Accelerating Genetic Gains
in Maize and Wheat

Genetic Gains in CIMMYT Maize Breeding Program in Africa

Yoseph Beyene and B.M. Prasanna
with CIMMYT-GMP colleagues in Africa

Presentation to AGG-EiB Webinar on
Enhancing and Measuring Genetic Gain in Crop Breeding, 19 November 2020

CIMMYT
International Maize and Wheat Improvement Center

Increasing Genetic Gain in Breeding Programs

Fundamentals

- Experimental designs and control of plot-to-plot variability
- Effective population size
- Multi-environment trials
- Phenotyping throughput and accuracy
- Genetic diversity
- Reducing cycle time

i
selection intensity

r
selection accuracy

$$R_t = \frac{i r \sigma_A}{y}$$

y
cycle time

genetic variability
$\boldsymbol{\sigma_A}$

<u>Years/Cycle</u>
→ Genomic selection
→ Doubled haploids
→ Off-season nursery

AGG-Maize Target: Develop climate-resilient products delivering 1.5 to 2.0% annual genetic gains

CIMMYT Maize Breeding Pipelines

Eastern and Southern Africa

Code	Pipeline description	Target Countries	Est. Area (M ha)
EA-PP1	**Early/intermediate-maturing, white maize** varieties with **drought-tolerance, NUE** and resistance to GLS, TLB, Ear rots, MSV and **MLN**, and suitable for food use in Eastern African **tropical rainfed dry/wet mid-altitude areas.**	Ethiopia, Kenya, Uganda, Tanzania (Northern)	3.17
EA-PP2	**Late-maturing**, **white maize** varieties with **drought tolerance, NUE,** and resistance to GLS, TLB, MSV, common rust, and ear rots, adapted to **Eastern African tropical rainfed wet, upper mid-altitude areas**, and used mainly for food purposes.	Ethiopia, Kenya, Uganda, Tanzania (Southern)	3.38
EA-PP3	**Late-maturing**, **multiple stress-tolerant white maize** varieties for the **Eastern African tropical rainfed highlands** and used mainly for food purposes.	Ethiopia, Kenya, Uganda, Tanzania (Southern)	1.75
SA-PP1	**Intermediate/late maturing**, nitrogen-use efficient (NUE), **drought- and heat-tolerant white maize** varieties for the Southern African tropical rainfed mid-altitude/transition areas and used mainly for food purposes.	Mozambique, Zimbabwe, Malawi, Zambia, Tanzania (Southern); drought-prone smallholder farm areas in South Africa	3.74
SA-PP2	**Early-maturing, drought-, heat- and low soil pH stress-tolerant white maize** varieties for the **Southern African dry/wet lowland and mid-altitude areas** and used mainly for food purposes.	Zimbabwe, Malawi, Zambia, Tanzania (Southern), drought-prone smallholder farmers, about 2-3% of total maize area)	2.03

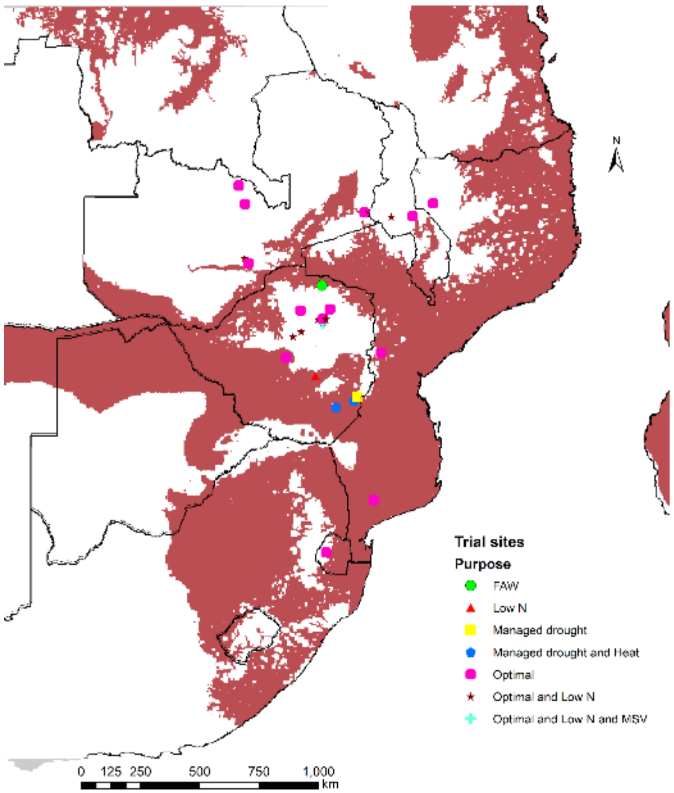
CIMMYT Eastern Africa Maize Breeding Pipelines

- **An extensive field network to screen for various "must have" and "good-to-have traits" within the Target Population of Environments (TPE).**
- The network is managed between CIMMYT, NARS and private sector – in Eastern Africa, NARS accounts for **~80%** of network, and in Southern Africa **50-65%**.

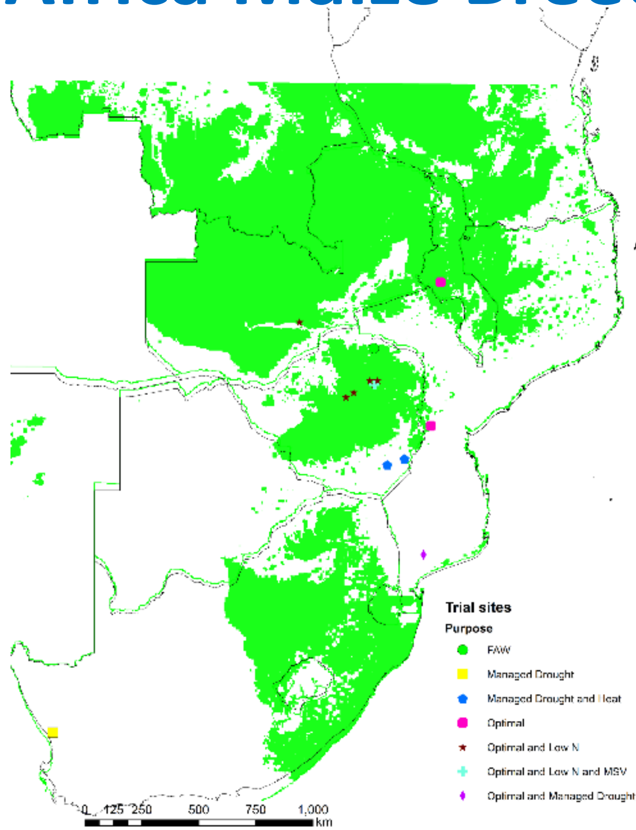
Key Testing Locations

Location	Key Traits
Kiboko (KE)	Yield under drought, low N, Optimal, FAW, stem borers
Kakamega (KE)	Yield, GLS, TLB, common rust, Fusarium ear rot
Elgon downs (KE)	Yield, GLS, TLB, common rust, Fusarium ear rot
Bako (ET)	Yield under optimal and low N, GLS, TLB
Karatu (TZ)	Yield, common rust
Uyole (TZ)	Yield, GLS, TLB
Bulindi (UG)	Yield, TLB
Bulegeni (UG)	Yield, GLS
Embu (KE)	Yield under optimal, low N
Alupe, Kibos (KE)	Striga (artificial infestation)
Naivasha (KE)	MLN (artificial inoculation)

CIMMYT Southern Africa Maize Breeding Pipelines



SA-PP1
(Intermediate maturity)



SA-PP2
(Early/Extra-early maturity)

Key Traits

Yield	High grain yield
Grain color	White
Good agronomic traits	Lodging tolerance; Husk cover
Abiotic stress tolerance	Drought, Heat, NUE, Soil acidity
Biotic stress resistance	GLS, TLB, Rust, FER, MSV, FAW, MLN
Seed producibility	Female-male synchrony; Female parent yield

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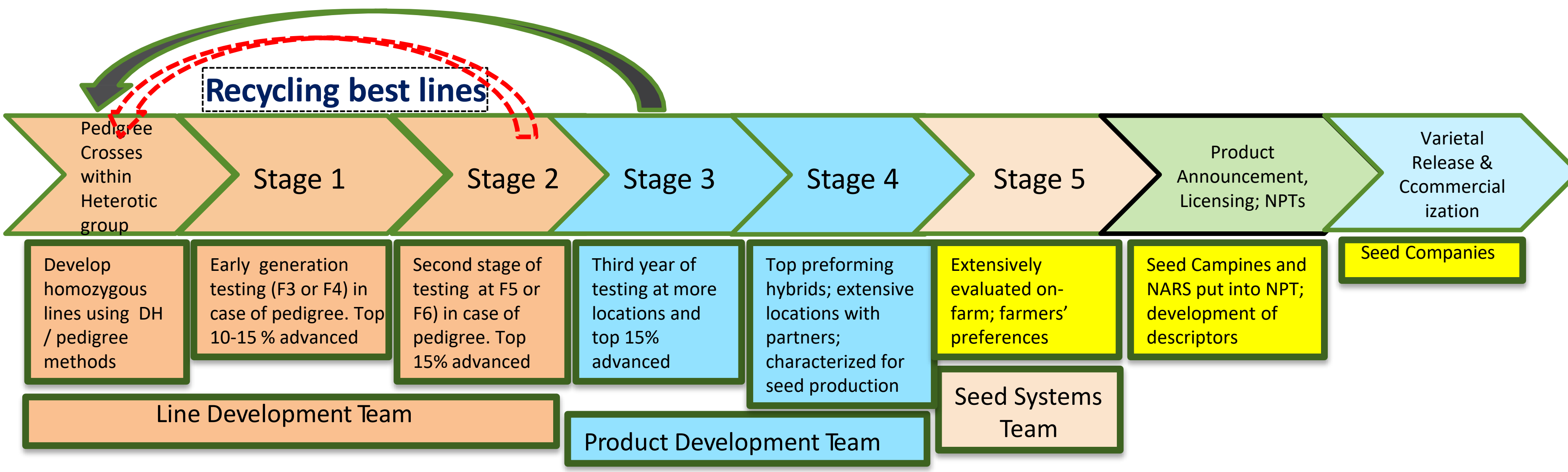
CIMMYT Maize Breeding: Stage-Gate Process



