Accelerated Cassava Breeding to Meet Farmers' Needs

Xiaofei Zhang

Cassava Breeder

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Alliance

Bioversity International

CIAT International Center for Tropical Agriculture

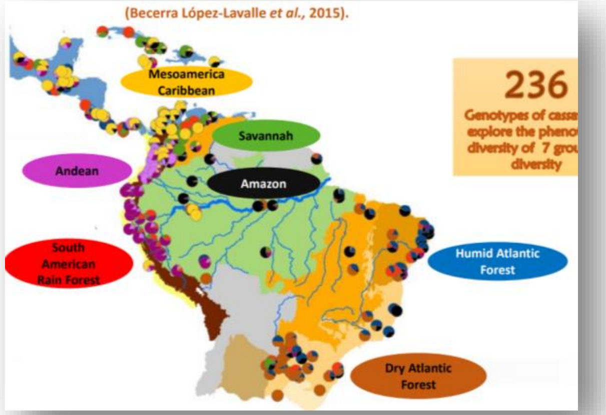
Since 1967 Science to cultivate change

Cassava, *Manihot esculenta*

Root crop
Clonal propagation using stems

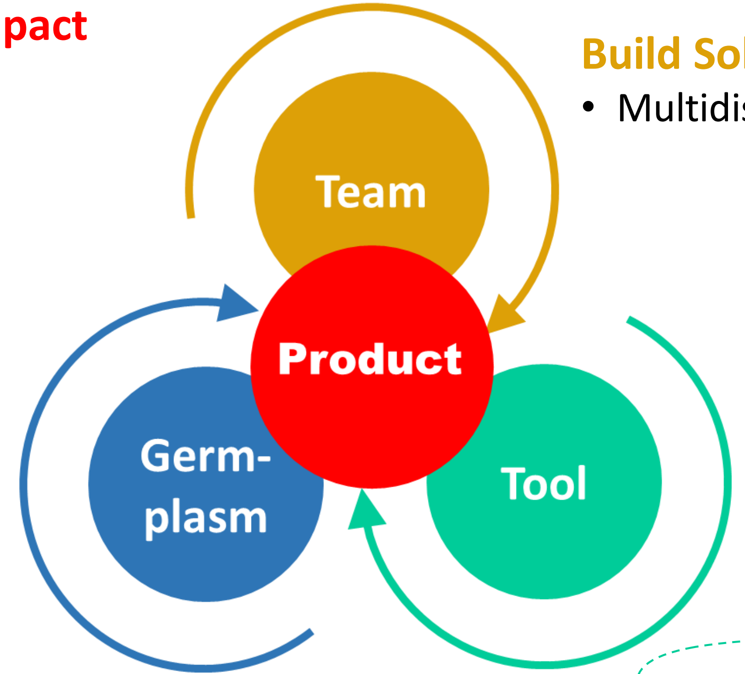
Staple crop
2^{nd} largest crop for starch production

Diploid, 2n = 36
Cross-pollination
Self-compatible



Key Elements of Plant Breeding

Enhance Global Impact
- Market segments
- Product profiles
- Breeding pipelines



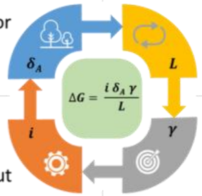
Build Solid Foundation
- Multidisciplinary team

Create New Opportunities
- High and stable dry matter
- Waxy starch
- High pro-vitamin A
- CBSD resistance
- Whitefly resistance
- Good cooking quality
- Small granule
- Drought and heat tolerance

Modernize Breeding Program

Genetic Diversity
- 20-30 progenitors for each pipeline

Duration of Selection Cycle
- Flower Inducing
- Genomic Prediction



Intensity
- High throughput phenotyping

Accuracy
- CassavaBase
- TPE, ≥ 2 Environments
- Row-column design
- ≥ 5 Checks, BLUP
- NIRS

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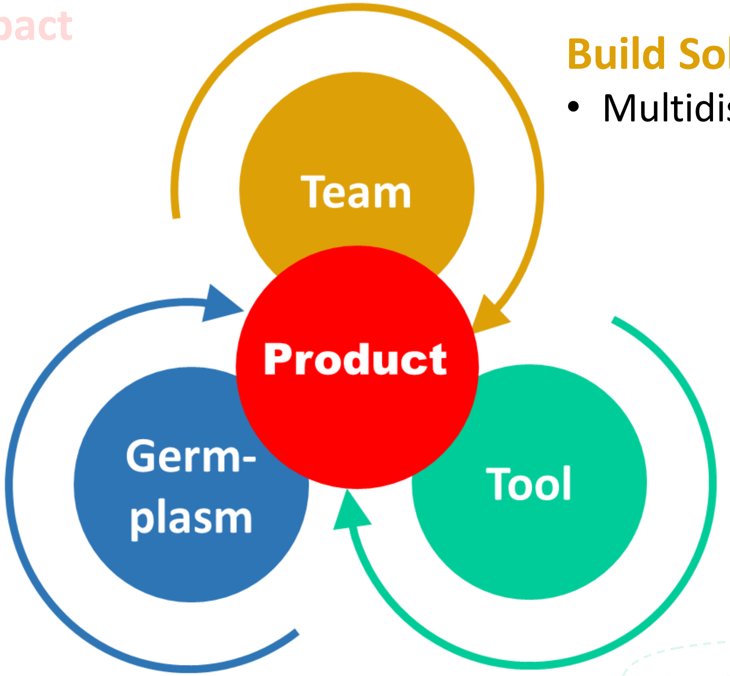

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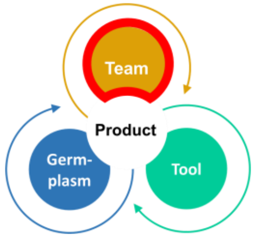
CASSAVA PROGRAM
Enhancement of Genetic Resources
RSA1
BREEDING
Xiaofei Zhang PhD
GENETICS
Augusto Becerra PhD
BIOINFORMATICS
Anestis Gkanogiannis PhD
GENE EDITING
Paul Chavarriaga PhD
TISSUE CULTURE
Adriana Bohorquez PhD
Agronomy and Soil Management
RSA2
CROP NUTRITION
Inram Malik PhD
PHYSIOLOGY
Michael Selvaraj PhD
Crop Protection
RSA3
VIROLOGY
Wilmer Cuellar PhD
PATHOLOGY
Nami Minato PhD
ENTOMOLOGY
Maria Isabel Gomez MSc
Seed Systems and Harvesting
RSA4
CLEAN SEED
Roosevelt Escobar MSc
SEED NETWORKS
Erik Delaquis MSc
Post Harvest & Enhanced Nutrition
RSA5
PROCESSING
Thierry Tran PhD
ROOT QUALITY
John Belalcazar MSc
Value Chain and Policy
RSA6
DEVELOPMENT
Jonathan Newby PhD
GENDER
Vanya Slavchevska PhD
IMPACT ASSES.
Ricardo Labarta PhD
FORESIGTH
Steve Prager PhD



Team
Product
Germ-plasm
Tool

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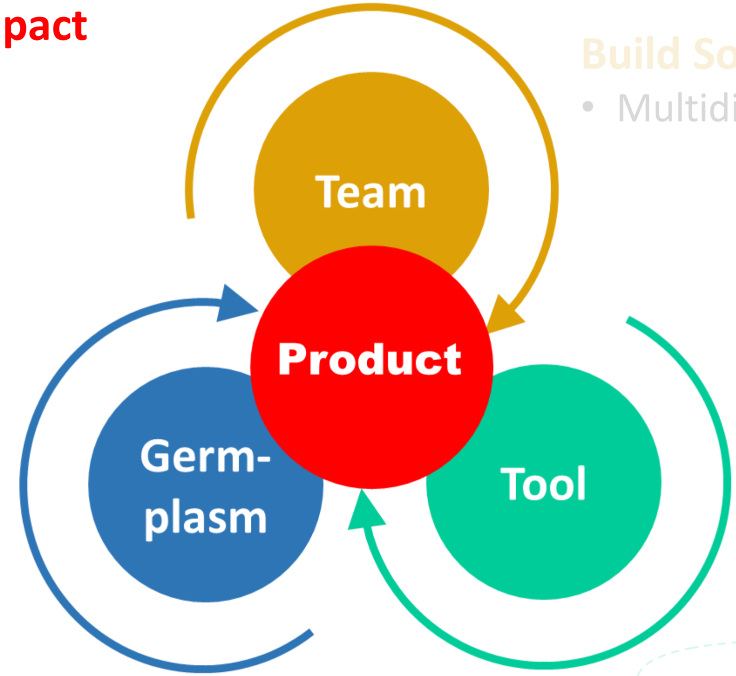

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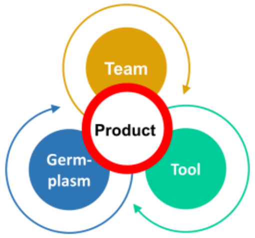
Cassava Products

Biofortified cassava for human consumption

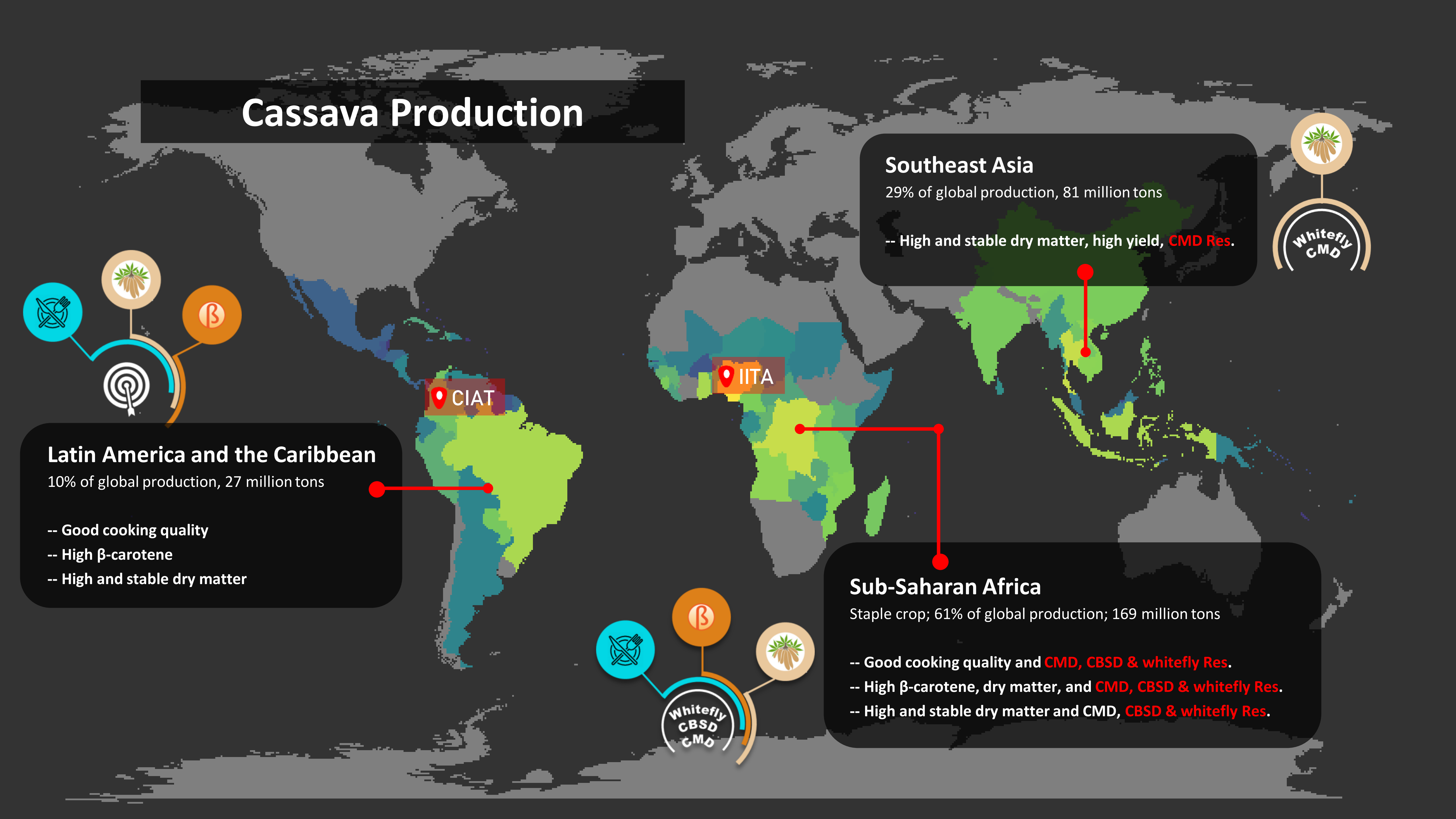
Fresh and Dried roots for human consumption

