Plant Physiol. 2008;147:969-977

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TERRA Performer Portfolio

(6 Integrated Systems Teams: Plant Biology, Robotic Sensors, Computer Science)

Public Reference Data Team

- Donald Danforth Plant Science Center — Discovery | Community | Impact
- USDA ARS
- HudsonAlpha Institute for Biotechnology
- JGI
- LemnaTec
- Washington University in St. Louis
- Illinois
- The University of Arizona
- Kansas State University
- Texas A&M University
- Clemson University

Full System Teams

Purdue University

College of Agriculture,
College of Biological Engineering,
College of Aeronautics

- IBM Research
- CSIRO — Australia Plant Phenomics: Commonwealth Scientific and Industrial Research Organization

Clemson University

College of Agriculture, Forestry, and Life Sciences

- Carnegie Mellon Robotics Institute
- Near Earth Autonomy
- Donald Danforth Plant Science Center

"Component" Focus Systems Teams

- Texas A&M AgriLife Research
- National Robotics Engineering Center (NREC)
- ceres

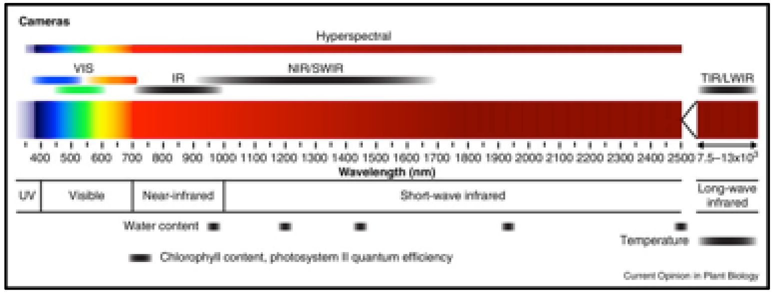
- Pacific Northwest National Laboratory
- Blue River Technology
- Chromatin
- University of California Agriculture and Natural Resources
- Berkeley Lab — Lawrence Berkeley National Laboratory

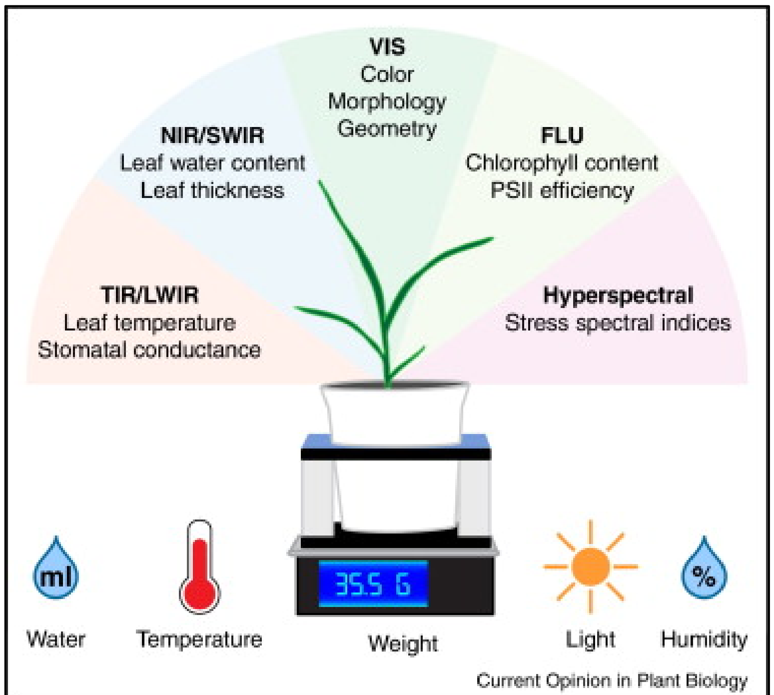
- Illinois — University of Illinois at Urbana-Champaign
- Cornell University — College of Agriculture and Life Sciences
- Berkeley EECS — Electrical Engineering & Computer Sciences
- USDA ARS