- **Stage 1** – First testcross evaluation; one tester; 2 reps, 3-5 sites
- **Stage 2** – Selected lines (10-15% S.I.) from Stage 1 trials; 3 testers; 2 reps, 8-10 sites
- **Stage 3** – Selected lines from Stage 2 trials (15% S.I.); Cross with 5 testers; 2 reps, 10-15 locations
- **Stage 4 (Regional On-station Trials)** – Best products from Stage 3; 2 rows, 3 reps, 45-60 entries
- **Stage 5 (Regional On-Farm Trials)** – 30-50 on-farm trials per Product Profile; Farmers' preferences
- **Final Product Advancement Meeting** to identify products/pre-commercial hybrids to be announced to the partners through CIMMYT Website

Process & Criteria for Stage-Gate Advancement

Stage 1 to Stage 2 [Line Development Team]

- Line entering Stage 1 TC are pre-selected for disease resistance (e.g., MSV, MLN) using markers.
- GEBV of the line estimated
- Hybrid performance (yield under optimal, and abiotic stresses, diseases)
- Selection intensity of 10-15% applied
- Use of weights as appropriate using inhouse Fieldbook software
- Number of lines used in Stage 1 varies: 1000-1500.

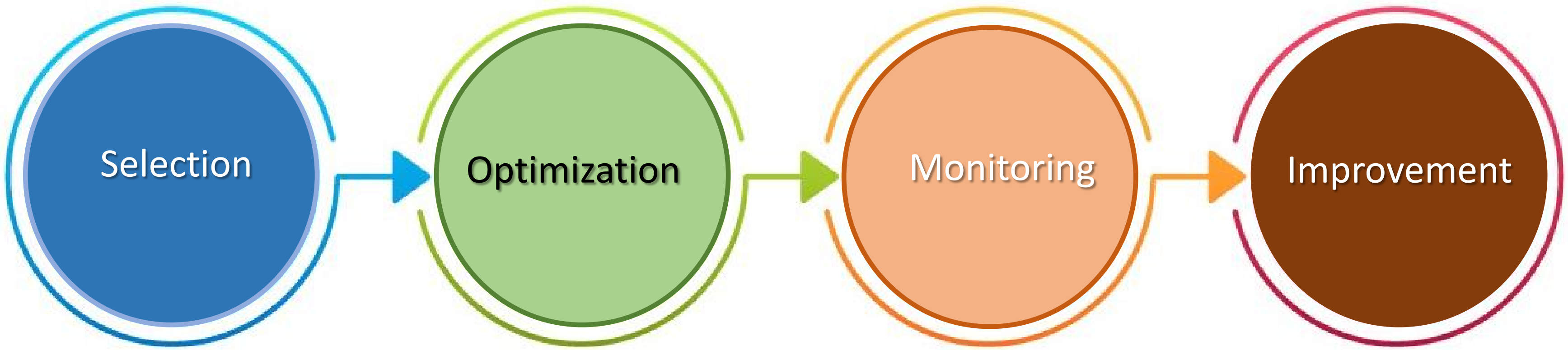
Stage 2 to Stage 3 [Line Development Team]

- GCA of the line with three testers
- Hybrid performance at more locations relative to Stage 1 (5 optimal; 1 drought; 1 low N; 1 MLN; 1 Striga; 1 for foliar diseases)
- Sites with low heritability (<0.10) discarded
- Selection intensity of 10-15% applied.

Stage 3 to Stage 4 [Product Development Team; Advancement Committee]

- Hybrid performance at more locations (10-15) relative to Stage 2 (7 optimal; 1 drought; 2 low N; 1 MLN; 2 Striga; 2 for foliar diseases)
- Sites with low heritability (<0.10) discarded
- Selection intensity of 15% applied
- Breeding Team decision on lines to be recycled

Testing Site Selection and Optimization

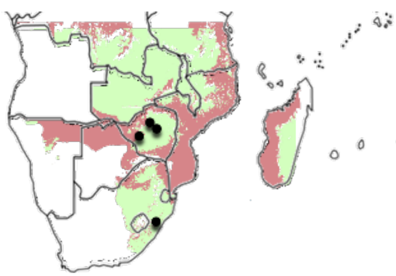


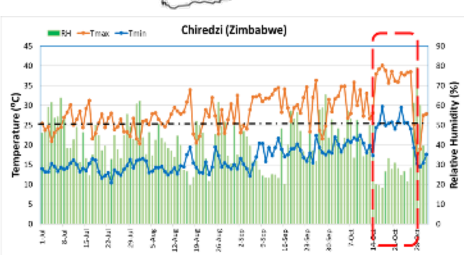
Product Profiles based selection

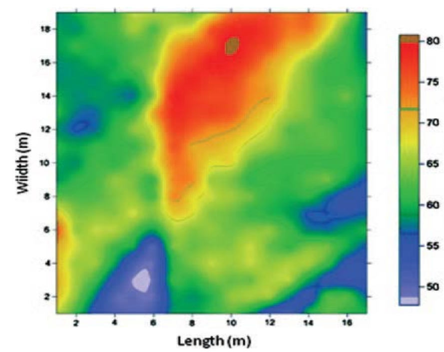
Uniformity trial/testing

Tracking variability

Increasing precision

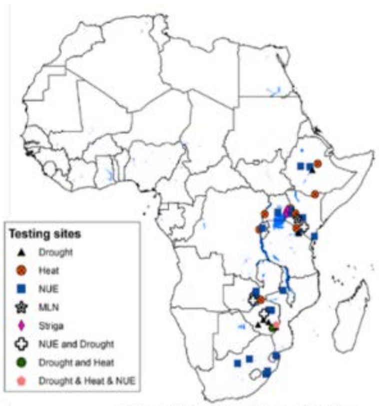






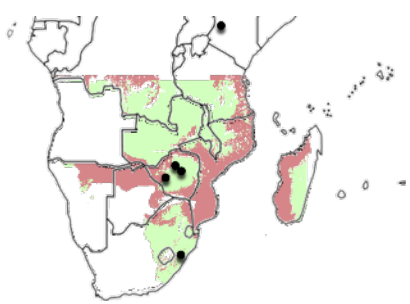
Improving Phenotyping Accuracy and Selection Efficiency

Network



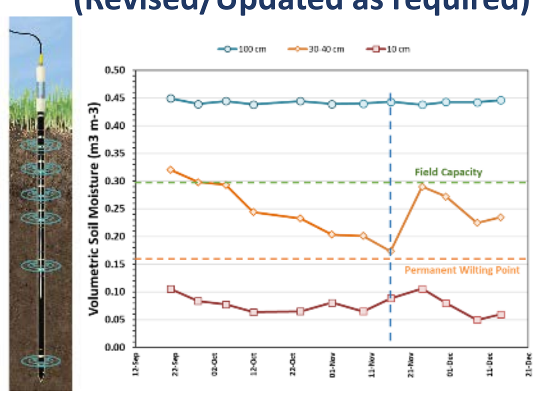
updated from Prasanna et al. 2013

Product Profiles based testing network



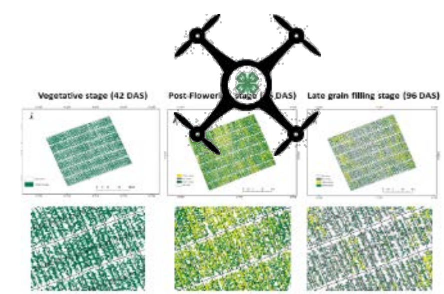
Protocols

Harmonized Protocols (Revised/Updated as required)



