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

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The Gates Foundation invests in public crop improvement to alleviate poverty by increasing the yields of smallholders, thereby reducing food costs

- Initial investment strategy was to "solve" the problem of drought by breeding drought tolerant varieties
- Adoption and productivity gains (post-GR) have been less than expected
- Began thinking hard about the problem of supporting a more effective public breeding system in 2013

Trait-based approaches are very successful in identifying large-effect alleles, but insufficient for delivering climate change adaptation

- Focus is shifting to supporting effective cultivar development and dissemination pipelines

Rates of genetic gain in staple crops: rarely estimated, and often 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</td>
<td>Corn Belt</td>
<td>1980-2010</td>
<td>99 (1.2%)</td>
<td>Durick (2005)</td>
</tr>
<tr>
<td>Maize</td>
<td>CIMMYT</td>
<td>2000-2010</td>
<td>109 (1.4%)</td>
<td>B. Masuka (unpublished data)</td>
</tr>
<tr>
<td>Wheat</td>
<td>CIMMYT</td>
<td>High-yield envs</td>
<td>1977-2008</td>
<td>64 (0.9%)</td>
</tr>
<tr>
<td>Wheat</td>
<td>CIMMYT</td>
<td>Drought envs</td>
<td>1977-2008</td>
<td>15 (0.6%)</td>
</tr>
<tr>
<td>Maize</td>
<td>CIMMYT</td>
<td>Low N</td>
<td>2000-2010</td>
<td>21 (0.6%)</td>
</tr>
<tr>
<td>Rice</td>
<td>IRRI Wet season</td>
<td>1966-2013</td>
<td>22 (0.7%)</td>
<td>IRRI (unpublished data)</td>
</tr>
<tr>
<td>Rice</td>
<td>IRRI 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IRRI (unpublished data)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

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>Poja</td>
<td>1999</td>
<td>988</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>1999</td>
<td>277</td>
<td>2</td>
</tr>
<tr>
<td>Mahaul</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 Mahauli</td>
<td>1989</td>
<td>220</td>
<td>1.6</td>
</tr>
<tr>
<td>ARIZE 6444</td>
<td>2010</td>
<td>681</td>
<td>4.9</td>
</tr>
<tr>
<td>Satju-52</td>
<td>1992</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>99</td>
<td>6.5</td>
</tr>
<tr>
<td>Other traditional</td>
<td></td>
<td>4.5</td>
<td></td>
</tr>
<tr>
<td>Unknown</td>
<td></td>
<td>13.1</td>
<td></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

To double rates of gain, we must transform public breeding programs serving the developing world.

- Some elements of CGIAR trait pipelines and breeding programs are world-class...
What’s missing from public crop improvement?

- **Management, incentive, and accountability systems** appropriate for product development;
- **Strategic product profiles** based on strong understanding of target markets and production systems;
- **Modern breeding informatics systems** to improve selection accuracy, document performance;
- **Centralized consulting support** for breeding pipeline optimization;
- **Mechanized and automated trial and nursery management** to increase throughput and accuracy of phenotyping and population development;
- **Comprehensive genomics databases** integrating sequence, high-density, and low-density marker data;
- **Low-cost genotyping technologies** that allow genomics information to be applied in forward breeding;
- **Strong product advancement, support, and promotion systems** allowing breeding programs to confidently warrant that their products are truly superior;
- **Well-trained staff**: PhD’s in plant breeding are usually geneticists, not breeders.

Key services and functions for increasing the rate of genetic gains from public breeding programs

Integrated breeding information management systems (BMS, B4R, Cassavabase, AgroBase, Prism, KD-DArT)

- Prequisite to any other modernization step (use of markers, local error control, high-throughput phenotyping);
- Migration is always painful and expensive- it must be fully supported and mandated by research managers.
- Migrate now, curate later. Old trials and nurseries quickly lose importance.
- Breeding informatics systems are management as well as research tools; data belong to the institution, not the scientist.
- For breeders and techs, all key repeated tasks need to be done in one interface.
- Breeding tasks are nearly identical among crops. We need to prevent needless system duplication to build deep user culture.
- Graduate students need to train on the system.

High-quality and high-throughput phenotyping means controlling field noise

Experimental Design + Statistical Analysis

- **Resequenced key ancestors** ($3k)
- **Parents profiled via GBS** ($30)
- **Selection candidates profiled with low density panels / highly multiplexed GBS** ($30)
- **Variograms**
- **Heat Maps**

Strategic genotyping and haplotype tracking will be made possible by GOBII

- **Reference genome** ($100K)
- **Resequenced key ancestors** ($3k)
- **Parents profiled via GBS** ($30)
- **Selection candidates profiled with low density panels / highly multiplexed GBS** ($30)

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

Key services and functions for increasing the rate of genetic gains from public breeding programs

Global Open Breeding Informatics Initiative (GOBII)

- Huge volumes of sequence, GBS, and marker data have been assembled in most staple crops, but are unusable in breeding.
- No individual public breeding program can afford to create the bioinformatics systems needed to use genomic data in selection
- GOBII will organize sequence, GBS, and uniplex marker data from different systems onto a single scaffold.
- GOBII will provide a suite of tools for supporting selection decisions based on sequence and marker data (eg MAS, GS, IBD segment tracking, relationship analysis)
- Will be seamlessly linked to breeding informatics systems.
Centralized support: high-density profiling

- The Integrated Genotyping Service and Support (IGSS, $9 M) 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 ($4 M) will provide uniplex SNP assays through a commercial service provider with labs in Europe, Australia, and India
- Will deliver SNP genotyping for $0.05 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

Low-cost genotyping must drive a complete redesign of pipelines so opportunities for higher selection intensity can be exploited

Key BMS Components

- Breeding Strategy
- Phenotypic Information
- Environmental Information
- Genomic Information
- Analysis Pipelines
- Skilled Breeders

Key GOBII Components

- Breeding Strategy
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- Environmental Information
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Transforming Rice Breeding at IRRI

- Pedigree breeding replaced with indoor SSD (3-4 generations per year)
- Line development costs of < $5
- 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

Speeding up the pipeline: pre-2012 pedigree breeding scheme

- Breeding cycle = 8-9 years

New breeding scheme halves cycle time

- Breeding cycle = 3 years
Centralized support systems are needed to help 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

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
- Research management for product development (incentives, accountability, metrics)
- A single window for technology transfer from MNSCs
- The CGIAR needs a strong, central consultancy/clearing house to support modernization

Putting it all together: EMBRAPA upland rice 1984-2009

- To achieve a higher rate of gain, a higher level of management and better coordination among internal and external service functions and breeding programs will be needed.
- The potential results are worth it!