Modernizing public plant breeding programs to deliver higher rates of genetic gain to farmers in the developing world

Gary Atlin
The Gates Foundation invests in public crop improvement to alleviate poverty by increasing the yields of smallholders.

- Increased yields result in increased food security and incomes for smallholders, lower food prices for the non-farming poor.
- Initial investment strategy was to “solve” the problem of drought by breeding drought tolerant varieties

- Plant breeding is also the primary mechanism for the adaptation of cropping systems to climate change
How is Gates’ approach to investing in crop improvement changing?

- We will remain in crop improvement and R&D but likely at a lower level. Multiple grants per crop/CGIAR center will likely be replaced with one investment.
- Less focus on rice, maize and wheat, more on other crops.
- Less focus on specific traits, more on optimizing the rate of genetic gain delivered to farmers’ fields, modernizing breeding and seed systems.
- Benefit to women and women’s access to products is critical.
- Strengthening national capacity is as or more important than direct products.
- Our investments will focus more on improving breeding system.
- We rely on metrics related to genetic gain and adoption.
What is the current viewpoint of donors about the CGIAR and Ag R4D? What do donors want?

- Donors have diverse views, but are concerned about governance and research impact. Business as usual will not attract new funds.
- In terms of crop improvement, CGIAR is not considered to be cutting edge.
- USAID is adopting the Gates’ focus on genetic gains; DfID, ACIAR, and JICA have similar interests in breeding modernization.
- CG centers need to position themselves as the best providers of modern breeding approaches to NARES.
- The CG needs to operate as a system, sharing services for higher quality, lower cost. Plans need to come from centers, not donors.
- Funding will not return to previous levels from the traditional donors unless there is a food crisis. New funds from governments of rice-producing countries, private sector are needed.
- Because funding decreases are likely permanent, centers need to relentlessly increase efficiency, reduce costs, and prioritize.
- The best ways to attract funding are to (i) modernize, (ii) help NARES modernize, and (iii) demonstrate impact on productivity.
Trait-based approaches are very successful in identifying large-effect alleles, but insufficient for delivering broad yield gains or climate change adaptation.

Submergence tolerance

Anaerobic germination
## Area and age of rice varieties grown in rainfed eastern India: 2014 wet season (T. Yamano, IRRI)

<table>
<thead>
<tr>
<th>Variety name</th>
<th>Year of release</th>
<th>Total area (x 1000 ha)</th>
<th>Proportion of total area under rice (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Swarna</td>
<td>1980</td>
<td>3,808</td>
<td>27.7</td>
</tr>
<tr>
<td>Pooja</td>
<td>1999</td>
<td>998</td>
<td>7.3</td>
</tr>
<tr>
<td>Lalat</td>
<td>1989</td>
<td>898</td>
<td>6.5</td>
</tr>
<tr>
<td>Moti</td>
<td>1989</td>
<td>277</td>
<td>2</td>
</tr>
<tr>
<td>Mahsuri</td>
<td>1975</td>
<td>1,208</td>
<td>8.8</td>
</tr>
<tr>
<td>Swarna-Sub1</td>
<td>2009</td>
<td>367</td>
<td>2.7</td>
</tr>
<tr>
<td>Sambha Mahsuri</td>
<td>1989</td>
<td>220</td>
<td>1.6</td>
</tr>
<tr>
<td>ARIZE 6444</td>
<td>2004</td>
<td>681</td>
<td>4.9</td>
</tr>
<tr>
<td>Sarju-52</td>
<td>1982</td>
<td>350</td>
<td>2.5</td>
</tr>
<tr>
<td>MTU1001</td>
<td>1997</td>
<td>523</td>
<td>3.8</td>
</tr>
<tr>
<td>MTU1010</td>
<td>2000</td>
<td>346</td>
<td>2.5</td>
</tr>
<tr>
<td>Sahbhagi Dhan</td>
<td>2012</td>
<td>35</td>
<td>0.3</td>
</tr>
<tr>
<td>Samba-Sub1</td>
<td>2012</td>
<td>30</td>
<td>0.2</td>
</tr>
<tr>
<td>Other hybrid</td>
<td></td>
<td>232</td>
<td>1.7</td>
</tr>
<tr>
<td>Other improved</td>
<td></td>
<td></td>
<td>9.9</td>
</tr>
<tr>
<td>Other traditional</td>
<td></td>
<td></td>
<td>4.5</td>
</tr>
<tr>
<td>Unknown</td>
<td></td>
<td>1,800</td>
<td>13.1</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>13,758</td>
<td>100</td>
</tr>
</tbody>
</table>