20th Century Crop Phenotyping SOA

Phenotype Sensing - High-throughput Imaging

Data to quantify genotype by phenotype by environmental interactions





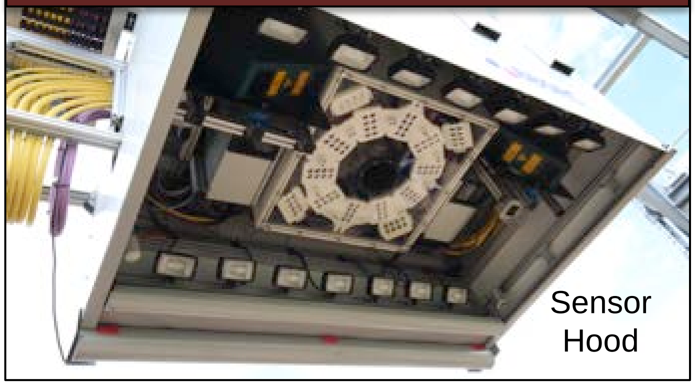
High-throughput plant phenotyping; Noah Fahlgren, Malia A Gehan, Ivan Baxter; Plant Biology [Volume 24, April 2015, Pages 93–99](#)

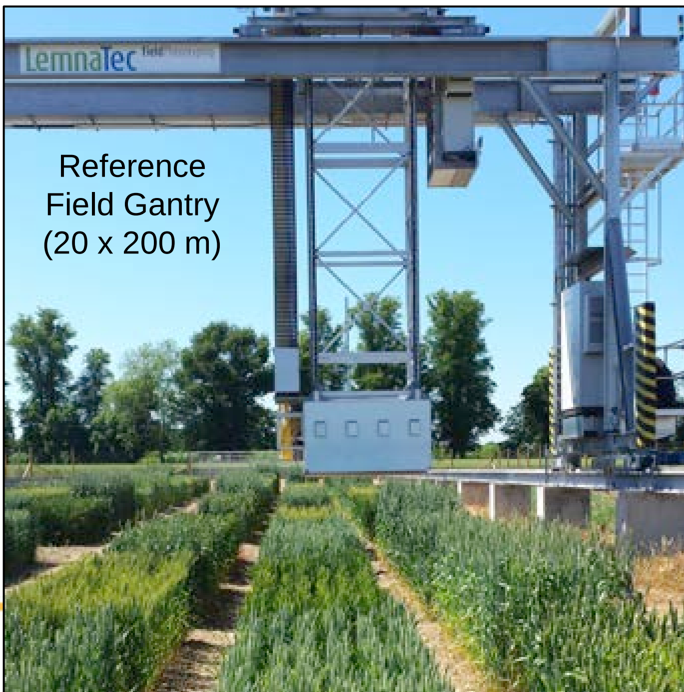
Cameras capture signal from visible and infrared spectrum of light.

- VIS cameras detect light in the visible range from ~400 to 700 nm to measure morphological, geometric, and color properties of plants .
- Infrared (IR) cameras detect near-infrared (NIR) light for night imaging.
- NIR cameras detect NIR and short-wave infrared (SWIR) light useful for detecting leaf water content.
- Thermal infrared (TIR) cameras detect long-wave infrared (LWIR) light that is emitted by leaves in a temperature-dependent intensity.
- Hyperspectral cameras detect hundreds of spectral bands with nm-level resolution between 350 and 2500 nm to detect plant stress.
- Specialized imaging systems measure chlorophyll fluorescence after excitation.

TERRA Robotic Platforms are Diverse and Data Rich

GFE Reference Field Phenotyping Platform
Danforth Center, USDA, UAZ



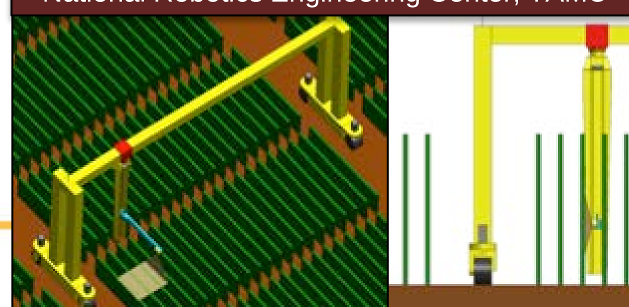


Performance Comparison	Current Breeding Manual	TERRA Ground & Aerial Vehicles
# Breeder Plots	1,000	1,000
# Phenotypes	10's	1000's
Resolution	1 m	1 cm
Bandwidth (nm)	400-700	100-2500
Data Collection	Bytes	Terabytes
Cycle Time	8 hrs	1 min UAV 4 hrs AGV