Data Collection methods

Digitization and sensor-based phenotyping



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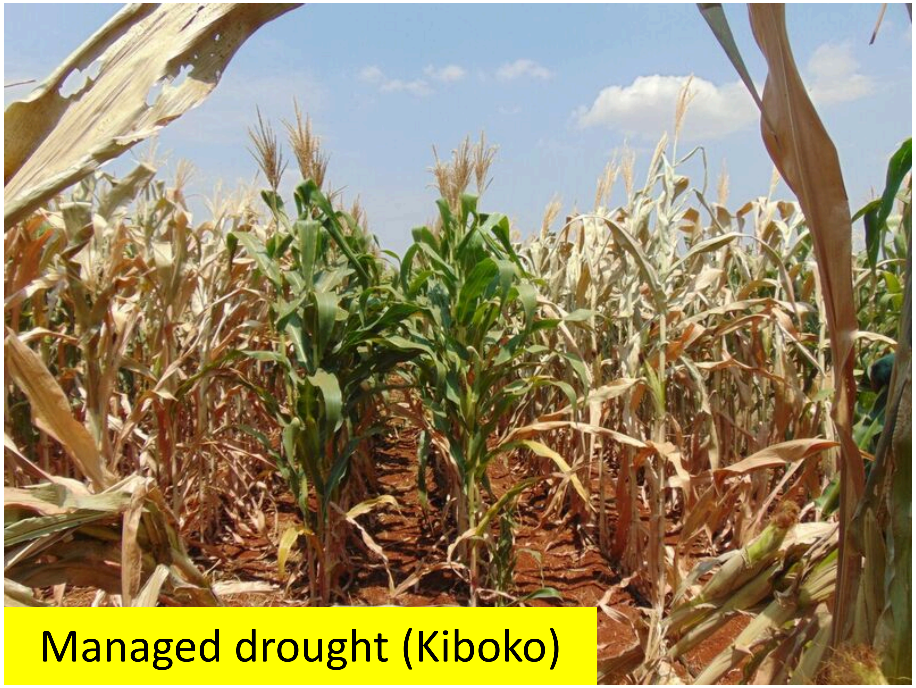
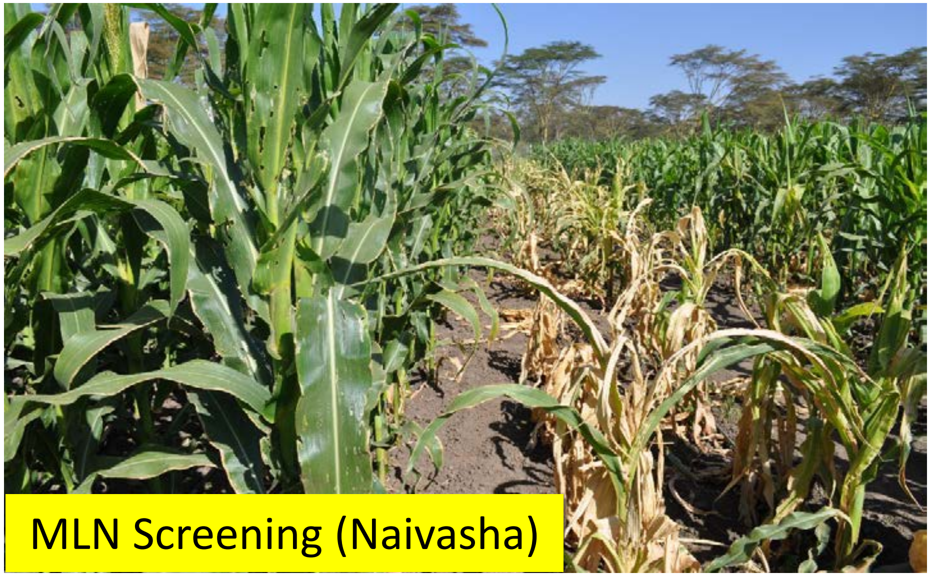
Phenotyping for "Must-have" and "Value-added" Traits



Managed drought (Kiboko)

Turcicum leaf blight (Kakamega)

GY under Optimum (Embu)



MLN Screening (Naivasha)

Integrating DH in Maize Breeding in ESA

- DH lines developed from **2124 populations** with an average of **160 DH lines per population**.
- These DH lines were evaluated for per se performance, including responses to major leaf diseases in Africa.
- Testcrosses developed and evaluated in Stages 1, 2 & 3 and Regional Trials across locations in different countries
- DH-based hybrids released in Kenya, Uganda, Tanzania, South Africa and nominated in Mozambique

Over **350,000 maize DH lines** generated and tested by CIMMYT in the last 7 years

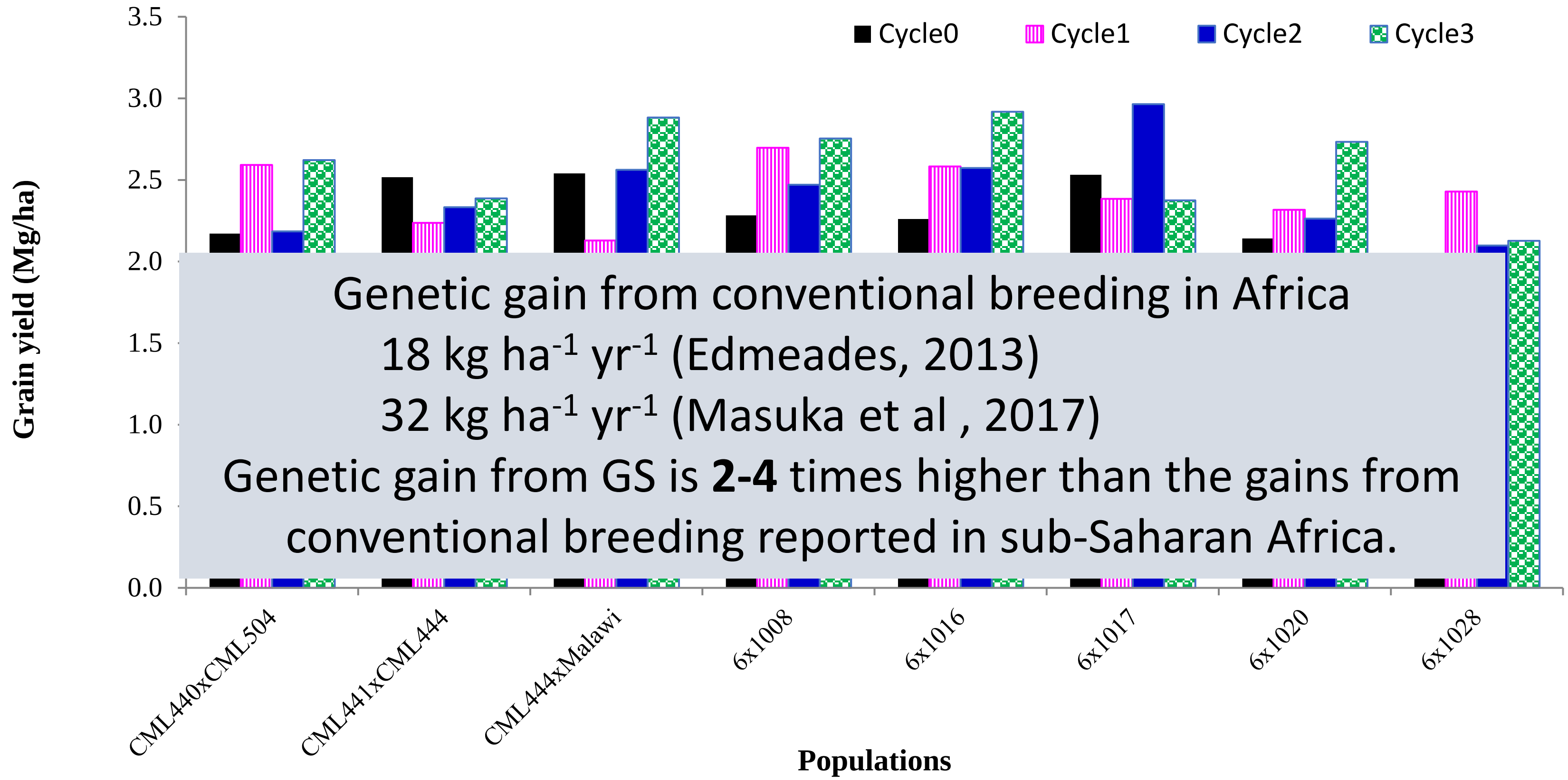
Forward Breeding: Using Msv1 haplotype for selection of MSV resistance at early stage of testcross formation

SNP	Trait	Chr	SNP	RR	SS
PZE0186065237	MSV	1	C/T	C:C	T:T
PZE0186365075	MSV	1	C/A	C:C	A:A
PZE-10109395	MSV	1	A/G	A:A	G:G

Sampling leaf tissue in the DH nursery

Population	PZE-101093951	PZE0186065237	PZE0186365075	Comment on msv1 data	Decision
CML312/INTA-F2-192-2-1-1-1-B*7-2-B-10-B-B-B:@	A:A	C:C	C:C	Homozygous for favorable alleles at 3 loci	Select
CML312/INTA-F2-192-2-1-1-1-B*7-2-B-10-B-B-B:@	A:A	C:C	C:C	Homozygous for favorable alleles at 3 loci	Select
CML312/LaPostaSeqC7-F18-3-2-1-1-B-B-B:@	A:A	C:C	C:C	Homozygous for favorable alleles at 3 loci	Select
CML312/LaPostaSeqC7-F18-3-2-1-1-B-B-B:@	A:A	C:C	C:C	Homozygous for favorable alleles at 3 loci	Select
CML312/LaPostaSeqC7-F18-3-2-1-1-B-B-B:@	G:G	T:T	A:A	Homozygous for unfavorable alleles at 3 loci	Reject
CML312/LaPostaSeqC7-F18-3-2-1-1-B-B-B:@	G:G	T:T	A:A	Homozygous for unfavorable alleles at 3 loci	Reject
CML312/LaPostaSeqC7-F18-3-2-1-1-B-B-B:@	G:G	T:T	A:A	Homozygous for unfavorable alleles at 3 loci	Reject
CML312/LaPostaSeqC7-F18-3-2-1-1-B-B-B:@	G:G	T:T	A:A	Homozygous for unfavorable alleles at 3 loci	Reject

Gain in grain yield using genomic selection under drought environments in ESA



Genetic gain from conventional breeding in Africa

18 kg ha^{-1} yr^{-1} (Edmeades, 2013)

32 kg ha^{-1} yr^{-1} (Masuka et al , 2017)

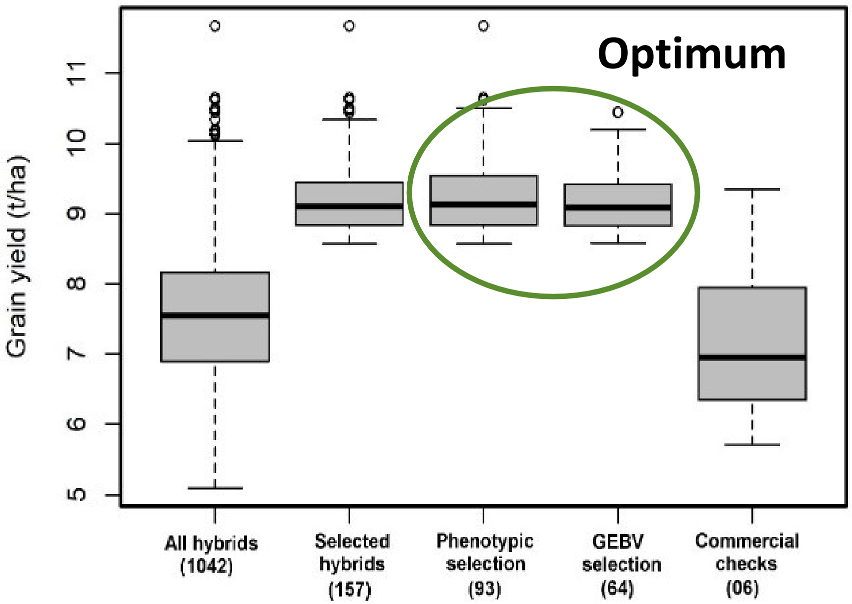
Genetic gain from GS is **2-4** times higher than the gains from conventional breeding reported in sub-Saharan Africa.