Area-weighted avg age of varieties = 28 yr
## Average area-weighted age of maize hybrids in Kenya: 2004-2010

<table>
<thead>
<tr>
<th>Year</th>
<th>Ave. area-weighted age</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004</td>
<td>15.4</td>
</tr>
<tr>
<td>2007</td>
<td>14.9</td>
</tr>
<tr>
<td>2010</td>
<td>17.3</td>
</tr>
</tbody>
</table>

**Smale and Olawande, 2014**

- In US, average commercial life for maize hybrids is 4 years. Same for barley in UK.
- Farmers producing in highly commercialized temperate systems are protected against climate change by rapid-cycle breeding; farmers in the developing world are not.
There will be no second Green Revolution, driven by large-effect QTL, without improved varietal “platforms”

- First-generation Green Revolution varieties “sold themselves” on the basis of large, visible differences induced by dwarfing genes
- Second-generation Green Revolution varieties “sold themselves” as a result of quality and disease resistance improvements
- Second-generation GR varieties got “stuck” in farmers’ fields because of lack of yield advantage in non-stress conditions
Estimates of rates of genetic gain in staple grain crops: rarely measured, and too low to drive adoption

<table>
<thead>
<tr>
<th>Species</th>
<th>Region/environment</th>
<th>Period</th>
<th>Rate of genetic gain (kg ha(^{-1}) yr(^{-1}))</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maize (Pioneer)</td>
<td>Corn Belt</td>
<td>1930-2010</td>
<td>89 (1.2%)</td>
<td>Duvick (2005)</td>
</tr>
<tr>
<td>Maize (CIMMYT)</td>
<td>Optimal environments</td>
<td>2000-2010</td>
<td>109 (1.4%)</td>
<td>B. Masuka (unpublished data)</td>
</tr>
<tr>
<td>Wheat (CIMMYT)</td>
<td>High-yield envs</td>
<td>1977-2008</td>
<td>64 (0.9%)</td>
<td>Lopes et al. (2012)</td>
</tr>
<tr>
<td>Wheat (CIMMYT)</td>
<td>Drought envs</td>
<td>1977-2008</td>
<td>10 (0.6%)</td>
<td>Lopes et al. (2012)</td>
</tr>
<tr>
<td>Maize (CIMMYT)</td>
<td>Low-N</td>
<td>2000-2010</td>
<td>21 (0.6%)</td>
<td>B. Masuka (unpublished data)</td>
</tr>
<tr>
<td>Rice (IRRI)</td>
<td>Wet season</td>
<td>1966-2013</td>
<td>22 (0.7%)</td>
<td>IRRI (unpublished data)</td>
</tr>
<tr>
<td>Rice (IRRI)</td>
<td>Dry season</td>
<td>1966-2013</td>
<td>15 (0.2%)</td>
<td>IRRI (unpublished data)</td>
</tr>
</tbody>
</table>

- Note that these are gains measured in research plots. Gains in farmers’ fields are almost certainly lower.
THE GENETIC GAINS INITIATIVE AIMS TO (I) INCREASE THE RATE OF GAINS GENERATED THROUGH BREEDING AND (II) INCREASE THE RATE OF VARIETAL REPLACEMENT IN FARMERS’ FIELDS