Industrial Cassava – starch and animal feed

Cassava specialty starch

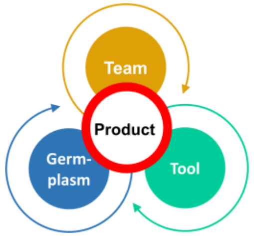


** Processing- granulated and Paste for human consumption*


Cassava Production
Southeast Asia
29% of global production, 81 million tons
-- High and stable dry matter, high yield, CMD Res.
Whitefly
CMD
CIAT
IITA
Latin America and the Caribbean
10% of global production, 27 million tons
-- Good cooking quality
-- High β-carotene
-- High and stable dry matter
Sub-Saharan Africa
Staple crop; 61% of global production; 169 million tons
-- Good cooking quality and CMD, CBSD & whitefly Res.
-- High β-carotene, dry matter, and CMD, CBSD & whitefly Res.
-- High and stable dry matter and CMD, CBSD & whitefly Res.
Whitefly
CBSD
CMD

Breeding Pipelines

		Market Segment	Product Profile		Stage 1.1	Stage 1.2	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6	Existing Products
2019 –		1.1	high pro-Vitamin A	+ CMD + CBSD + whitefly	6,000	480	180	3,000 seeds of improved populations for Africa IITA CGIAR				
2007 –		1.2		--	4,000	320	120	50	15	8	2	0
2019 –		2.1	good cooking quality	+ CMD + CBSD + whitefly	6,000	480	180	3,000 seeds of improved populations for Africa IITA CGIAR				
1980 –		2.2		--	4,000	320	120	50	15	8	2	2
2019 –		3.1	stable dry matter	+ CMD + CBSD + whitefly	6,000	480	180	3,000 seeds of improved populations for Africa IITA CGIAR and ASIA				
1980 –		3.2		--	4,000	320	120	50	15	8	2	3
2008 –		4	special starch	--	10,000	480	180	70	20	10	3	1
					40,000	2,880	1,080	220	65	34	9	



Product Profile

				Market segment 1, beta-carotene + CMD				
Crop				**Cassava**				
Geographical Region				**subhumid lowland and semi-arid lowland tropics**				
Biological Region/Eco System								
	Trait	**Unit**	**target**					
	CMD	MAS	yes	yes				no
	CBSD	MAS	TBD					
CO_334:0000175	CBB		<=2	1	2	3	4	5
CO_334:0002084	thrips		<=2	1	2	3	4	5
	green mite		<=2	1	2	3	4	5
CO_334:0000218	red spider mite		<=2	1	2	3	4	5
	mealybug		TBD					
	whitefly		TBD					
	frogskin		TBD					
	super elongation		TBD					
	witches' broom		TBD					
				population/variety				
				end use				
Production System				**human consuption**				
	Trait	Unit	Target					
	beta-carotene	ug/g fr.wt	>=10	3	5	10	15	20
	cooking time	min	<=30	10	20	30	40	50
	water absorption	%	>=10	5	10	15	20	25
	mealiness		TBD					
	sweetness		TBD					
	HCN	ug/g fr.wt	<100	50	100	150	200	250
CO_334:0000160	dry matter	%	>27	22	25	27	30	35
	dry matter stability		TBD					
	flesh color		3	1		2		3
CO_334:0000161	flesh color	1, white, 8, pink	> 5, yellow	1	3	5	7	8

F1C	BCF1C	CET	PYT	AYT	UYT	PEA

Team
Product
Germ-
plasm
Tool

Product Profile

Imput level				**low**				
Maturity				--				
Biofortification				**yes**				
Production/Multiplication Traits								
	Trait	Unit	Target					
CO_334:0000138	germination	%	>80	70	80	85	90	100
CO_334:0000220	vigor		>=3	1	2	3	4	5
CO_334:0000301	lodging		<=2	1		2		3
CO_334:0000099	plant type		<=3	1	2	3	4	5
CO_334:0000079	branch number		<=3	1	2	3	4	5
CO_334:0000018	height	cm	200-300	150	200	250	300	350
CO_334:0000106	height_1st_branch	cm	>150	50	100	150	200	250
CO_334:0002082	angle_1st_branch		TBD					
CO_334:0000123	stem length with leaves	cm	>30cm	20	30	40	50	60
CO_334:0000300	number_sticks_available		>=8	6	7	8	9	10
not in CassavaBase	easy harvest		<=2	1		2		3
	peduncle length_visual		2	1		2		3
CO_334:0000221	skin color		3	1		2		3
CO_334:0000228	root type		<=3	1	2	3	4	5
CO_334:0000109	constriction		1	1		2		3
CO_334:0000020	root shape		2-3	1	2	3	4	
CO_334:0000226	root length_visual		2	1		2		3
	easy peel		TBD	1		2		3
CO_334:0000011	root number	per plant	>=5	3	5	7	9	12
CO_334:0000169	commercial root num.	per plant	>=4	2	4	6	8	10
CO_334:0000458	rotted root	%	<=10	0	5	10	15	20
	yield of aboveground							
CO_334:0000013	yield	ton/ha	>20	15	20	25	30	35
	yield_check	% check	>=105%	90	100	105	110	115
CO_334:0000131	commercial yield	ton/ha	>18	15	18	21	24	27

BCF1C	BCF1C	CET	PYT	AYT	UYT	PEA

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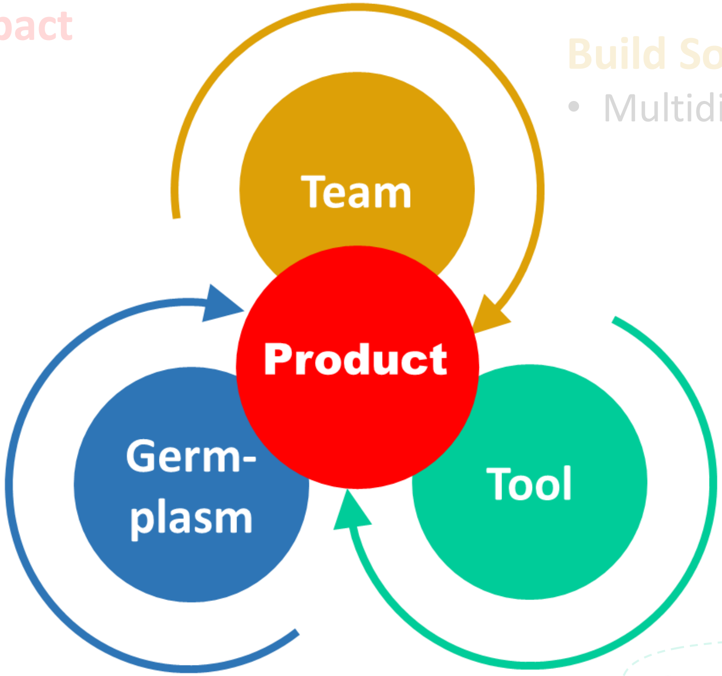