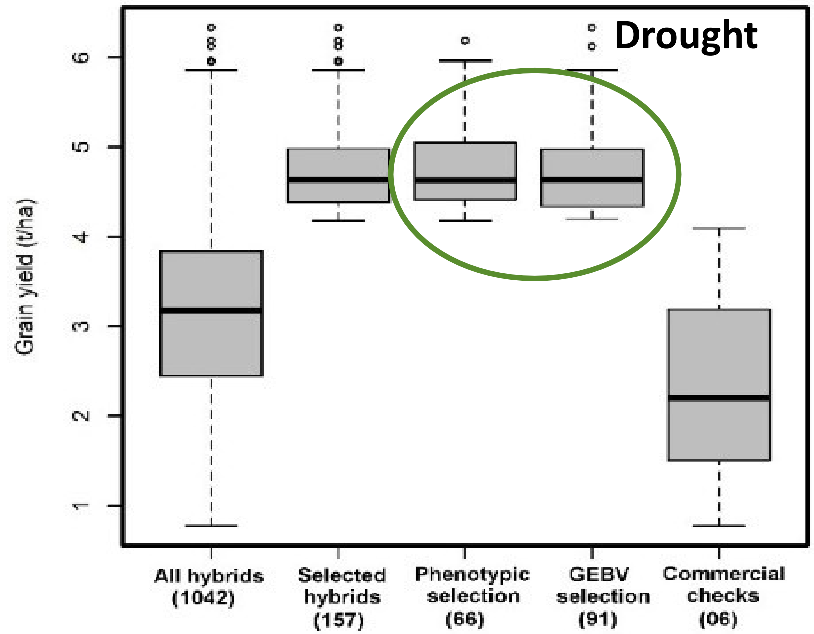
Overall gain in GY : 70.5 kg ha^{-1} $year^{-1}$

Beyene et al. 2015: Crop Sci.

Genomic selection shows clear benefits over PS alone

Category	# lines	# testers	# of hybrids
All stage II hybrids	348	3	1042
Hybrids advance through phenotype	176	3	526
Hybrids advance through GEBV	172	3	516





Stage1 TC:
50% Phenotyping + 50% genotyping

Methods	Total cost (US$)
Total cost of GS	91,870
Total cost of PS	134,280
GS:PS cost ratio	**0.68**

Beyene et al (2019). *Front. Plant Sci.* 10:1502. doi: 10.3389/fpls.2019.01502

RESEARCH

Genetic Gains in Grain Yield Through Genomic Selection in Eight Bi-parental Maize Populations under Drought Stress

Yoseph Beyene,* Kassa Semagn, Stephen Mugo, Amsal Tarekegne, Raman Babu, Barbara Meisel, Pierre Sehabiague, Dan Makumbi, Cosmos Magorokosho, Sylvester Oikeh, John Gakunga, Mateo Vargas, Michael Olsen, Boddupalli M. Prasanna, Marianne Banziger, and Jose Crossa

frontiers in Plant Science

ORIGINAL RESEARCH
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Effect of Trait Heritability, Training Population Size and Marker Density on Genomic Prediction Accuracy Estimation in 22 bi-parental Tropical Maize Populations

Ao Zhang[1,2‡], Hongwu Wang[2,3‡], Yoseph Beyene[4], Kassa Semagn[4†], Yubo Liu[1,2], Shiliang Cao[5], Zhenhai Cui[1], Yanye Ruan[1], Juan Burgueño[2], Felix San Vicente[2], Michael Olsen[4], Boddupalli M. Prasanna[4], José Crossa[2], Haiqiu Yu[1] and Xuecai Zhang[2*]*

Euphytica (2016) 208:285–297
DOI 10.1007/s10681-015-1590-1

CrossMark

Performance and grain yield stability of maize populations developed using marker-assisted recurrent selection and pedigree selection procedures

Yoseph Beyene · Kassa Semagn · Stephen Mugo · Boddupalli M. Prasanna · Amsal Tarekegne · John Gakunga · Pierre Sehabiague · Barbara Meisel · Sylvester O. Oikeh · Michael Olsen · Jose Crossa

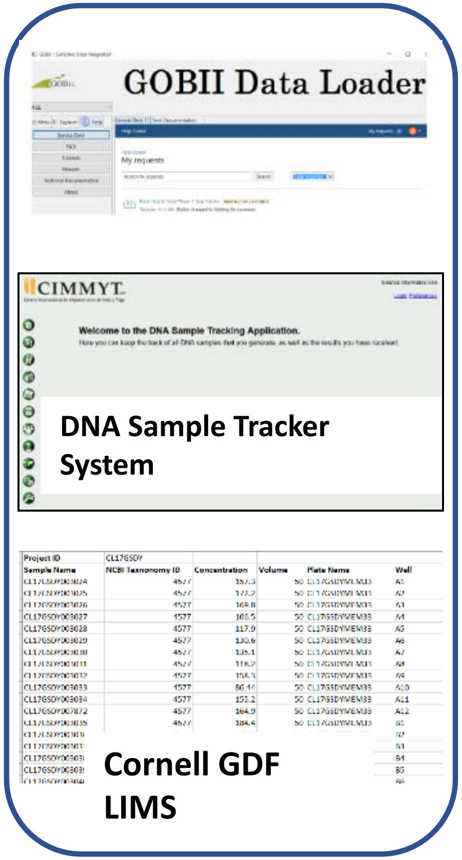
RESEARCH

Improving Maize Grain Yield under Drought Stress and Non-stress Environments in Sub-Saharan Africa using Marker-Assisted Recurrent Selection

Yoseph Beyene,* Kassa Semagn, Jose Crossa, Stephen Mugo, Gary N. Atlin, Amsal Tarekegne, Barbara Meisel, Pierre Sehabiague, Bindiganavile S. Vivek, Sylvester Oikeh, Gregorio Alvarado, Lewis Machida, Michael Olsen, Boddupalli M. Prasanna, and Marianne Bänziger

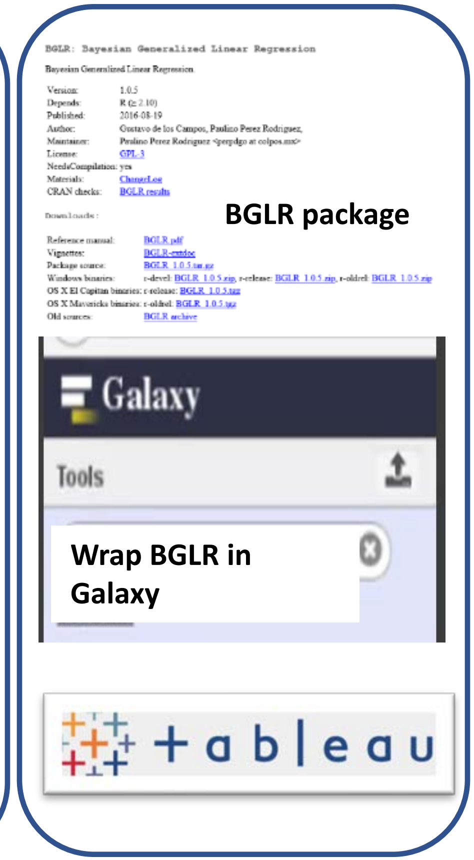
Integrating Phenotypic and Genotypic Data to Implement Forward Breeding and GS