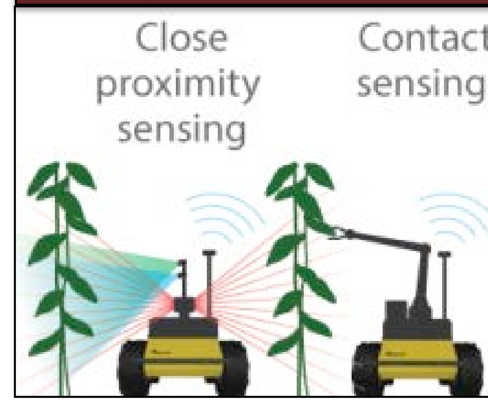
Reference Field Gantry Sensors:

- Hyperspectral i350-2500 nm
- Thermal infrared
- Dedicated NDVI sensor
- Dedicated PRI (photochemical reflectance)
- PAR sensor
- Color sensor
- Height Scanner
- 8 MP RGB down camera
- 2 side looking cameras
- Active reflectance in-field
- Fluorescence
- Environmental temperature, humidity, rainfall, wind, CO_2

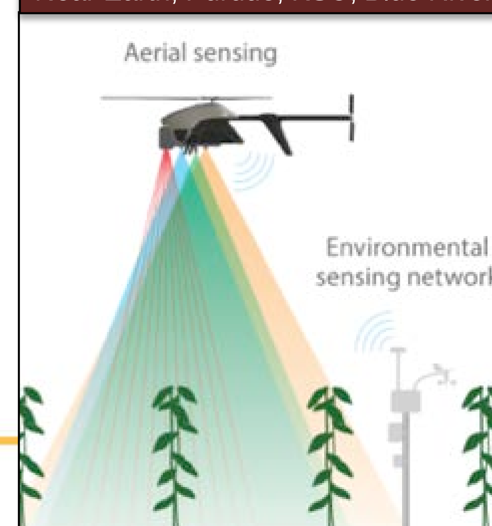
Deployable Gantry Plant Phenotyping Systems
National Robotics Engineering Center, TAMU