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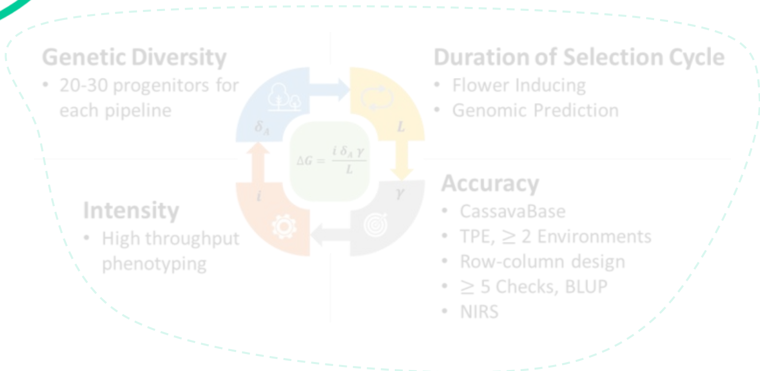
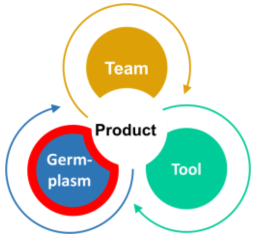
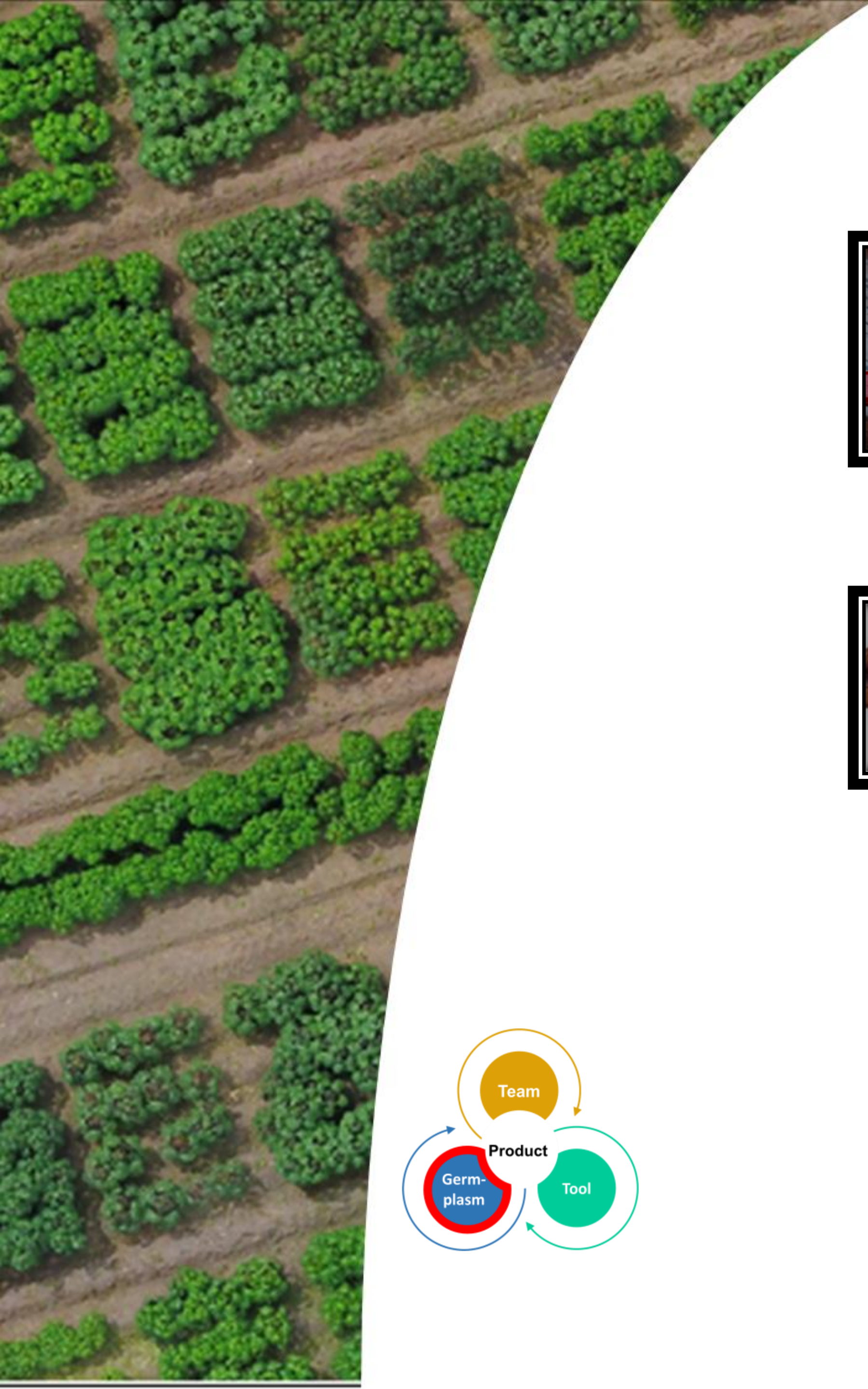
Modernize Breeding Program





*Standard approvals (SMTA, Export and import permits etc) are given by the authorized institutions.

New Germplasm Opens up New Opportunities



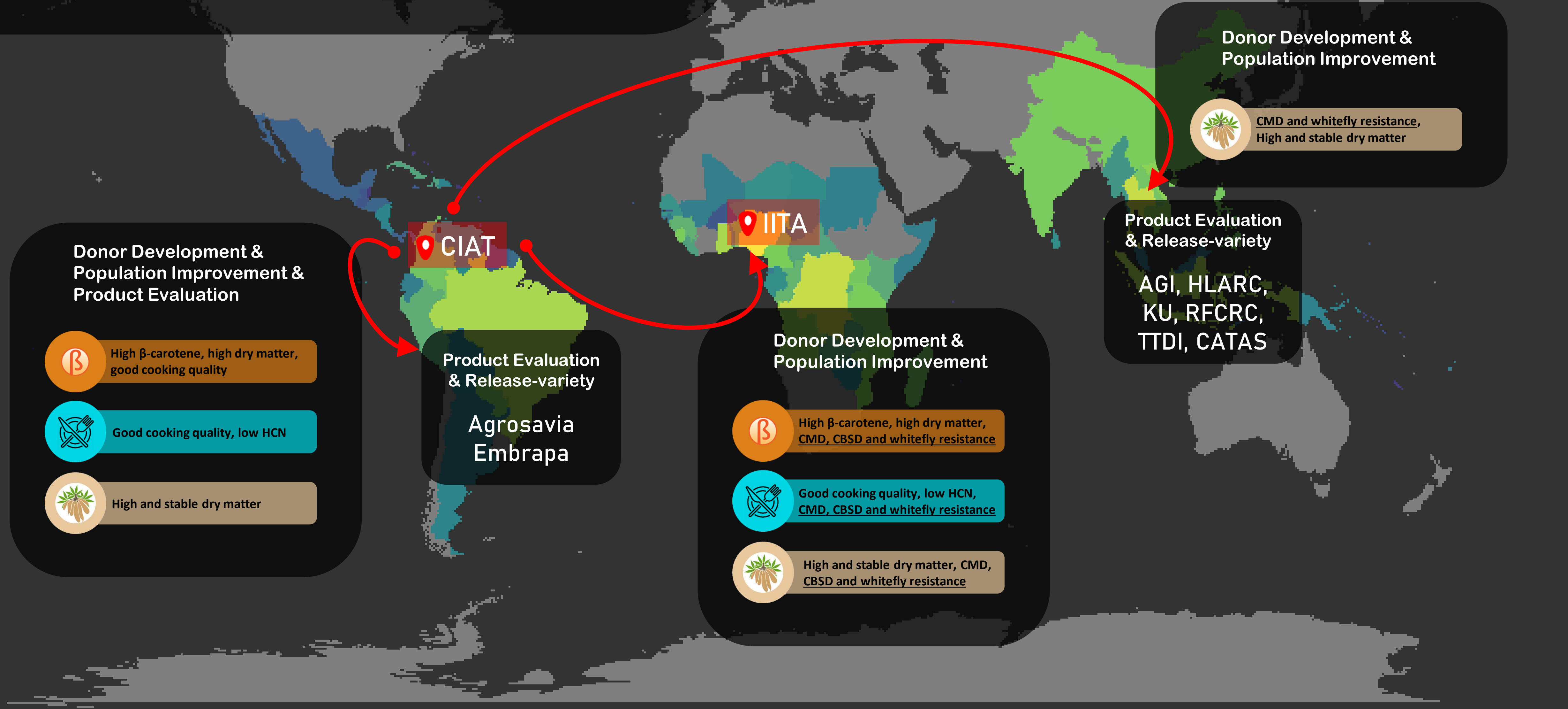
- CMD, CBSD and whitefly resistance
- High pro-vitamin A
- Good cooking quality
- Low hydrogen cyanide (HCN)
- Low Postharvest physiological deterioration (PPD)

- High and stable dry matter
- Waxy starch
- Small granule

- Drought tolerance
- Heat tolerance
- Haploid inducing
- High amylose
- Herbicide resistance
- Early maturity
- High density tolerance

GAME CHANGING

Provide both trait donors and improved breeding populations with CMD, CBSD, and whitefly resistance to IITA and NARS.



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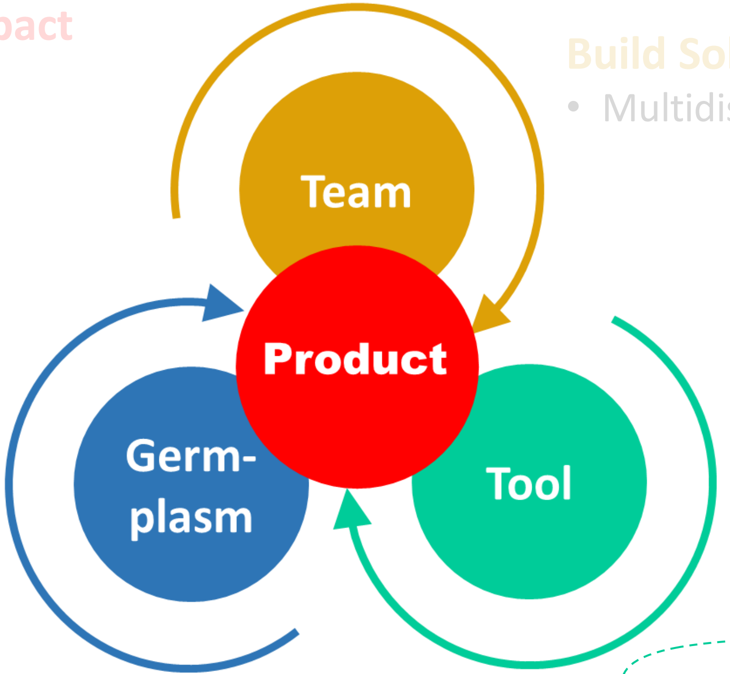

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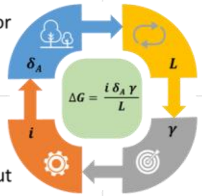