Trial preparation/
Field data collection



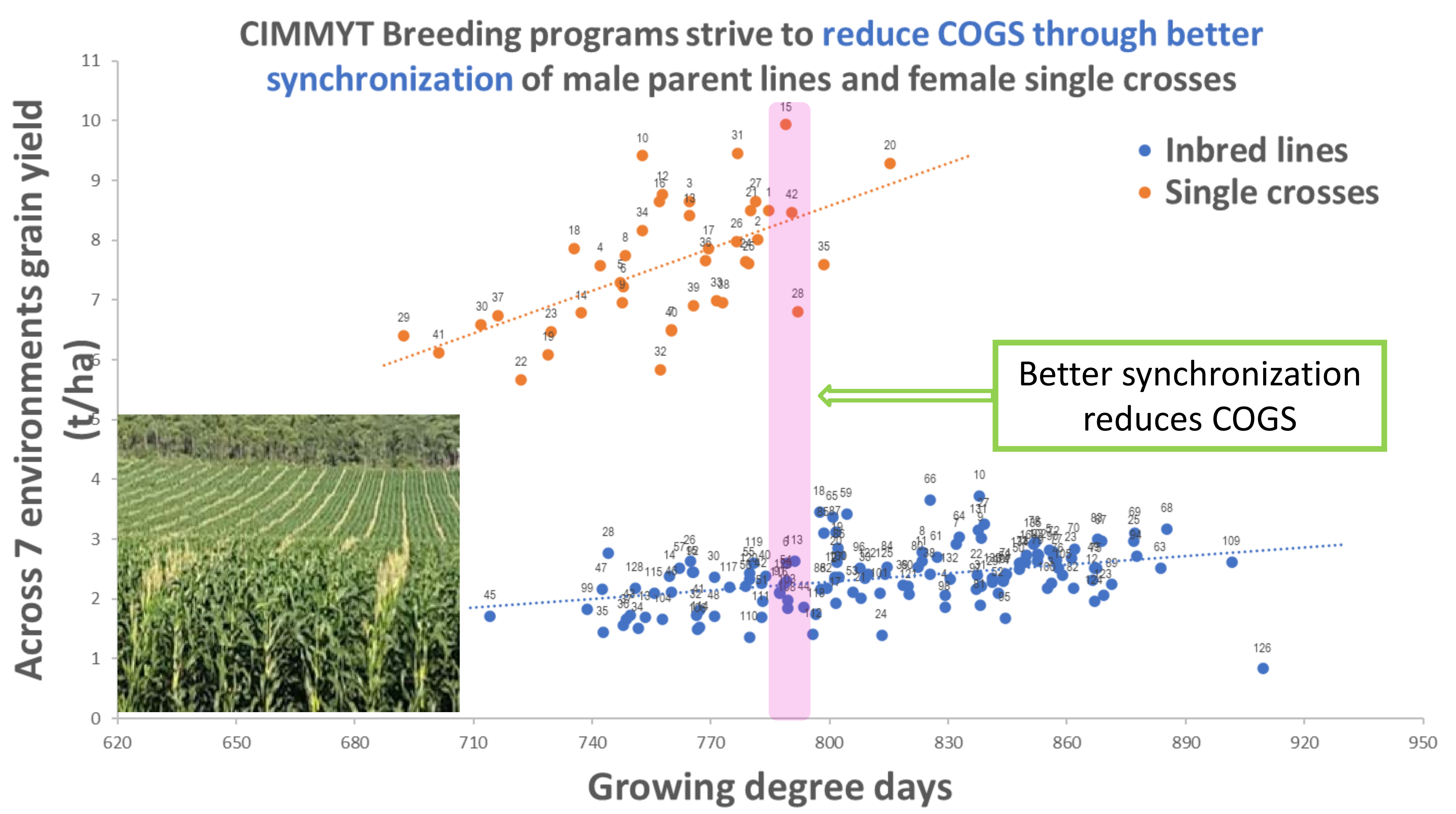
Genotypic data storage/
Links phenotypes with genotypes

Forward breeding/
selection and visualization tool



Genomic Prediction/
selection and visualization too

Seed Systems as an integral part of Maize Breeding



Parents of Stage 4 Hybrids, CIMMYT-Kenya, 2019

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Genetic Gains Assessment by CIMMYT Maize Program

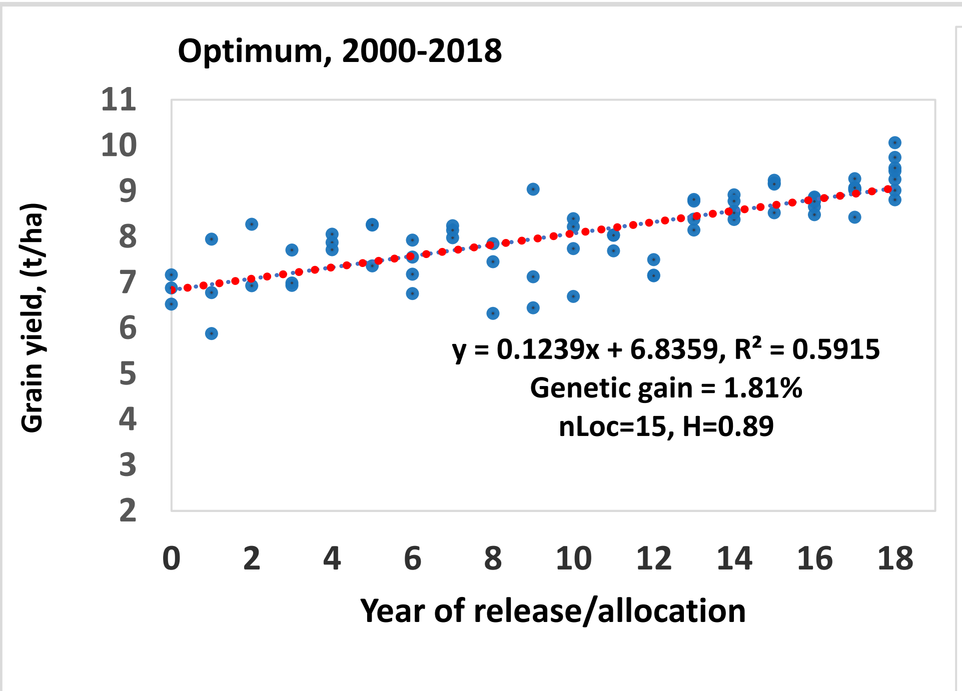
1. "Era study" – evaluates hybrids released/developed in different years together in common field trials (useful as a baseline, but expensive to implement)
2. Genetic gain estimate using historical/long-term yield trials (useful, especially for breeding programs with long-term history)
3. Annually comparing newer hybrids with baseline commercial hybrids and internal genetic gain checks (must-do in breeding programs)