Ground Plant Phenotyping Systems
Carnegie Mellon, UIUC, Purdue



Aerial Plant Phenotyping Systems
Near Earth, Purdue, KSU, Blue River



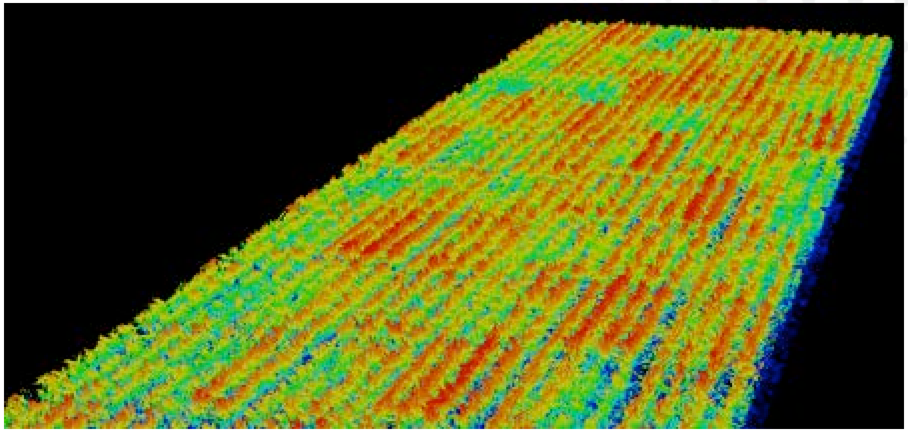
Phenotype Sensing – Drought Stress

Example:. TERRA Performer PNNL and Blue River Technology

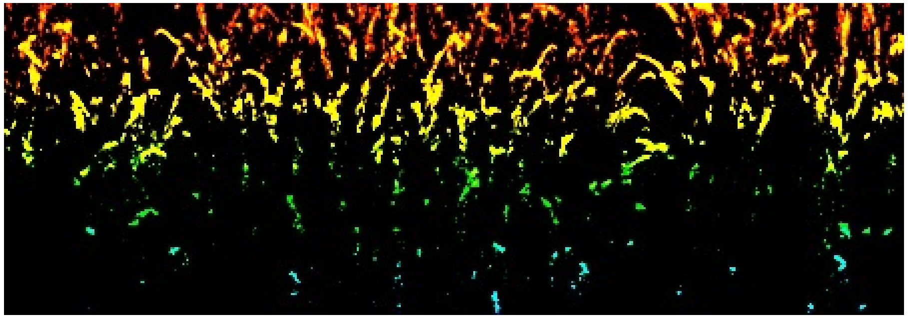
- Blue River Technology develops advanced computer vision, and robotics platforms.
- LiDAR, thermal, and multispectral imaging sensors measure over 1 million plants/day:
    - o Height
    - o Leaf Area
    - o Water stress
- Field-based 3D reconstruction of crop architecture demonstrated using ground-based cart in 2014.
- Sensors aboard new aerial platform will cover entire plant growth cycle.

APPS - Aerial Plant Phenotyping System

Automated, Aerial-based, 3D Imaging Customized for Plant Breeding



Corn breeding plots in a drought stress trial. Color is height measured by LiDAR.



Side-profile of a row of mature corn (10 ft tall) using downward-facing LiDAR (color indicates height), showing the high resolution and canopy penetration that Blue River's drone LiDAR data provide. Extracted from the full field above.

Credit: Matt Colgan, Blue River Technology

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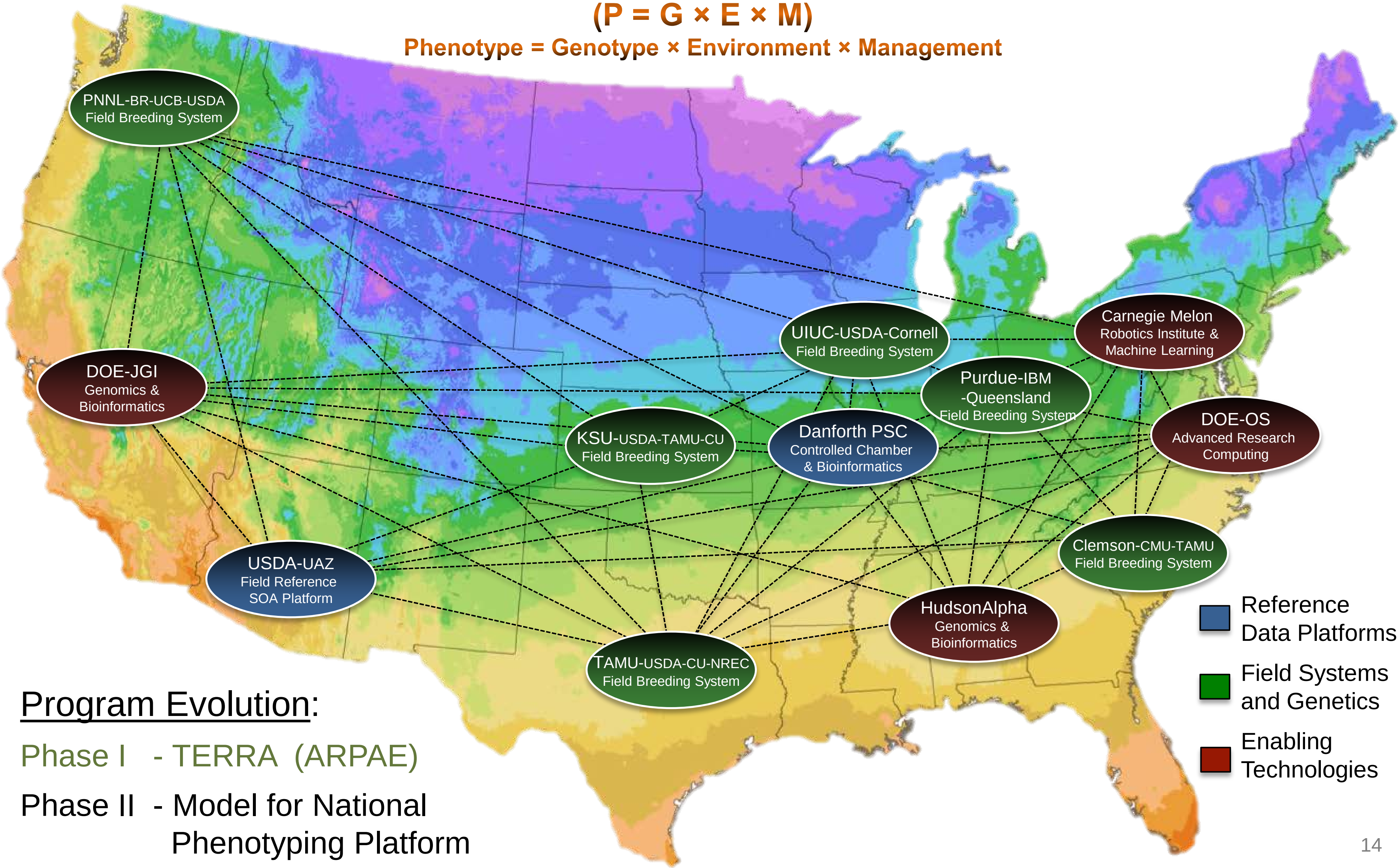
TERRA: Integrated Phenotyping Network