Intensity
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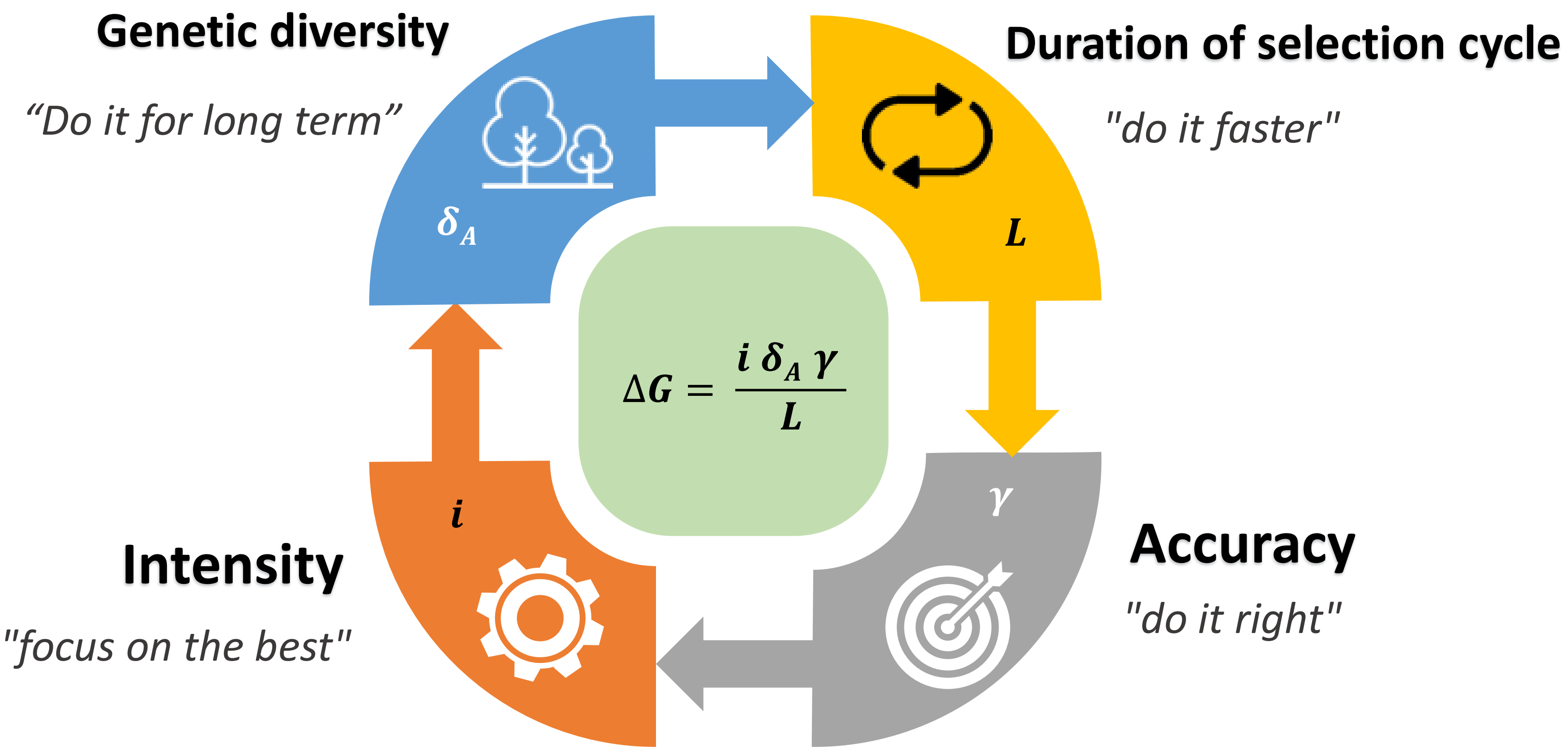
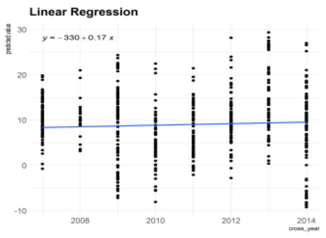
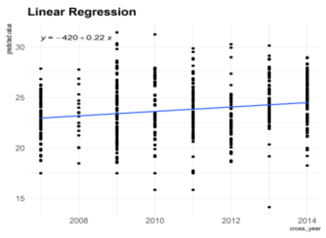
Breeder's Equation

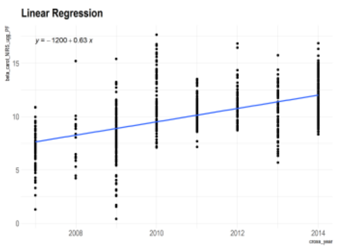


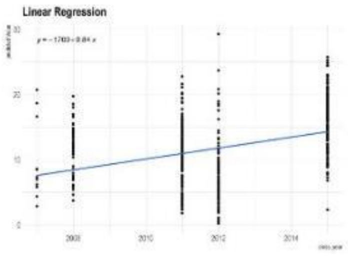
Realized Genetic Gain

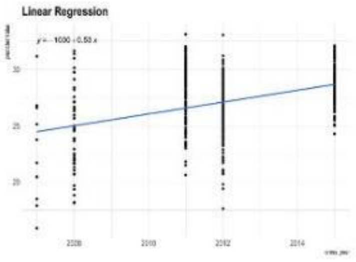
	Biofortified cassava for human consumption			Cassava specialty starch	
	Yield (ton/ha)	Dry matter (%)	Beta-carotene content (ug/g fresh weight)	Yield (ton/ha)	Dry matter (%)
Gain per year	**2.03%**	**0.96%**	**8.19%**	**12.2%**	**1.94%**
Num. of trials#	53	68	7	13	16
Year	2013-2019	2013-2019	2013-2019	2011-2020	2011-2020
Num. of loc*	13	20	1 (station)	9	10
Common checks	4	4	NA	4	4
Origin years	2007-2014	2007-2014	2007-2014	2008-2015	2008-2015



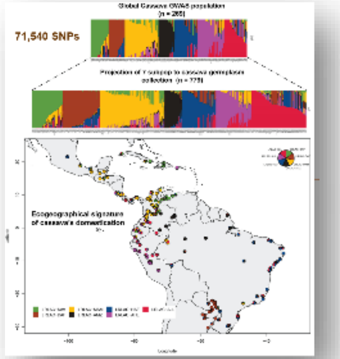








*Location TPE, sub-humid and semi-arid lowland tropics & farmer's field
#All data were stored in CassavaBase

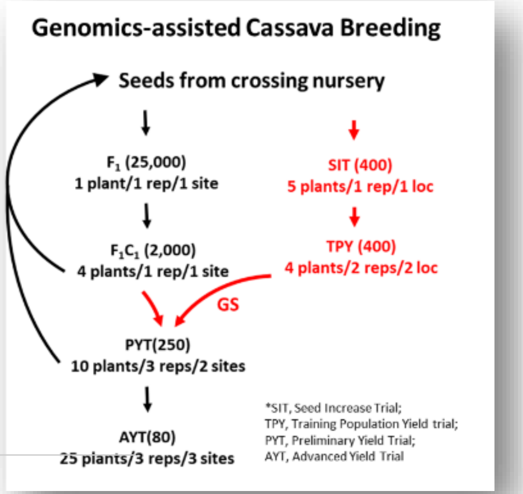


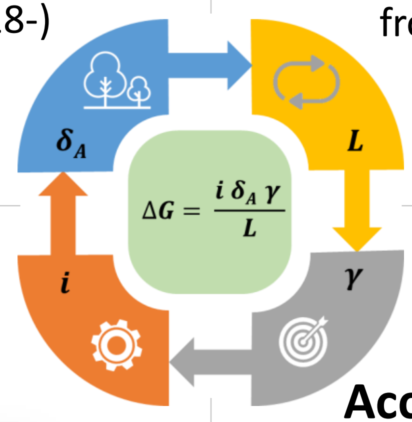
Genetic Diversity

- New traits, e.g., CBSD res., CMD res., good cooking quality et al.
- Sequencing of progenitors (2020-)
- Hybrid breeding (2018-)

Duration of Selection Cycle

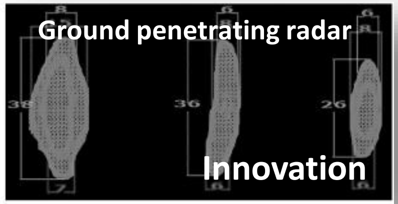
- Flower Inducing (2016-)
- Genomic Selection (2019-)
- Rapid Recycling Progenitors from 5 to 3 years (2019-)