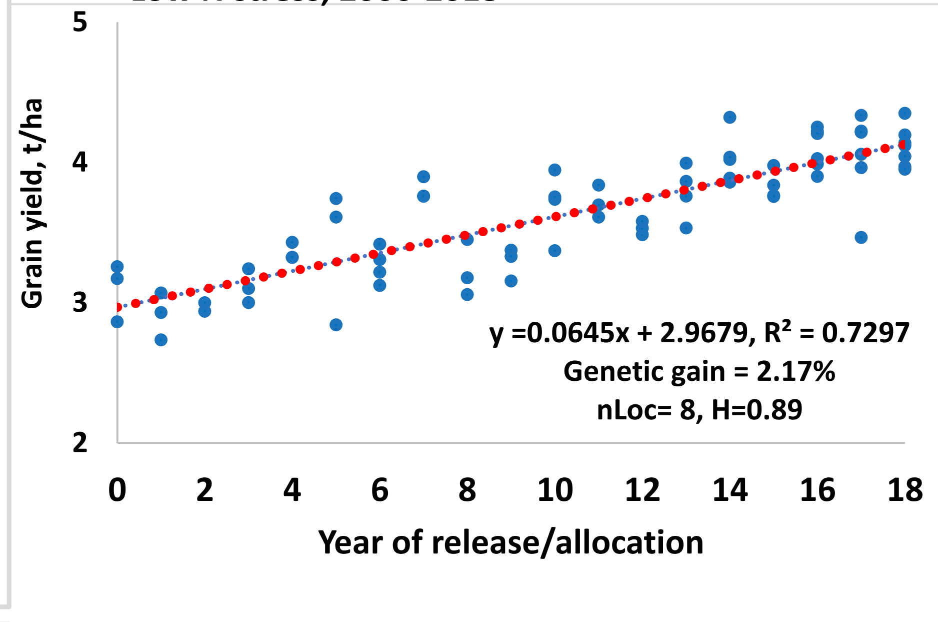
CIMMYT-ESA: Era Study

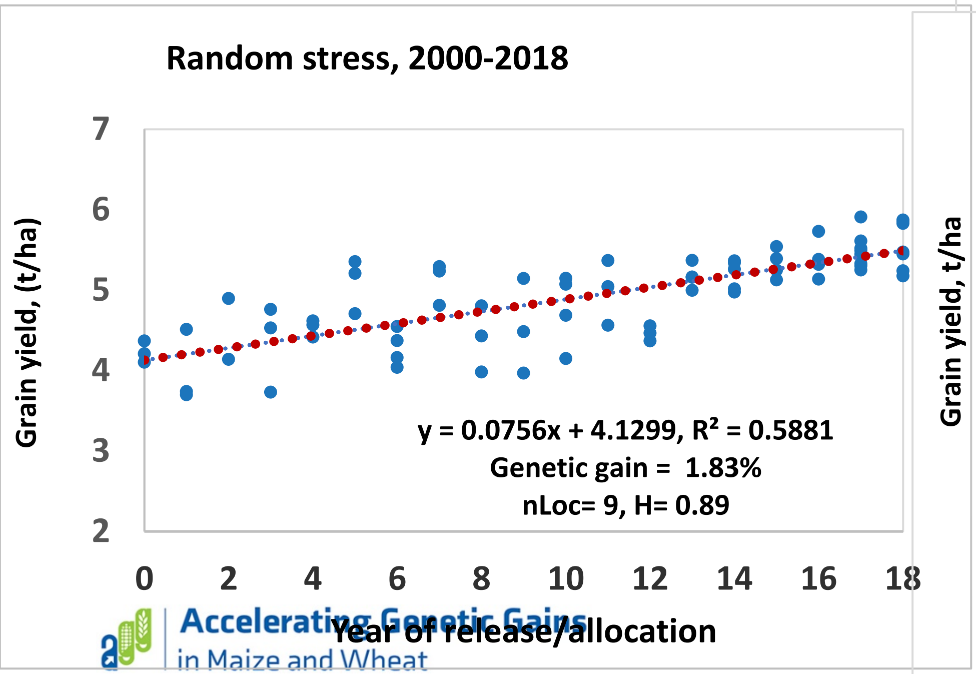
Trial Information Summery

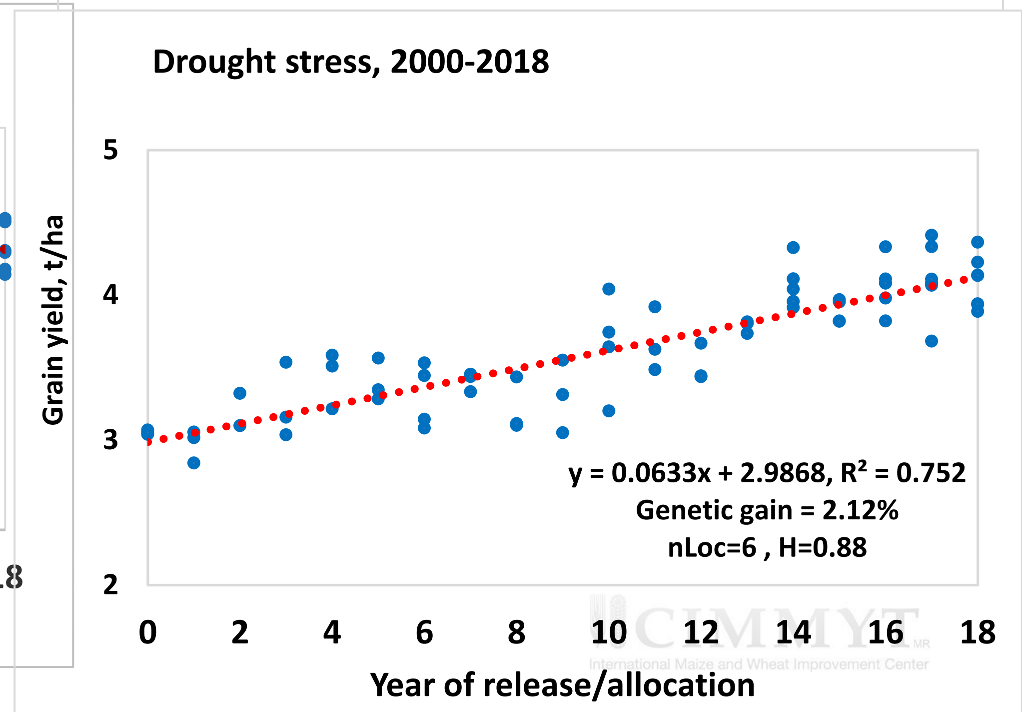
	SA	EA
Germplasm class	Early/e-early maturity	Medium maturity
Era	18-yr (2000-2018)	9-yr (2008-2016)
Comm. Checks	3 (pre-2000)	6 (pre-2008)
Entries	72	16
Sites	46	27
Year conducted	2 years (2017 , 2018)	2 years (2017, 2018)
Management group	4	2
Opt	15	20
RS	9	
Dt	10	7
LN	12	
Partner participation	Yes (private and NARS)	Yes (private and NARS)
Participating countries	7	3

laturing Hybrids (2000-2018)

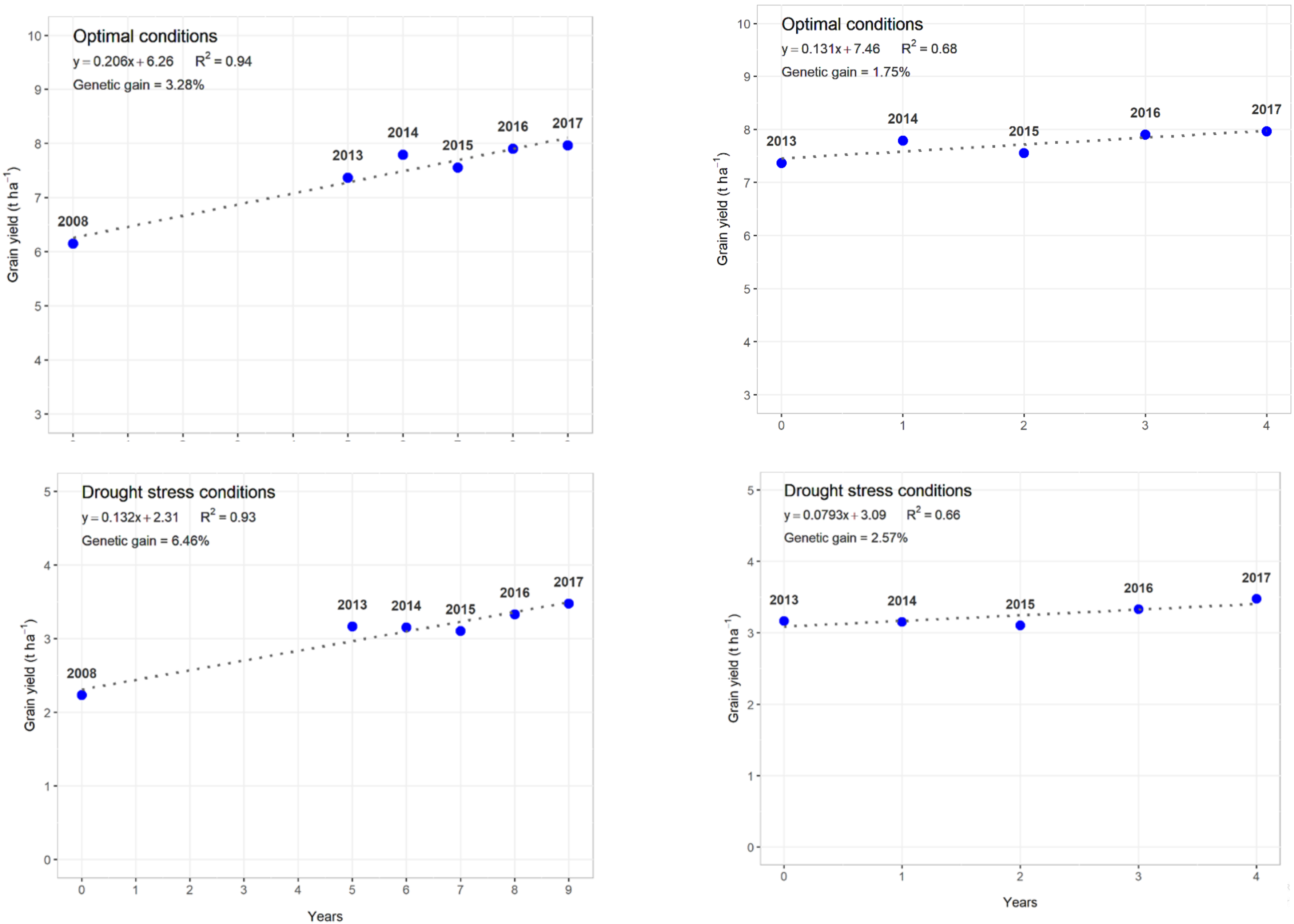






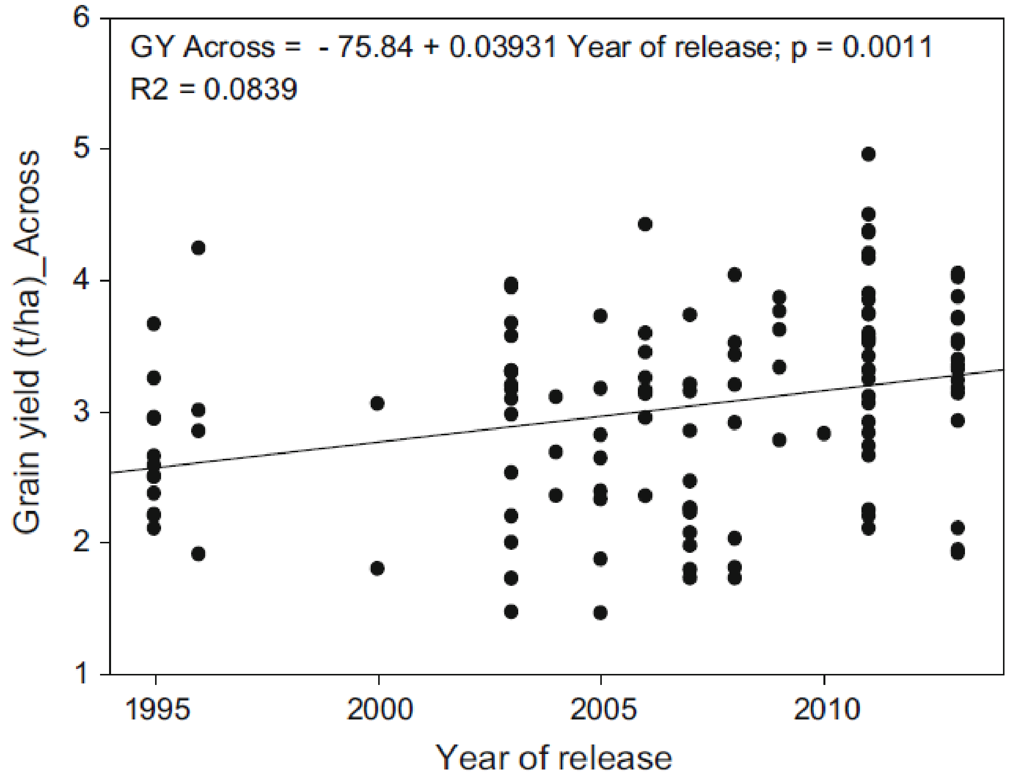


Genetic Gain in Intermediate Maturity Hybrids (2008-2017)



Genetic Gain in GY of Maize Inbred Lines

- # inbred lines = 124 (34 CMLs; 90 coded lines)
- Developed during 1996 to 2013 through pedigree and DH
  - Pre-1996 = 12 lines
  - 1996-2000 = 6 lines
  - 2001-2005 = 27 lines
  - 2006-2010 = 34 line
  - 2011-2013 = 45 lines
- Evaluated at 6 sites in Kenya and Uganda



Regasa et al. (2016)