- Genetic gains initiative aims to shorten breeding cycle from ~15 to 5 years while selecting more accurately
- Breeding-to-seed system handoff needs to be managed to provide rapid varietal turnover (average age of varieties in farmers’ fields should be <10 years (now 15-30)

Good systems *generate* and *deliver* genetic gains of >1.5% annually, most now <0.5%

[Diagram showing the process of genetic gains initiative]

- Discovery and Gene/Trait Mobilization
- Trait introgression
- Genomic prediction
- Intermate best lines
- Select superior lines
- Candidate cultivars that fit the product profile
- NARES identify and release superior replacements for current varieties (data!!)
- Continuously deliver new varieties (via foundation seed) to companies/GOs/NGOs
- Foundation seed
- Selection of the product: for dissemination: a weak link in the public system
- Continuous delivery of new varieties and replacement of old via the seed system (climate change adaptation)
- Rapid-cycle improvement of source population drives the rate of genetic gain (by changing gene frequencies)

May 3, 2016

Good systems *generate* and *deliver* genetic gains of >1.5% annually, most now <0.5%

Confidential

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Some key lessons from Gates-funded projects on dissemination of new staple crop varieties

- Yield potential, quality, and maturity drive demand for new varieties; stress tolerance alone does not unless stress is frequent and yield losses severe.

- Farmer-to-farmer spread rarely happens. Breeding organizations and seed systems must aggressively “push” varieties.

- Most public (and many private) breeding organizations don’t generate enough data to confidently recommend that farmers should adopt a new variety. It is the breeding organization’s job to generate the data and make the recommendation.

- Small farmers are buying seed. Seed companies are going to be the main pathway into farmers’ fields.
Key metrics for investments in crop improvement and seed systems:

- **Rate of genetic gain delivered to farmers’ fields**
  - Intermediate metrics are set out in the Breeding Program Assessment Tool (BPAT)
  - We are only interested in publication if it provides information that helps other programs or breeders increase their effectiveness (must be open-source)

- **Average area-weighted age of varieties in farmers’ fields**
  - Metric developed by Byerlee and applied by Melinda Smale
  - Number of varieties released is of little interest- it’s an intermediate step on the way to adoption
  - Tons of seed produced is also an intermediate metric. We are most interested in direct, survey-based estimates of adoption
What are the routes to increased genetic gains?

1. Bigger programs (= higher i for yield)
   - Mechanization, automation, digitization

2. More elite genetic variability
   - Elite exotic materials

3. More accurate selection (=higher heritability)
   - Higher-quality phenotyping, better experimental designs, more reps, MAS

4. Faster breeding cycles
   - State of the art program design, genomic prediction, and new parents

5. Management that is empowered and accountable for product delivery
   - Research managers lead product development, planning, monitor progress, provide supportive environment, and ensure effective coordination among teams

6. Well-trained staff who understand product development
   - Most breeders needs to be retrained to work in product development teams, learn how to design products, and optimize pipelines for gains per unit time and money
Breeding programs need to be redesigned to exploit low-cost diagnostic markers

- CGIAR programs and partners have developed many diagnostic markers for abiotic and biotic stress tolerance. These are currently used for backcrossing only, not forward breeding.

- The cost of SNP genotyping through commercial services (LGC, Intertek) is < $0.20 per marker now (plus DNA extraction at <$1).

- The Gates Foundation is supporting a 2-year project to help CGIAR and NARES programs access SNP genotyping through the Intertek lab in Hyderabad. Aiming for price of $1.5 per plant for 5-10 SNPs, including DNA extraction. Cheaper than phenotyping.

- This means that lines can be fixed for key diagnostic markers before they are subjected to expensive phenotyping for yield and quality.

- Ability of service providers to offer low costs depends on volume and coordination with clients!
A pathway to increased selection intensity for yield, stress tolerance, and quality at low cost, when diagnostic markers are available for “must-have” traits

1. Develop as many fixed lines as possible, at minimum cost per line, using a locally suitable variable of single-seed descent, in field or screenhouse. Pedigree breeding is too expensive and ineffective.