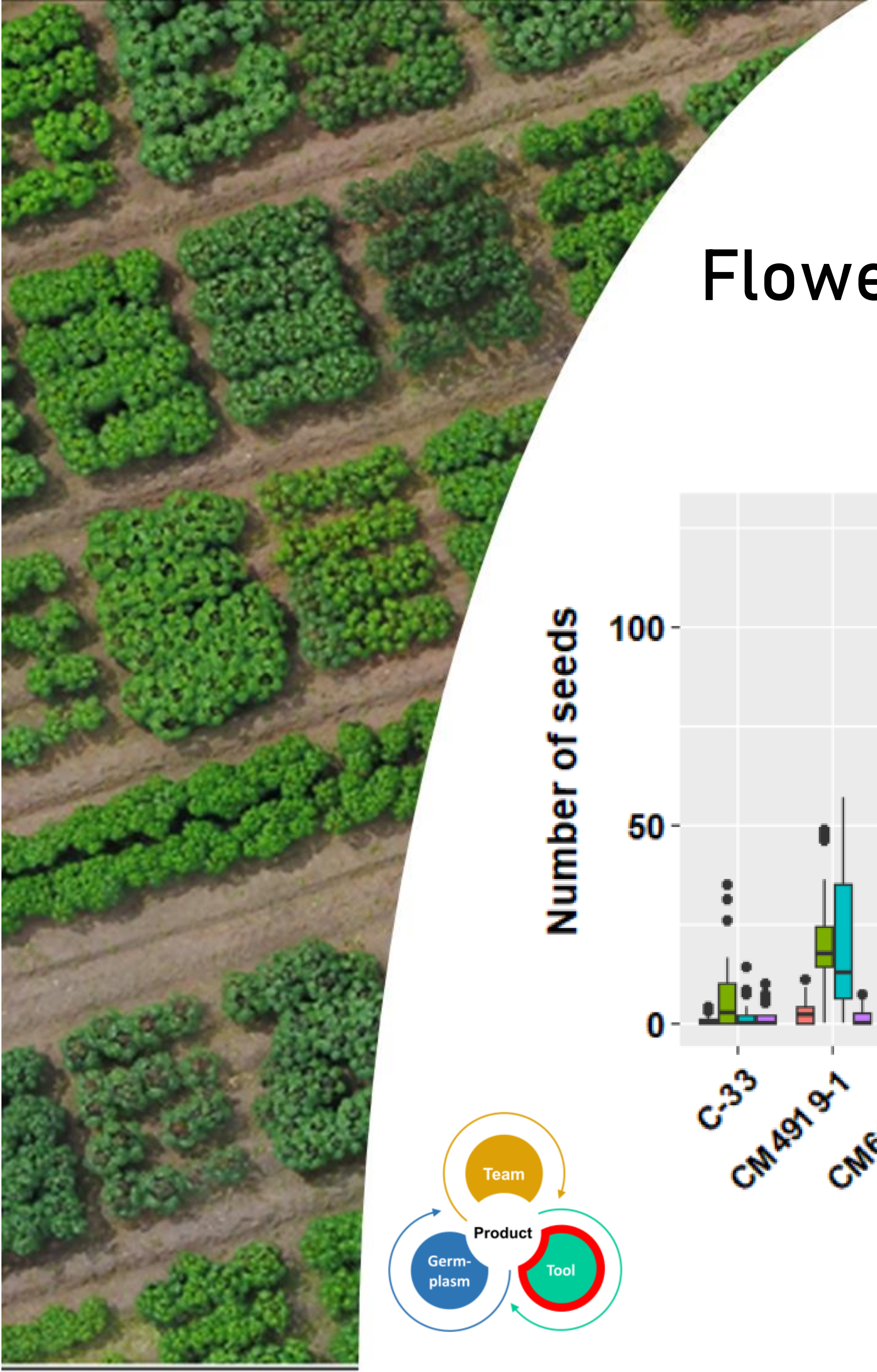
Intensity

- High throughput phenotyping

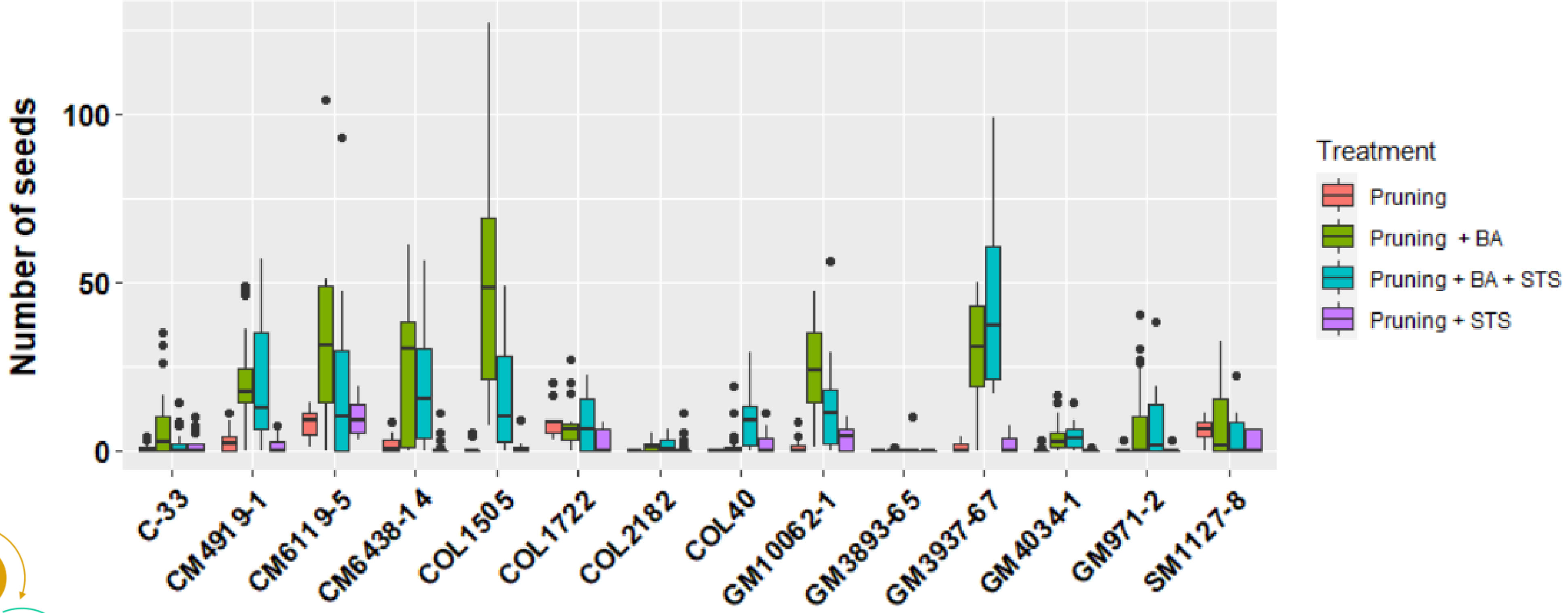


Accuracy

- CassavaBase, Fieldbook & Barcode (2018-)
- TPE, $\geq$ 2 Environments (2020-)
- $\geq$ 5 Checks, BLUP and GBLUP (2020-)
- Selection Index (2012-)
- NIRS & Image Analysis (2012-)
- Stage&Gate System (2020-)
- Operational Excellence (2019-)