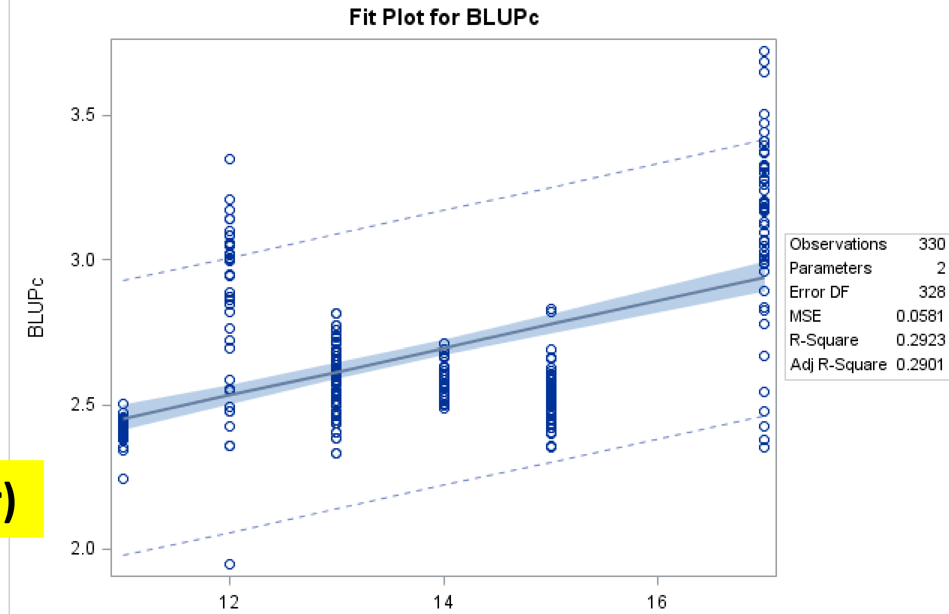
Estimating Genetic Gain using Historical Regional Trials Data

Eastern Africa - Early maturity

Summary of the drought trials

Management	Maturity	Year	Number of Trial	Number of rep	H2
Drought	Early	11	5	3	0.07
Drought	Early	12	7	2	0.67
Drought	Early	13	6	2	0.29
Drought	Early	14	4	2	0.21
Drought	Early	15	6	2	0.35
Drought	Early	16	6	2	0.29
Drought	Early	17	7	2	0.66

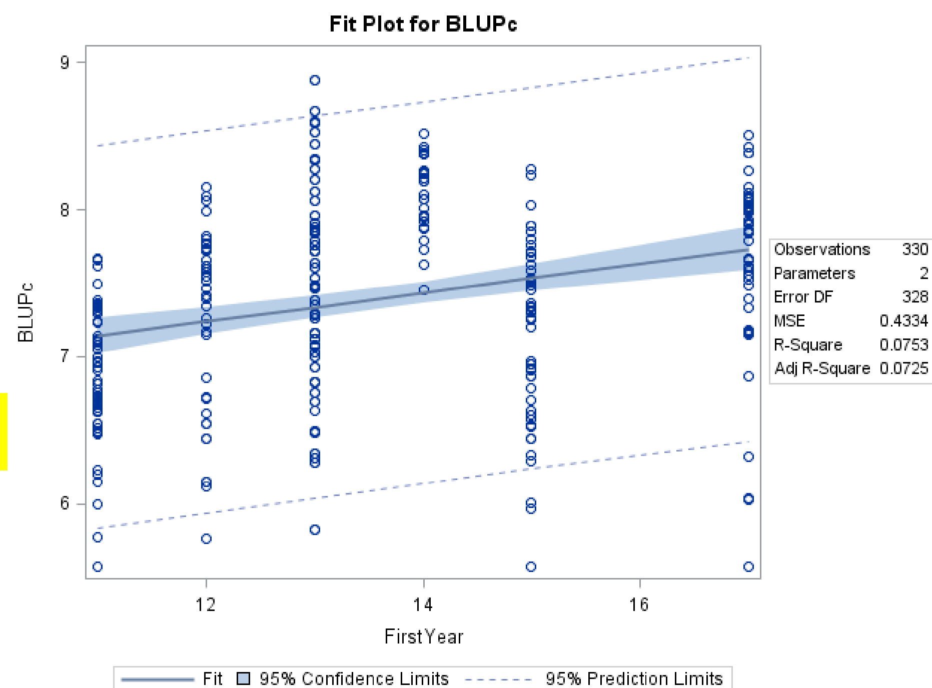
Estimated genetic gain= 2.6% (68 kg/ha/year)



Summary of the optimum trials

Management	Maturity	Year	Number of Trials	Number of rep	H2
Optimum	Early	11	9	3	0.70
Optimum	Early	12	11	2	0.81
Optimum	Early	13	31	2	0.95
Optimum	Early	14	22	2	0.91
Optimum	Early	15	29	2	0.89
Optimum	Early	16	31	2	0.95
Optimum	Early	17	23	2	0.91

Estimated genetic gain= 1.4% (98 Kg/ha/year)



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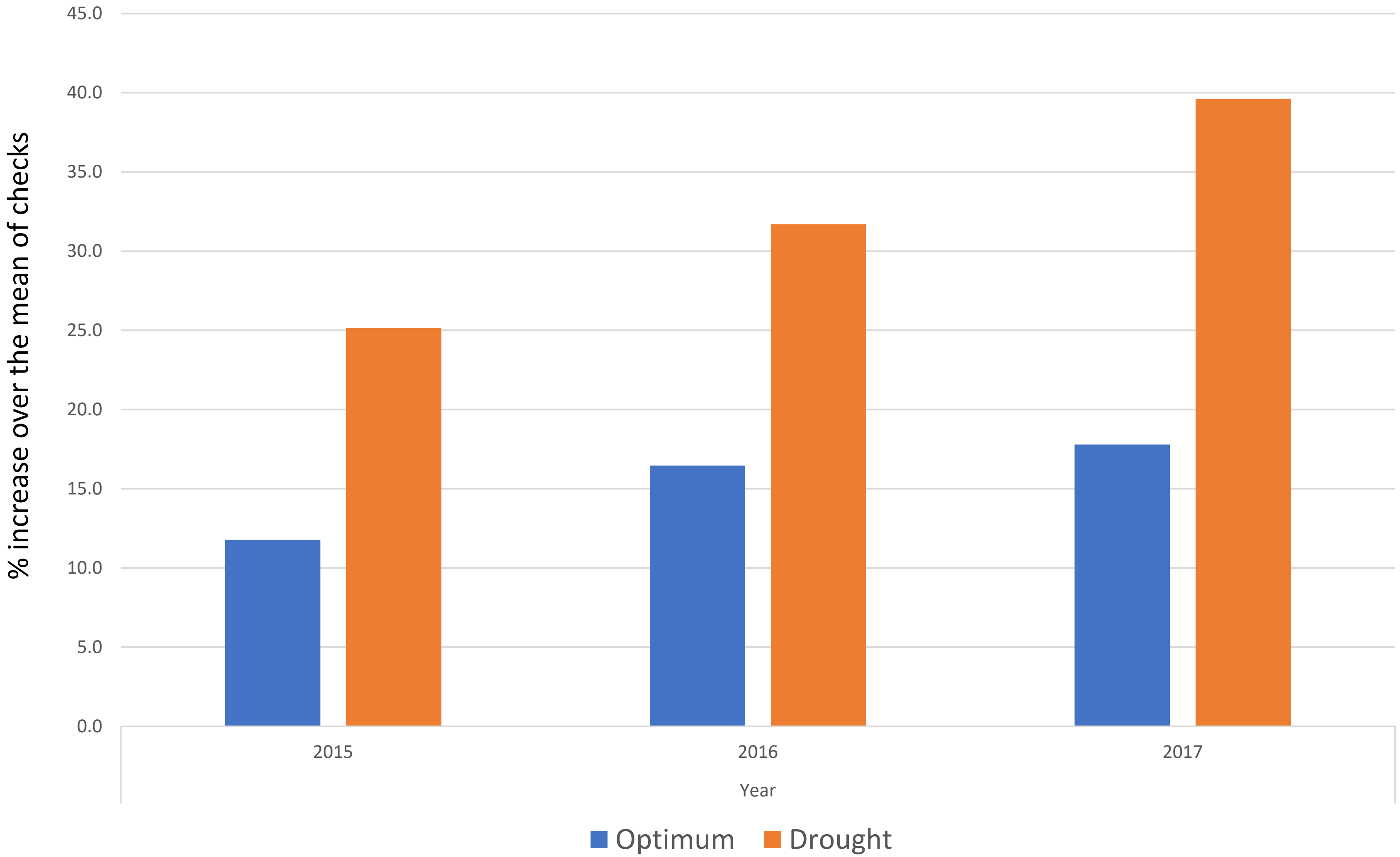
Comparing newer hybrids with baseline commercial checks