2. Conduct low-cost, high-throughput screens for “must-have” quality (NIR) and disease resistance (low cost SNPs), and plant type (a single row or small plot in the field)

3. Screen all survivors in preliminary yield MET, unreplicated within locations, targeting H>0.5 for the combined analysis. Aim to shift resources from pedigree screening to preliminary yield testing

4. Use managed stress screens carefully, ensuring that (a) correlation with TPE is high, and (b) heritability is high. Do not give high weight to low-H screens
IRRI irrigated rice Era experiment

Wet season annual yield gain = 0.67%

Unpublished data. Vit Lopena, Rafiq Islam, Gina Vergara & Glenn Gregorio
IRRI irrigated rice ERA experiment

Dry season annual yield gain = 0.15%

Unpublished data. Vit Lopena, Rafiq Islam, Gina Vergara & Glenn Gregorio

Slide by Bert Collard
Transforming Rice Breeding (TRB) at IRRI

- As a result of low rates of genetic gain in the IRRI irrigated breeding program from the release of IR8 through 2013, the program was re-designed.
- Line development was accelerated, and its cost greatly reduced, by replacing pedigree breeding with RGA.
- Selection pressure for yield was greatly increased by expanding MET and introducing it at a much earlier stage.
- The breeding cycle was shortened by aggressively introducing promising new lines into the crossing block after PYT and AYT.
- An integrated breeding informatics system, B4R, was developed, adopted, and is now used to manage all aspects of line development, phenotyping, and selection.
- Field data collection is completely electronic.
- Planting (direct seeding) and threshing were mechanized to reduce costs and increase accuracy.
Speeding up the pipeline: pre-2012 pedigree breeding scheme

Year 1
- HYBRIDIZATION

Year 2
- PEDIGREE METHOD
  - F2
  - F3
  - F4
  - F5
  - F6
  - F7
  - F7:8

Year 3
- OYT
  - N = 600-800
  - 2 reps, 1 loc

Year 4
- RYT
  - N = 500
  - 3 reps, 1 loc

Year 5

Year 6

Year 7, 8

Breeding cycle = 8-9 years

MULTI-LOCATION TRIALS

N=30
Reducing line development costs and time: indoor single-seed descent at IRRI
New breeding scheme halves cycle time

Year 1
- HYBRIDIZATION

Year 2
- F2
- F3
- F4
- F5
- F5:6

Year 3
- OYT

Year 4
- PYT

Year 5
- AYT

Breeding cycle = 3 years

Genomic selection

MULTI-LOCATION TRIALS

N ~1400 unreplicated
N = 480 ~1.2 reps
Increasing $r, h_2$ through managed stress screening
Pedigree breeding replaced with indoor SSD (3-4 generations per year)

Line development costs were reduced to < $5

Breeding cycle length reduced from 9 years to 3

Ca. 10-fold increase in population sizes tested for yield in METs

Plants can be easily culled with diagnostic markers before field phenotyping

Survivors can be profiled before MET testing, with genomic prediction of value as parents
Variety product profiles

## IRRIGATED SOUTH-EAST ASIA

**Target regions:** High yielding production areas of South-East Asia
1. Philippines, Indonesia, Vietnam
2. Myanmar

**Requirements:**
- **Yield:** >5% over NSICRc222 (WS); Ciferang (Indonesia): OM4900 (Vietnam)
- **Agronomic traits:**
  - Height: 105-130 cm
  - Duration: 100-120 days; want to widen the current maturity window towards earlier varieties (SPB90c10)
  - Shorter duration (90-100 days) for intensive cropping systems
- **Disease resistance:**
  - Bacterial leaf blight and blast
  - Philippines: tolerance to Tungro virus (min. = NSICRc222)
- **Quality:**
  - Medium long slender grain; amylose content: intermediate (21-22%); OTR: intermediate; Gel consistency = soft (IR64 = benchmark)