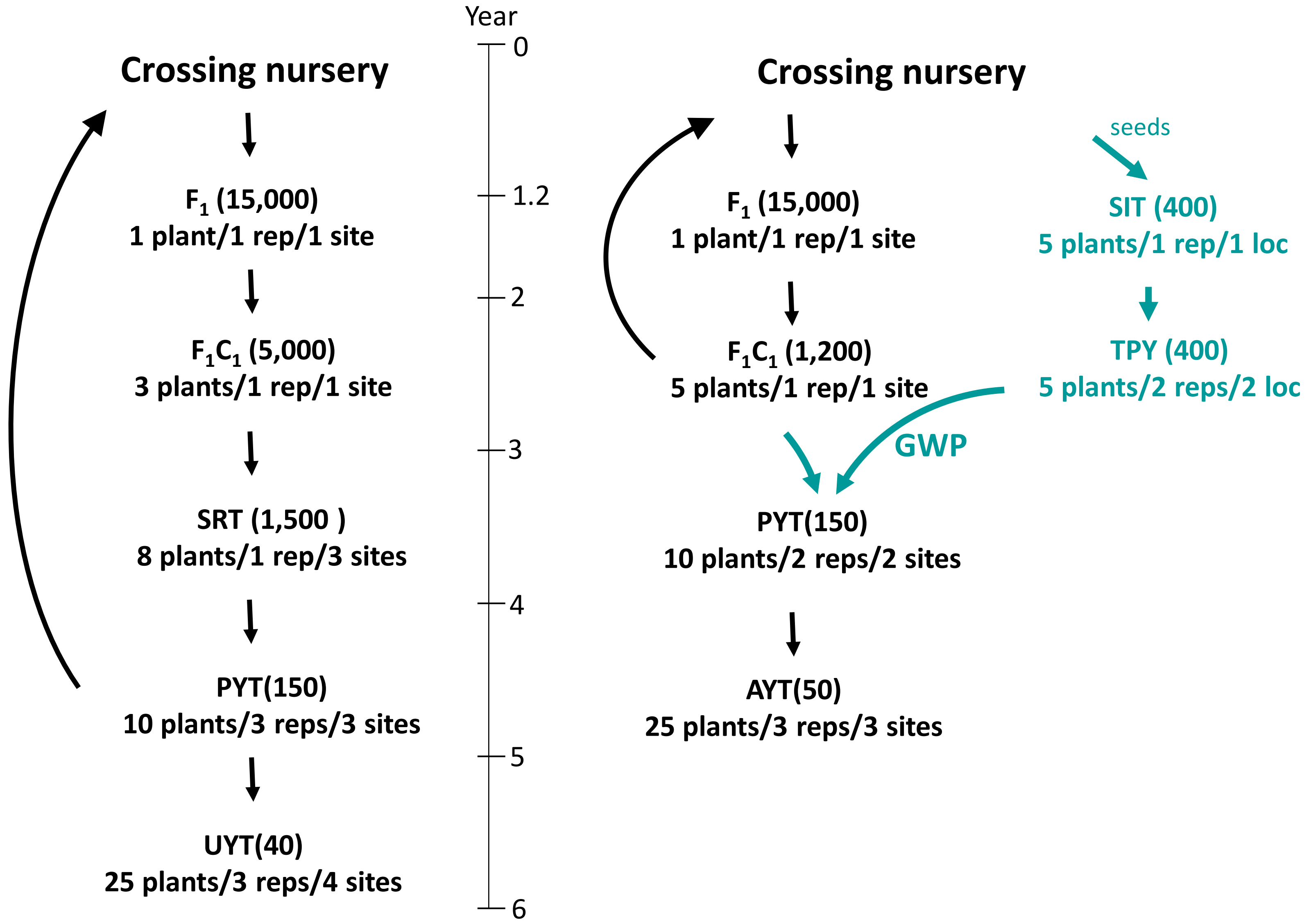


Flower Inducing Technology



BA, 6-Benzylaminopurine; STS, silver thiosulfate

Genome Wide Prediction-based Recurrent Selection



Diploid

Cross-pollinated

Self-compatible

Inbreeding depression

Heterosis

Clonal propagation

– no seed production system

Pollination is labor-intensive

Cell

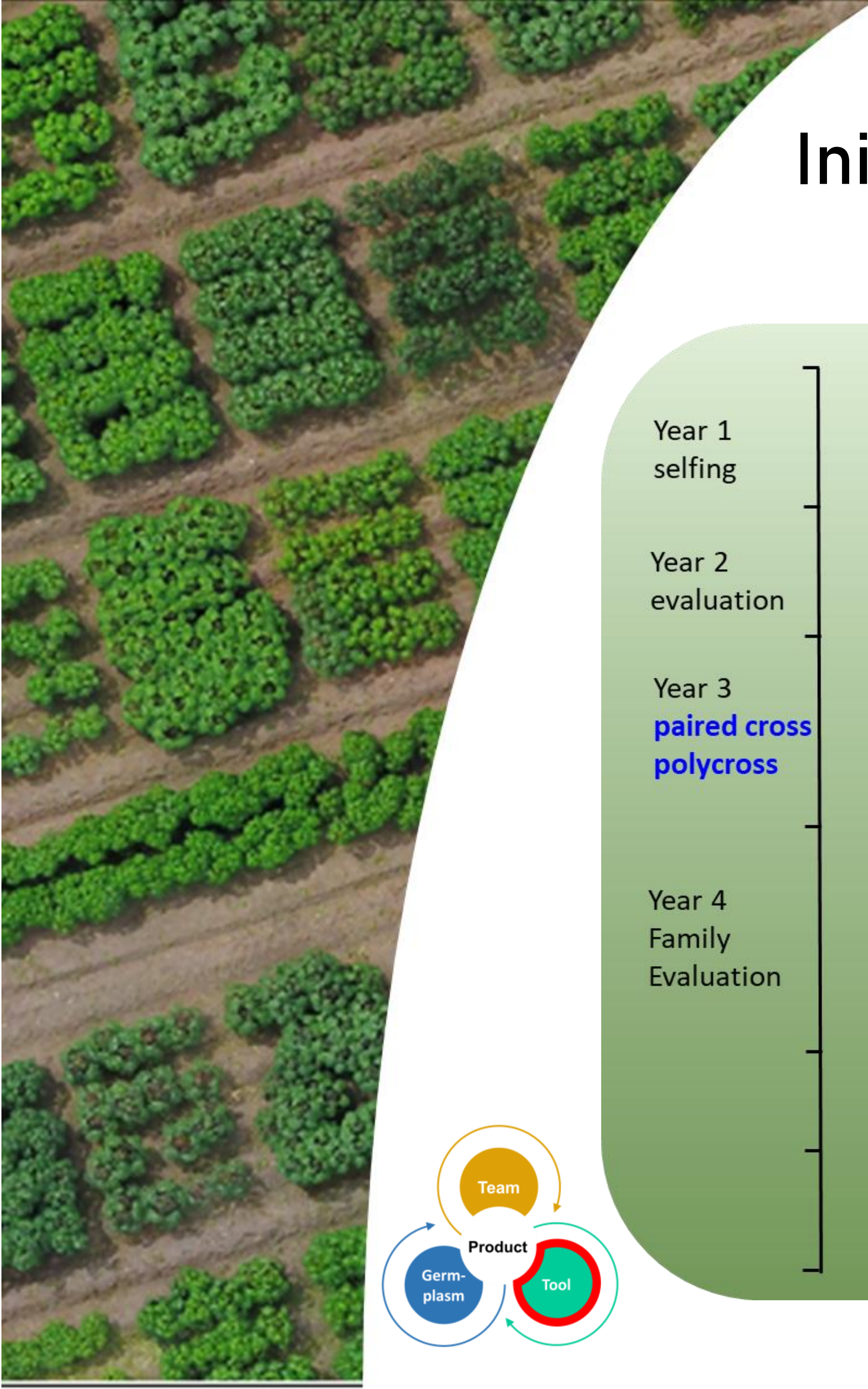
CellPress

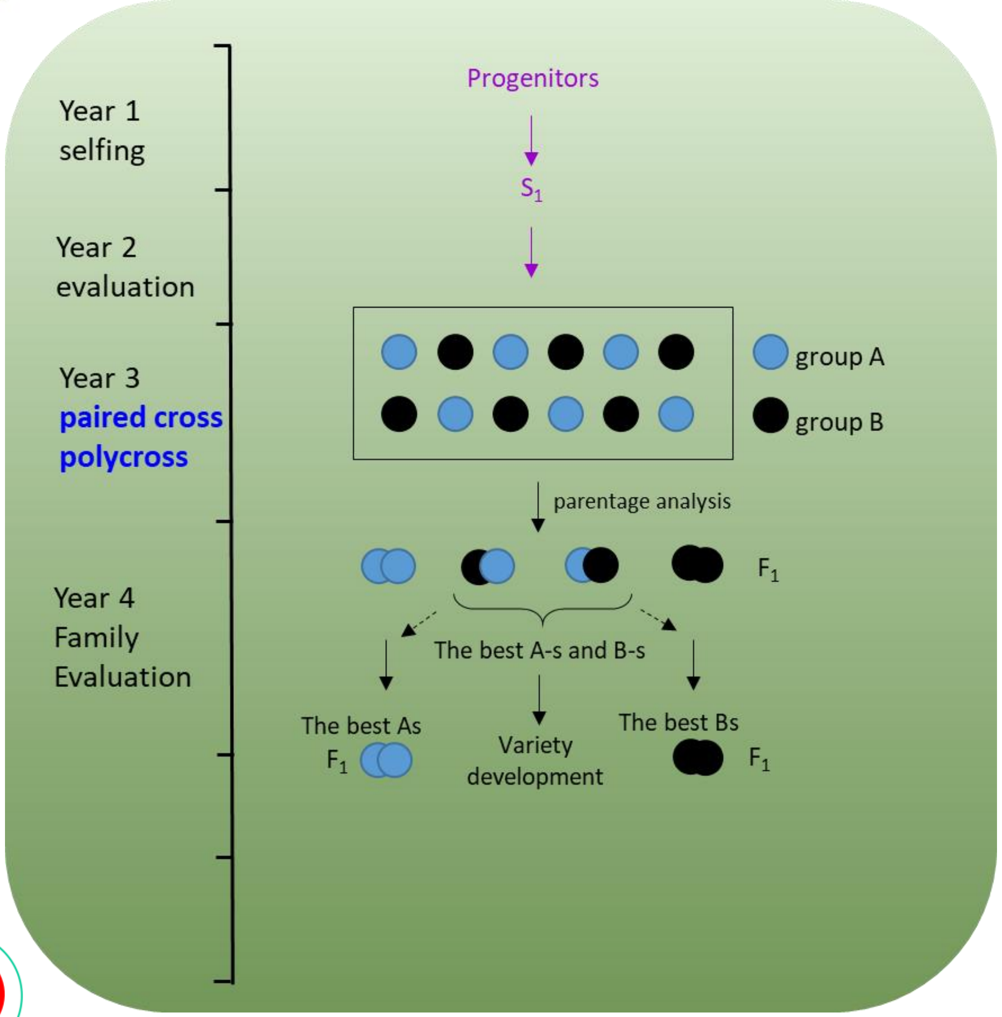
Article

Genome design of hybrid potato

Chunzhi Zhang,[1] Zhongmin Yang,[1] Dié Tang,[1] Yanhui Zhu,[1] Pei Wang,[1] Dawei Li,[1] Guangtao Zhu,[2] Xingyao Xiong,[1] Yi Shang,[2] Canhui Li,[2] and Sanwen Huang[1,3,*]
[1]Shenzhen Branch, Guangdong Laboratory of Lingnan Modern Agriculture, Genome Analysis Laboratory of the Ministry of Agriculture and Rural Area, Agricultural Genomics Institute at Shenzhen, Chinese Academy of Agricultural Sciences, Shenzhen, Guangdong 518120, China
[2]The AGISCAAS-YNNU Joint Academy of Potato Sciences, Yunnan Normal University, Kunming, Yunnan 650500, China
[3]Lead contact
*Correspondence: huangsanwen@caas.cn
https://doi.org/10.1016/j.cell.2021.06.006

Initiate Hybrid Breeding





Select progenitors:

1) Different progenitors of breeding pops
2) Historical progenitors from the genebank
3) Breeding progenitors from Brazil

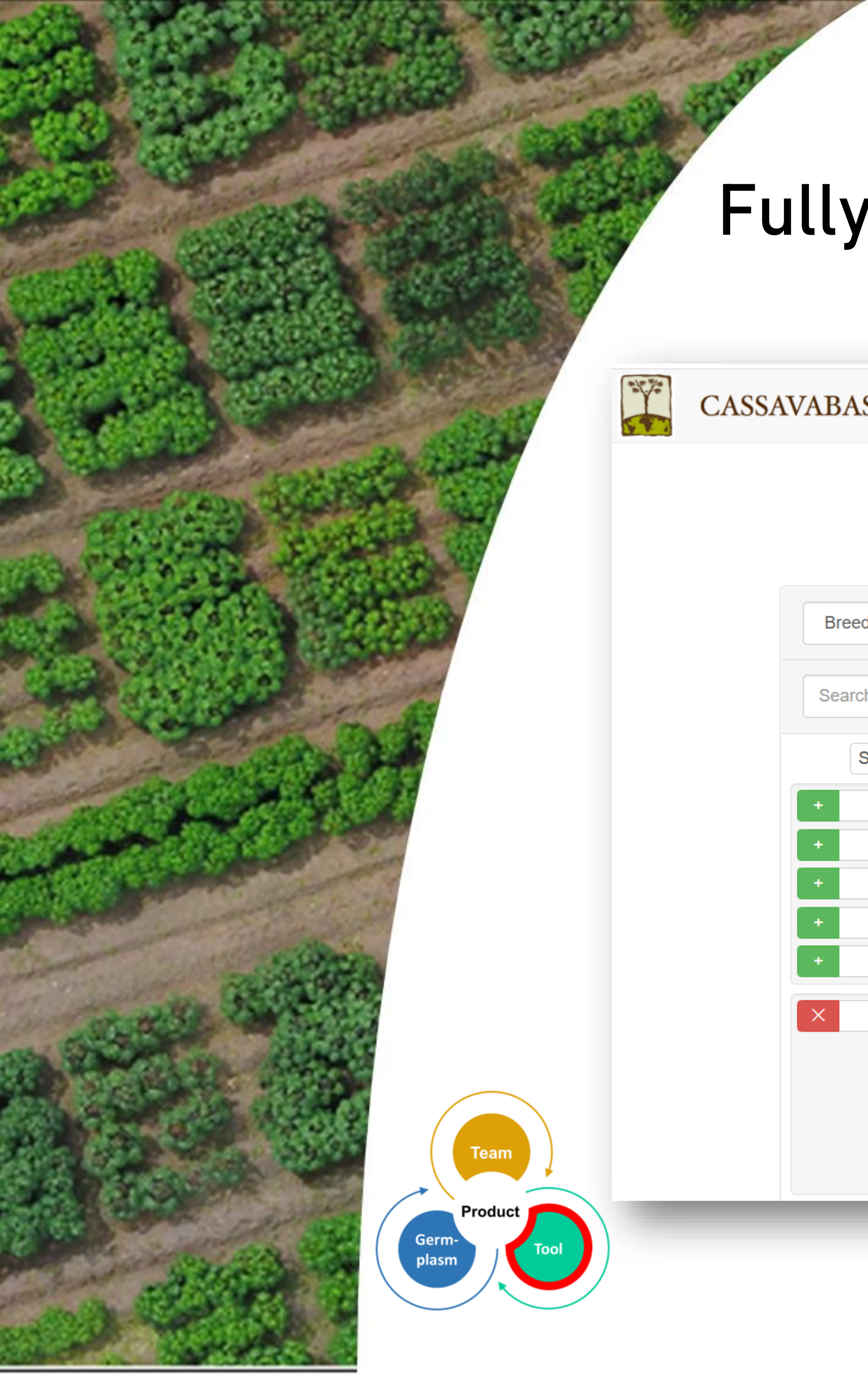
Data collection:

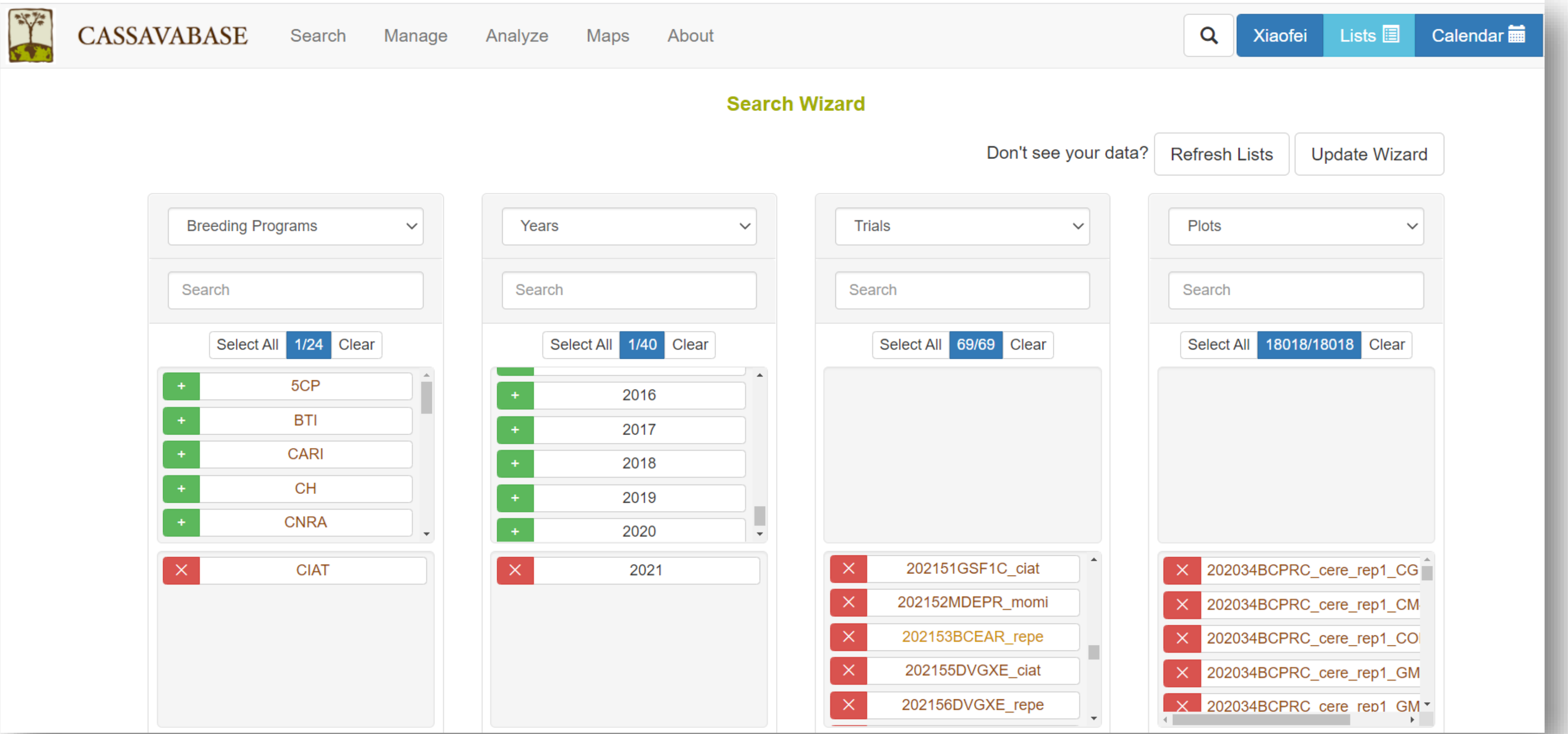
1) Genotypic and phenotypic data
2) Family effect, GCA, SCA, heterosis

Aim to:

- Understand the **heterosis** level and **inbreeding depression**;
- Identify **heterotic patterns**

Fully Use CassavaBase, FieldBook and Barcode





Markers for Quality Control and MAS

CGIAR

Excellence in Breeding Platform

KASP low density genotyping Platform

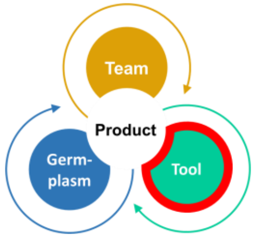
Tools

Genotyping / sequencing tools and services

A DNA-based molecular marker is a genomic DNA (gDNA) fragment located within a genome at a specific position that may or may not be linked to a specific trait of agricultural interest. Trait linked DNA based markers allow us to easily screen breeding materials for favorable alleles associated with traits of interest.