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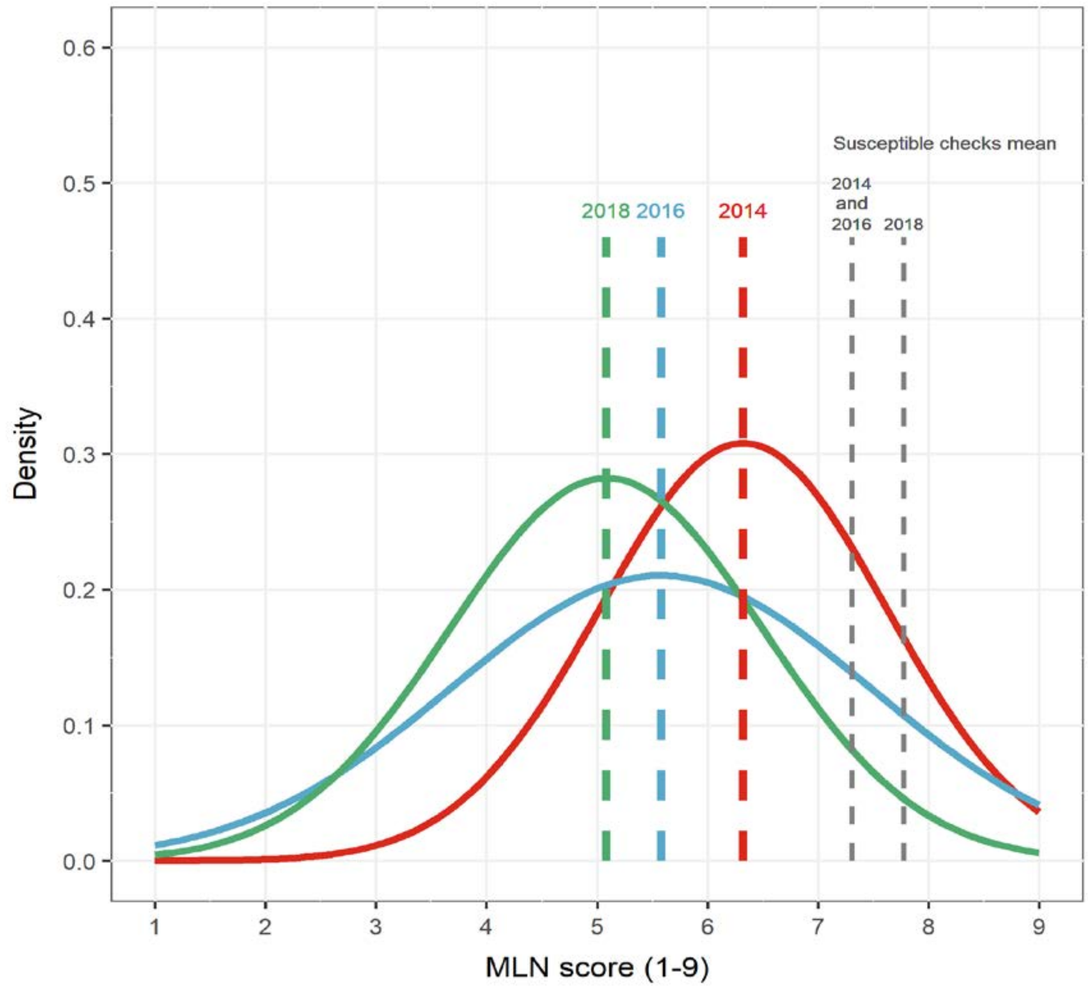
Breeding Progress for MLN tolerance

2012-2018

Year	# lines evaluated
2014	2876
2016	1522
2018	909
Total	5307

Recycling the best MLN tolerant/resistant parents, we could significantly increase MLN resistance among the populations from year to year.



Accelerating Genetic Gains in Maize and Wheat

Measuring Genetic Gain On-farm

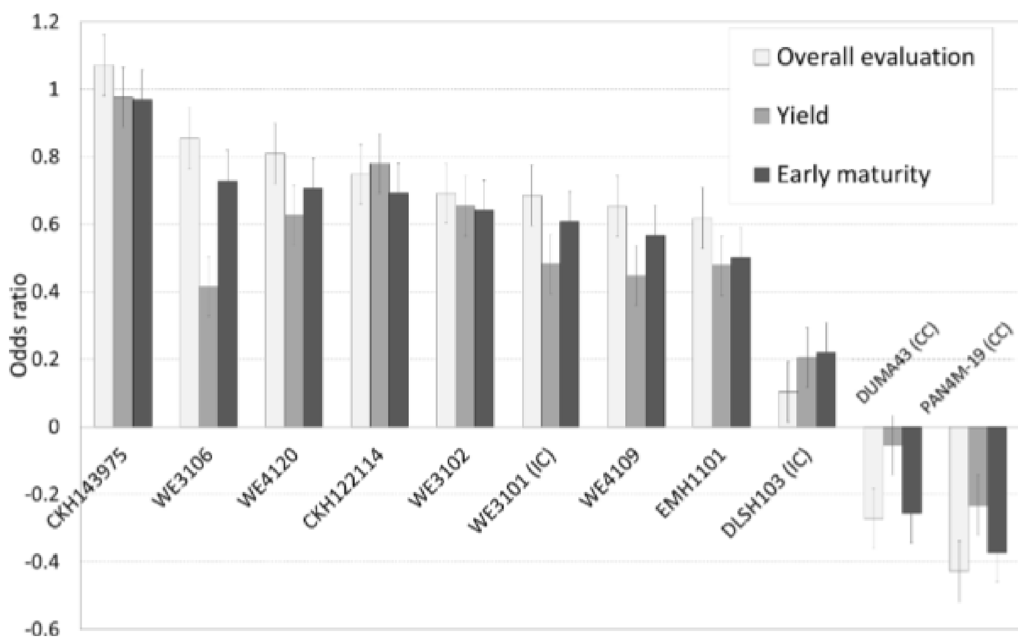
Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

On-farm performance and farmers' participatory assessment of new stress-tolerant maize hybrids in Eastern Africa

Mosisa Worku[a], Hugo De Groote[a,*], Bernard Munyua[a], Dan Makumbi[a], Fidelis Owino[a], Jose Crossa[b], Yoseph Beyene[a], Stephen Mugo[a], McDonald Jumbo[a], Godfrey Asea[c], Charles Mutinda[d], Daniel Bomet Kwemoi[c], Vincent Woyengo[e], Michael Olsen[a], Boddupalli M. Prasanna[a]



Farmer participatory evaluation of early-to-intermediate variety performance

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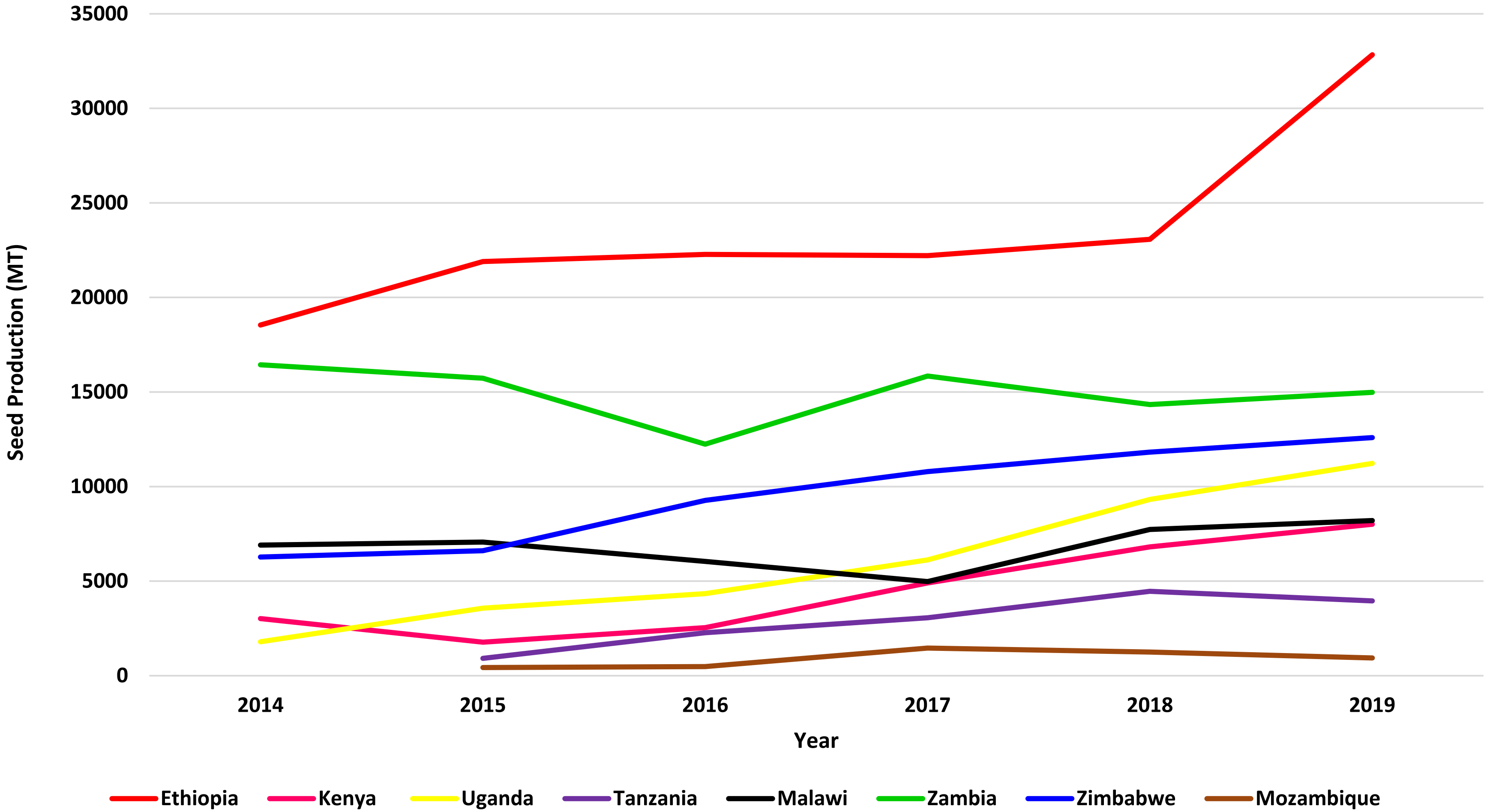
Certified Seed Production (MT) of CIMMYT-Derived Varieties (2014-2019) in ESA



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Thanks!

www.MAIZE.org

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