**Desirable traits:**
- Submergence tolerance (SubT)
- Enhanced resistance to BLB (Philippines: xa5, xa21)
- Enhanced BPH and GLH resistance

### IRRIGATED EAST-SOUTH AFRICA

**TARGET REGIONS:** Mozambique + Tanzania + Burundi + Rwanda + Kenya + Uganda + Madagascar

**MUST-TRAITS:**
- **Yield:** > 15% over check
- **Duration:** 100–130 days
- **Disease resistance:** Blast, BLB, RYMV, S55<3
- **Grain quality:** Indica, Medium to long, Amylose 20-23%, aroma 90-100 (Semi dwarf)
- **Height:**

**RANGE-TRAITS:**
- **Milling recovery:** >65%
- **Lodging resistance:**
- **Thresh ability:** Intermediate (6-25%)
- **Abiotic stresses:** Salinity

**WIN-TRAITS:**
- **Texture:** Relatively same texture after storage
- **Disease resistance:** High overall resistance including brown spot, sheath rot
- **Submergence tolerance:** Tolerance of complete flooding for 7-10 days at vegetative stage, S55 (required in Gaza and Maputo, Mozambique)
## How is ICRISAT doing on breeding modernization relative to other centers?

<table>
<thead>
<tr>
<th></th>
<th>ICRISAT</th>
<th>IRRI</th>
<th>CIMMYT Maize</th>
<th>CIMMYT Wheat</th>
<th>IITA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanization of breeding</td>
<td>***</td>
<td>***</td>
<td>*</td>
<td></td>
<td>***</td>
</tr>
<tr>
<td>Integrated data management</td>
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<td>Outsourcing genotyping</td>
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<tr>
<td>Optimizing pipelines</td>
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<tr>
<td>Formal product profiles</td>
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<tr>
<td>Formal advancement system</td>
<td></td>
<td>**</td>
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<td>*</td>
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<tr>
<td>Measuring and reporting genetic gain</td>
<td>***</td>
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<tr>
<td>Geo-referencing the farm</td>
<td>**</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* = Initiated; ** = In progress; *** = Advanced
The Genetic Gains Support Platform: helping CGIAR and NARES breeding programs modernize

- Few CGIAR or NARES breeding programs have the knowledge or management skill in-house to drive change of this magnitude.
- Changes required are both managerial and technical.
- Many more technology and management changes are on the horizon, including the application of operations research methods to plant breeding.
- Strong consultancy support will be needed to support breeding program modernization.
- The CGIAR should be well-positioned to provide this consultancy, but it cannot work easily across crops with a national system in its current structure.
What support systems for genetic gains improvement are missing?

- Product profile development
- Mechanization and automation of breeding operations
- Detailed support for pipeline optimization
- Formal advancement processes
- Dissemination support
- Research management for product development (incentives, accountability, metrics)
- A single window for technology transfer from MNSCs
Centralized support systems are needed to help CGIAR and NARES breeding programs modernize

- The Integrated Breeding Platform (IBP) is providing a common, customizable, web-based Breeding Management System.
- Manages population development, seed stocks, phenotyping, low-density markers
- Prerequisite to application of high-throughput phenotyping, genomic data in breeding
- Linking to other data management systems (e.g. B4R, CassavaBase, KDArT) are developing a common breeding API (BRAPI)
Strategic genotyping and haplotype tracking will be made possible by GOBII

Reference genome ($100K):

Resequenced key ancestors ($2k)

Parents profiled via GBS ($30)

Selection candidates profiled with low density panels / highly multiplexed GBS ($10)

Genotype projection in each target species, combined with pedigree information, will allow entire HapMap to be projected onto selection candidates using low density marker panels
Centralized support: high-density profiling

- The Integrated Genotyping Service and Support (IGSS) is a collaboration between DArT and BecA to provide GBS profiling services to African breeding programs
- IGSS will provide both profiles and support on how to apply them.