The EiB low-density genotyping service is based on KASP markers. Kompetitive Allele Specific PCR (KASP) is a simplified fluorescence-based methodology to genotype specific polymorphisms or INDELS. This approach is cost effective and offers rapid turnaround for low-density marker applications (between 1 and 200 markers), with applications including specific trait screening, quality control and marker assisted selection (MAS).

The markers available for use in low-density genotyping can be consulted below. This list is continuously updated and improved: kindly remember to revise the list of markers and consult with EiB genotyping services when planning for genotyping, especially new users.



Major Sources of CMD Resistance In South-East Asia

1) 5 IITA clones, all showing high resistance in Tay Nihn;

2) C33, C39, TME3 and other clones from CIAT and IITA

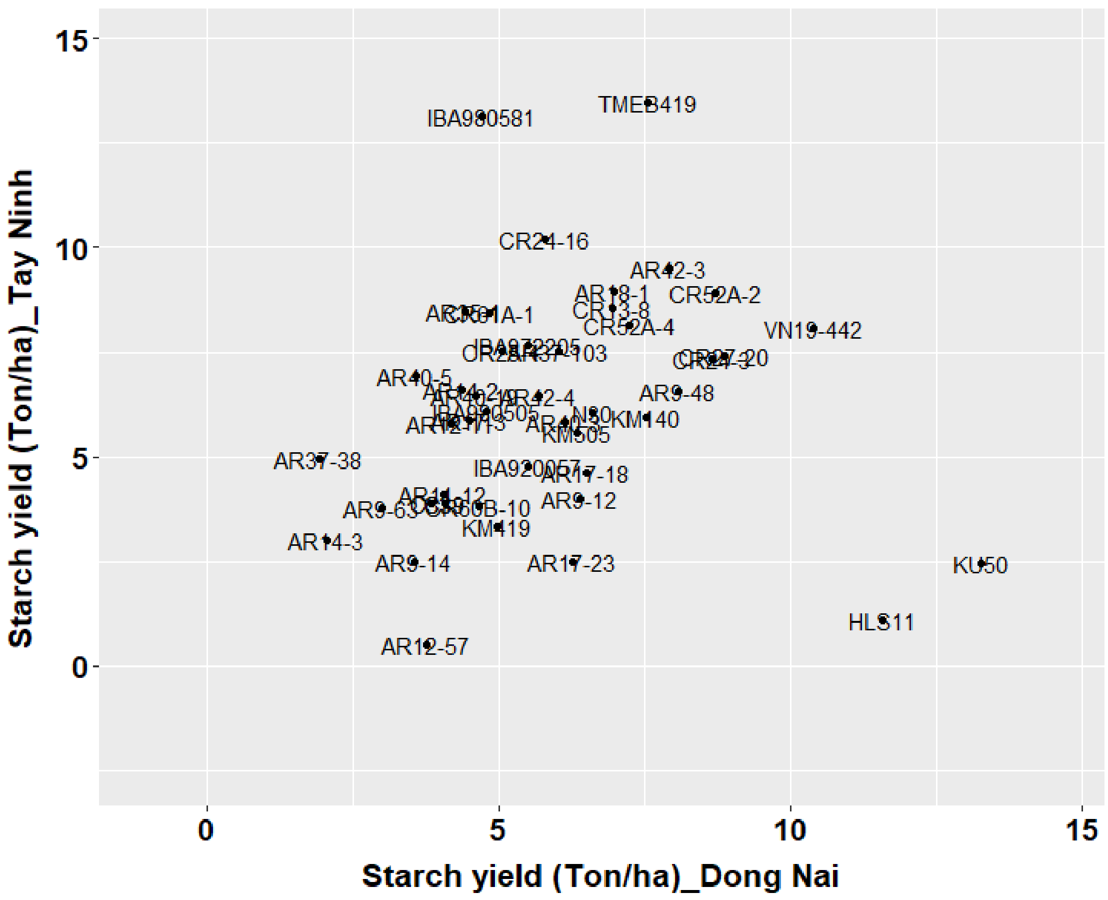
3) 10 resistant varieties from the clones collected in Vietnam

4) 102 CIAT clones containing CMD2 genes according to SSR markers

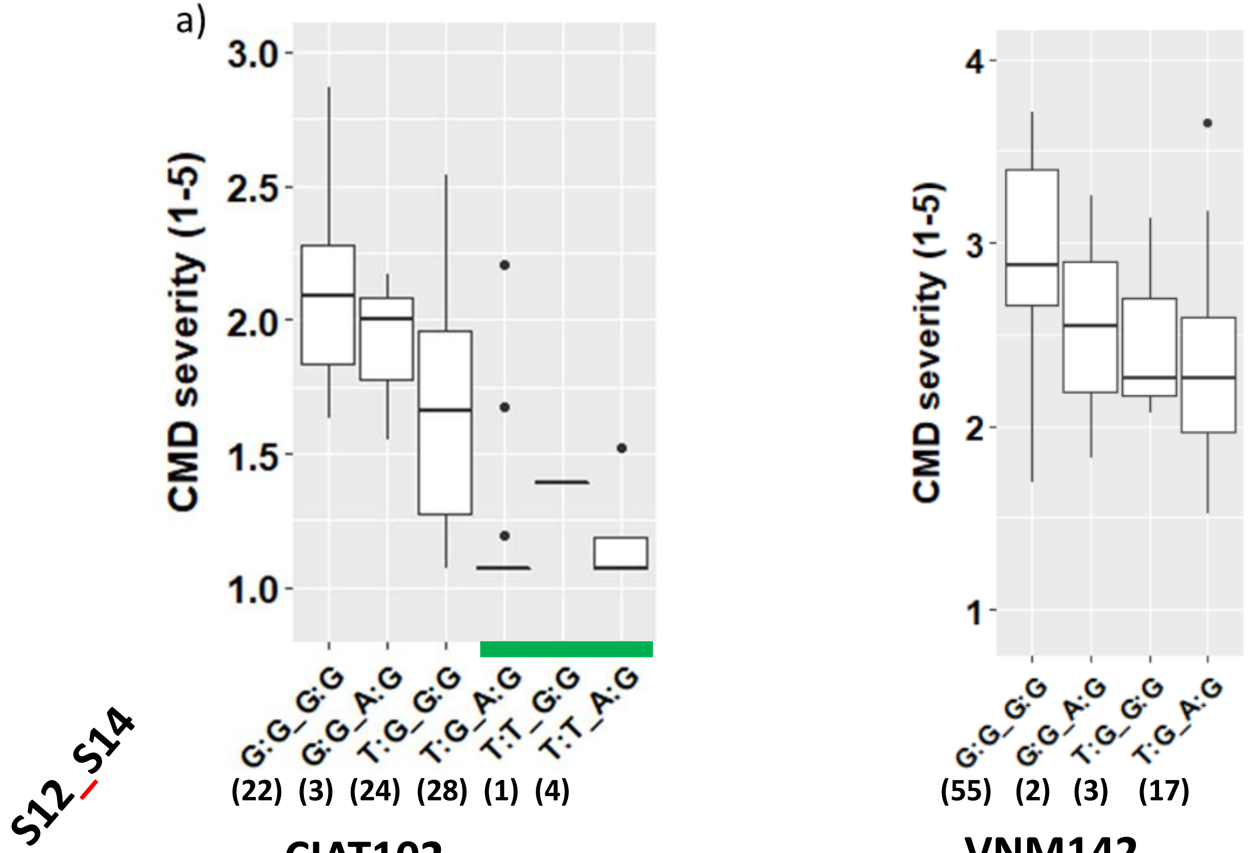
5) introduced seeds from Hawaii (progenitors from CIAT and IITA)

6) 474 seeds for genomic selection derived from CMD donors at CIAT

Stability of Starch Yield



Validation of *CMD2* markers in CIAT102 and VNM142



CIAT102

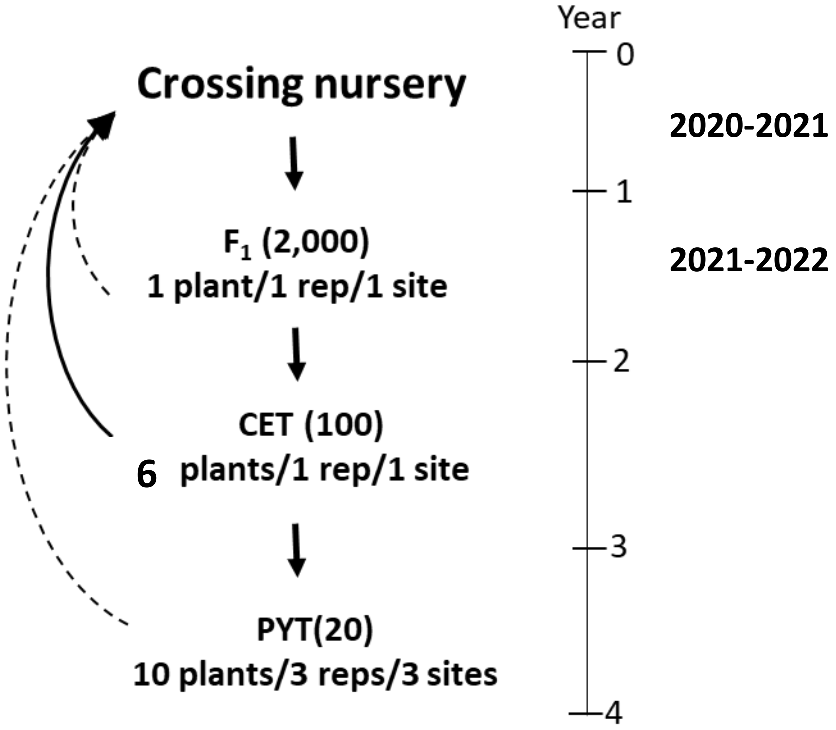
VNM142

S12_7926132 and S14_4626854

For marker S12, T is the resistant allele; For marker S14, A is the resistant allele