Breeding-Agronomy-Genetics-Physiology- Robotics-Sensors-Computation-Machine Learning

A "BIG DATA" HIGHWAY; A CATALYST FOR AGRICULTURAL PRODUCTIVITY

(P = G × E × M)

Phenotype = Genotype × Environment × Management



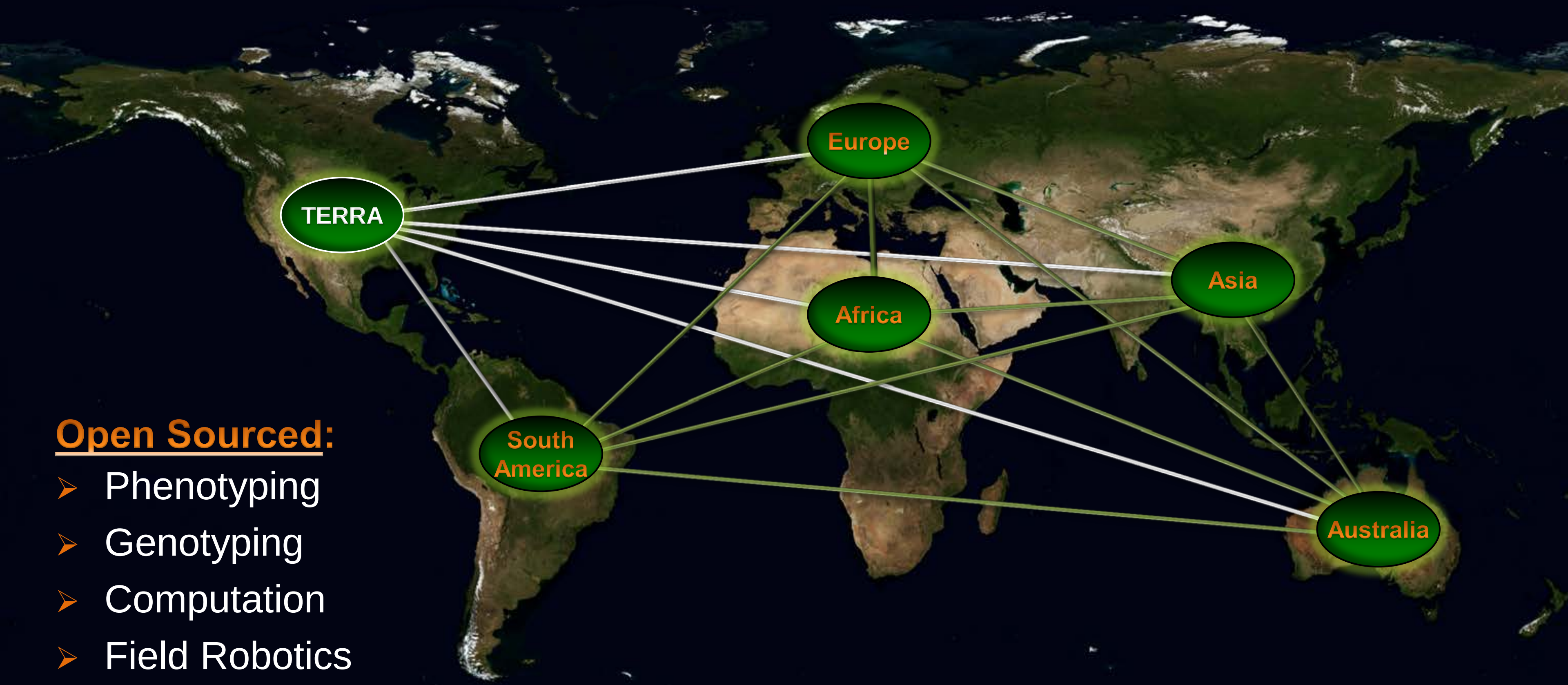
Program Evolution:

Phase I - TERRA (ARPAE)

Phase II - Model for National Phenotyping Platform

IMAGINE a 2nd Green Revolution

Powered by a National and International Phenotyping Network



Open Sourced:

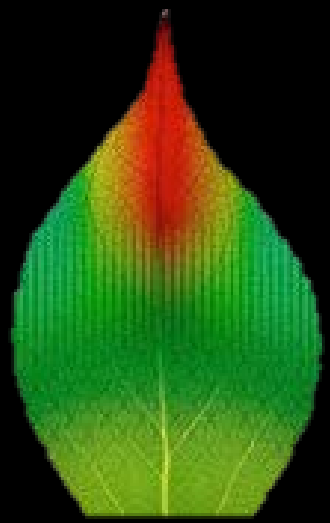
- Phenotyping
- Genotyping
- Computation
- Field Robotics

An Information Highway that is a Catalyst for Agricultural Productivity

Food – Fuel – Feed – Fiber

TERRA

Transportation Energy Resources from Renewable Agriculture



HT Plant Phenotyping

P = G × E × M

Integrated Breeding Systems

Genetics & Bioinformatics

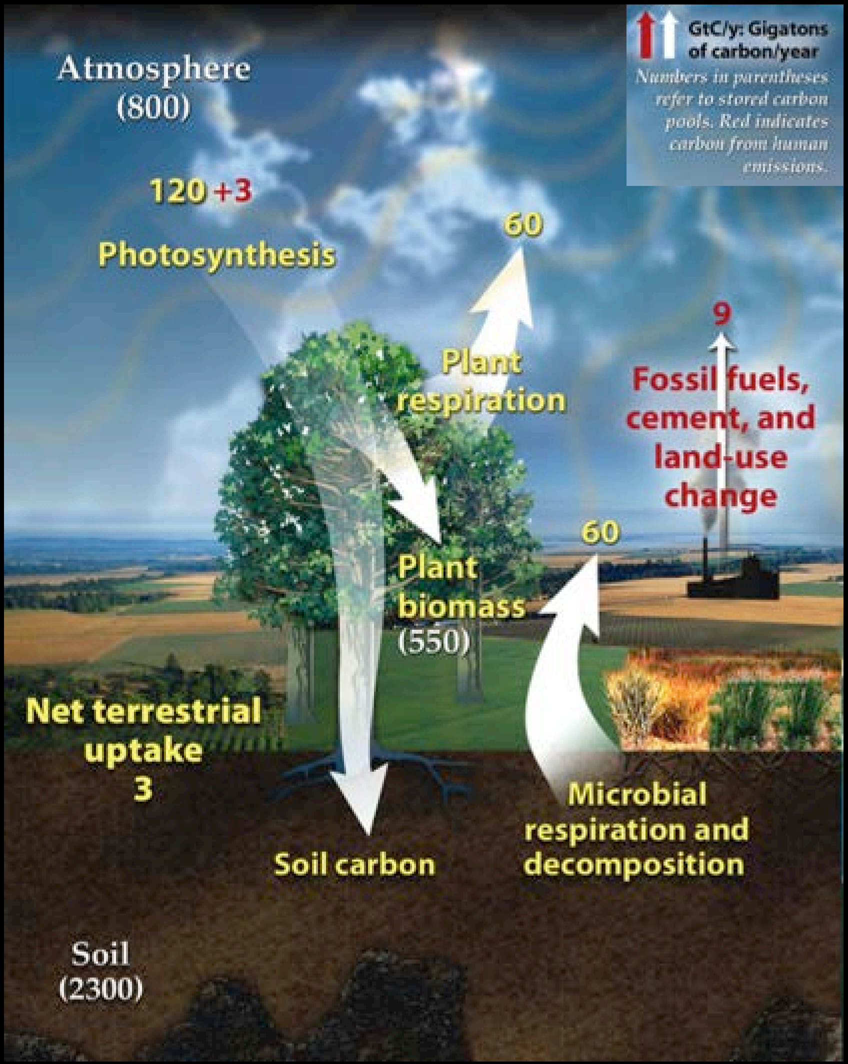
Field Robotics & Sensors

Computational Analytics

Potential New Program

Soil Health

“Biogeochemistry”