Centralized support: shared Industrial-Scale High-Throughput Genotyping Facility (led by ICRISAT)

- The Shared High-Throughput Genotyping Service will provide uniplex SNP assays through a commercial service provider with labs in Europe, Australia, and India
- Will deliver SNP genotyping for $.05 per data point, with DNA extraction at $0.50. Target is to deliver a 5-10 SNP genotype for $1
- Allows selection for diagnostic markers at very low cost, with profiling restricted to a small subset.
- Will permit large increases in selection intensity
- Complete redesign of pipelines will be needed
Centralized support: planning and supporting program modernization

Breeding Program Assessment Tool (BPAT)

- Detailed questionnaire that evaluates ability of a program to deliver high rates of genetic gain
- Assesses targeting, technical effectiveness, pipeline optimization, support services, product development focus, and accountability systems
- Suggests basic areas for improvement
- Administered by UQ
- All Gates-funded (and probably other donor-funded) programs will need to undergo the assessment
What support systems for genetic gains improvement are missing?

- Product profile development
- Mechanization and automation of breeding operations
- Detailed support for pipeline optimization
- Formal advancement processes
- Dissemination support
The need to share some key services across centers and programs

- Individual CG centers and NARES cannot provide high-quality, low-cost services in genotyping, bioinformatics, biometrics, engineering, and breeding program optimization.
- By sharing capacity (GOBII) or bargaining power (HTG), the quality of service provided to breeding programs can be greatly increased, and costs reduced. (Labs generating SSRs at $5 per data point need to be closed now).
- By sharing capacity (GOBII) or bargaining power (HTG), the quality of service provided to breeding programs can be greatly increased, and costs reduced. (Labs generating $5 SSRs need to close now).
- Shared services need to be managed by and for users, to deliver higher rates of genetic gain.
- The CGIAR “system” needs to take responsibility for shared services. Gates has initiated BMS, GOBII, BPAT, etc, but the CG must be an effective partner in developing and maintaining them.
What should a genetic gains support platform do?

- Provide consultancy support for redesigning and improving CGIAR and NARES programs
- Promote and support best practice and monitor program performance
- Develop and manage low-cost, high-quality shared services where these are needed by aggregating capacity and bargaining power
- Aggressively link with MNSCs, technology licensers, and ARIs to acquire technology and rights for use in the service of SHF in the developing world

What should a genetic gains support platform not do?

- Directly manage breeding programs
- Promote centralization where there is not a clear benefit
The need for stronger support for NARES modernization

- NARES *institutional* capacity improvement is a high priority for donors
- Needs to be provided at the institutional level, across crops, in the form of a long-term consultancy
- Multi-crop centers should have an advantage in providing such services, but need to be state-of-the-art themselves
“Open-source” genomic selection breeding plan
“Open-source” genomic selection breeding plan

Rapid-cycle marker-only selection

Line extracted, genotyped: untested, proprietary DH lines provided to companies based on GEBVs
“Open-source” genomic selection breeding plan

Rapid-cycle marker-only selection

Line extracted, genotyped: untested, proprietary DH lines provided to companies based on GEBVs

Phenotyping: company 1
Phenotyping: company 2
Phenotyping: company 3
“Open-source” genomic selection breeding plan

Rapid-cycle marker-only selection

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"Open-source" genomic selection breeding plan

Rapid-cycle marker-only selection

Line extracted, genotyped: untested, proprietary DH lines provided to companies based on GEBVs

Phenotyping: company 1
Phenotyping: company 2
Phenotyping: company 3

Commercialization: company 1
Commercialization: company 2
Commercialization: company 3
What is the Gates Foundation doing as a partner to the CGIAR and its donors to increase genetic gains support?

- We have invested about $700 million in crop improvement in the CGIAR
- We have already spent or committed about $65 million on shared services, and $21 million on NARES and CGIAR breeding program upgrade projects
- We have $10 million in the 2017 pipeline for some type of genetic gains support unit for the CGIAR and partners
- We will continue to help our partners design, advocate for, and seek resources for an international crop improvement system that will help alleviate poverty more effectively.