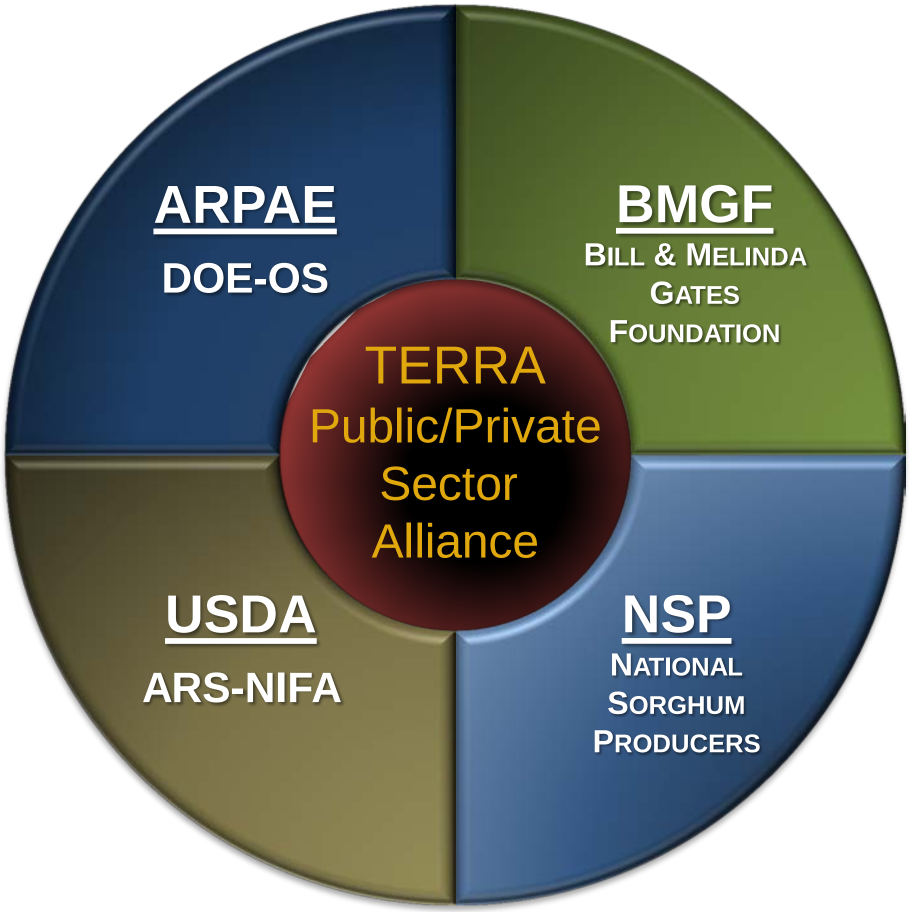
ARPAE TERRA Program
"standing upon the shoulders of giants"

Mission Alignment Creates Scale to Tackle the Really Big Problems

USDA
ars
NIFA
NSF
U.S. DEPARTMENT OF ENERGY
Office of Science
USAID
NASA
NIST
National Institute of Standards and Technology
U.S. Department of Commerce
DARPA

- Germplasm Development
- Crop Management
- Genomics
- Bioinformatics
- Computational Analytics
- Remote Sensing
- Autonomous Robotics

Building a Strategic Collaboration Network



COMPLEMENTARY INTERESTS

- Agricultural Productivity and Food Security
- Affordable and Sustainable Renewable Energy
- Economic Growth for Small Stakeholders
- International Market Development (Bio-Economy)
- Environmental Stewardship and Resiliency

As well as other Federal Agencies; Trade Associations; Agricultural Companies and Information Technology Companies.