S12_7926132 and S14_4626854 worked well for segregation populations, but not for diversity populations

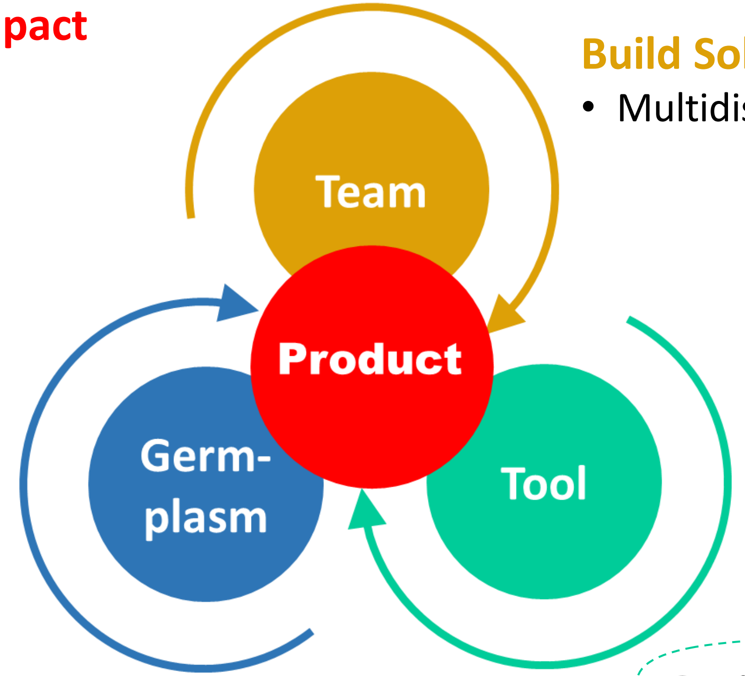
Recurrent Selection for Improving the Breeding Population



Two cycles of quick recurrent selection to introgress CMD resistance to elite variety to provide improve breeding populations to NARS.

MAS for *CMD2* locus increased the selection efficiency.

Key Elements of Plant Breeding



Enhance Global Impact
- Market segments
- Product profiles
- Breeding pipelines

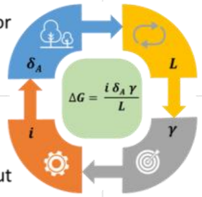
Build Solid Foundation
- Multidisciplinary team

Create New Opportunities
- High and stable dry matter
- Waxy starch
- High pro-vitamin A
- CBSD resistance
- Whitefly resistance
- Good cooking quality
- Small granule
- Drought and heat tolerance

Modernize Breeding Program

Genetic Diversity
- 20-30 progenitors for each pipeline

Duration of Selection Cycle
- Flower Inducing
- Genomic Prediction



Intensity
- High throughput phenotyping

Accuracy
- CassavaBase
- TPE, ≥ 2 Environments
- Row-column design
- ≥ 5 Checks, BLUP
- NIRS

Theoretical and Applied Genetics (2021) 134:2335–2353
https://doi.org/10.1007/s00122-021-03852-9

REVIEW

Check for updates

Fifty years of a public cassava breeding program: evolution of breeding objectives, methods, and decision-making processes

Hernán Ceballos[1,2] · Clair Hershey[3] · Carlos Iglesias[4] · Xiaofei Zhang[1,2]

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Abstract

This paper reviews and analyzes key features from cassava breeding at the International Center for Tropical Agriculture (CIAT) over 50 years and draws lessons for public breeding efforts broadly. The breeding team, jointly with national program partners and the private processing sector, defined breeding objectives and guiding business plans. These have evolved through the decades and currently focus on four global product profiles. The recurrent selection method also evolved and included innovations such as estimation of phenotypic breeding values, increasing the number of locations in the first stage of agronomic evaluations, gradual reduction of the duration of breeding cycles (including rapid cycling for high-heritability traits), the development of protocols for the induction of flowering, and the introduction of genome-wide predictions. The impact of cassava breeding depends significantly on the type of target markets. When roots are used for large processing facilities for starch, animal feeding or ethanol production (such as in SE Asia), the adoption of improved varieties is nearly universal and productivity at the regional scale increases significantly. When markets and relevant infrastructure are weak or considerable proportion of the production goes for local artisanal processing and on-farm consumption, the impact has been lower. The potential of novel breeding tools needs to be properly assessed for the most effective allocation of resources. Finally, a brief summary of challenges and opportunities for the future of cassava breeding is presented. The paper describes multiple ways that public and private sector breeding programs can learn from each other to optimize success.

HarvestPlus
Better Crops • Better Nutrition

RTBfoods

Australian Government
Australian Centre for International Agricultural Research

Ingredion

华大生命科学研究院
BGI • research

AGROSAVIA

CGIAR
Excellence in Breeding Platform

AGI

PPRI

NAFRI

PPC

KASETSART UNIVERSITY 1943

CATAS 1954

TTDI

Makerere University

USDA ARS
United States Department of Agriculture
Agricultural Research Service

NaCRRI

Embrapa

BTI BOYCE THOMPSON INSTITUTE

University of Hawai'i

Foreign, Commonwealth & Development Office

Bill & Melinda Gates foundation

Cornell University

DSMZ

CGIAR
Research Program on Roots, Tubers and Bananas

WACCI
West Africa Centre for Crop Improvement

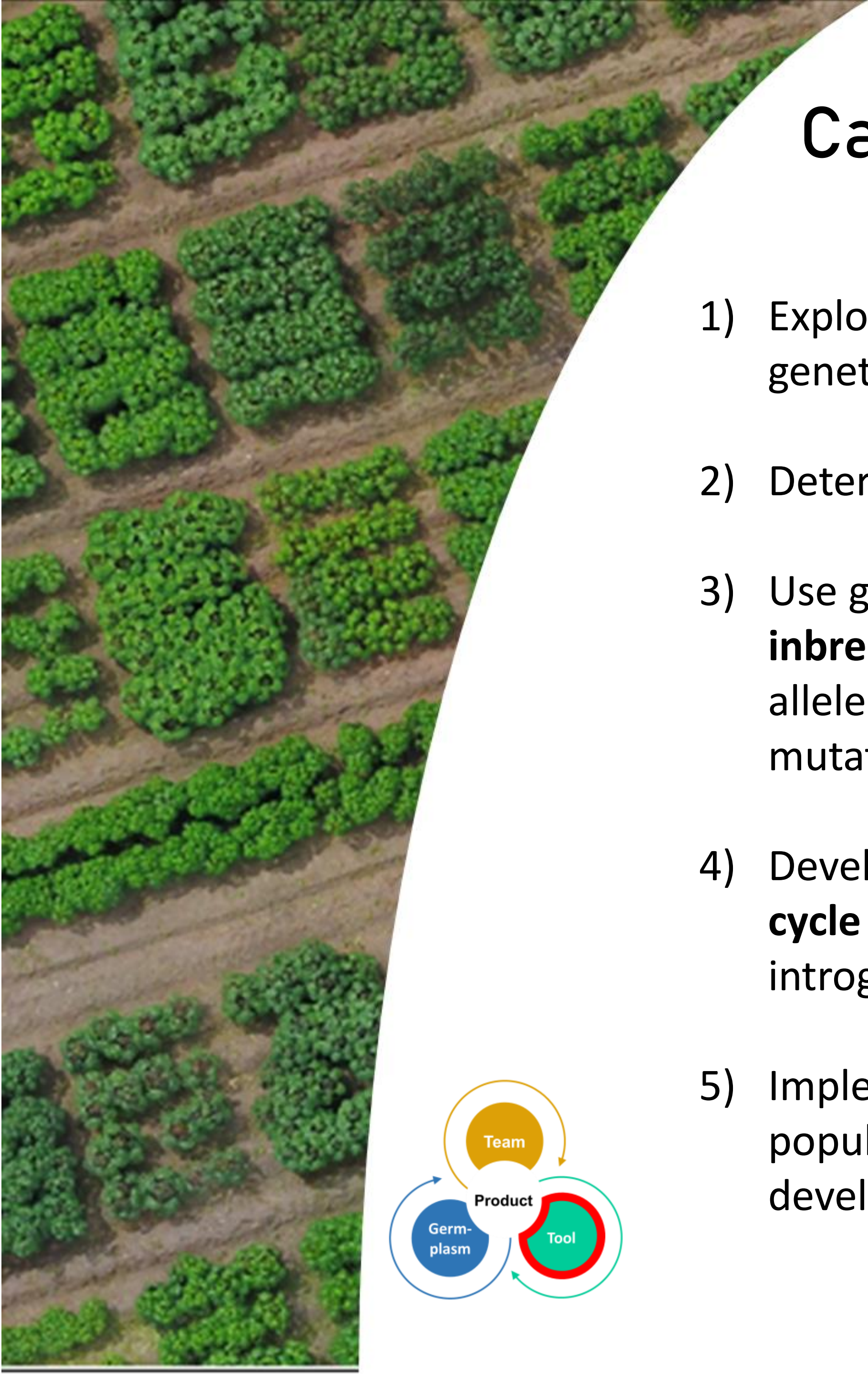
IITA
Transforming African Agriculture

CIAT

National Root Crops Research Institute

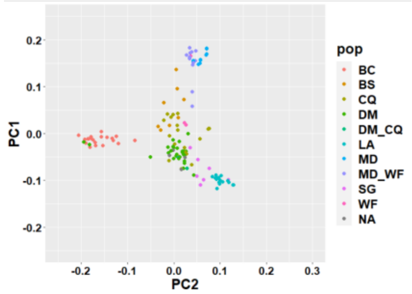
TARI
Transforming Agriculture


H.Usma



Cassava Hybrid Breeding

1) Explore **germplasm pools** to understand the genetic distance and heterosis among pools;



2) Determine **heterotic patterns**

3) Use genomics technology to understand **inbreeding depression** and identify favorable alleles to select for and major deleterious mutations to select against;

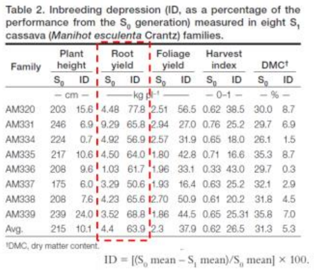


Table 2. Inbreeding depression (ID, as a percentage of the performance from the S_0 generation) measured in eight S_1 cassava (*Manihot esculenta* Crantz) families.

Family	Plant height		Root yield		Foliage yield		Harvest index		DMC†	
	S_0	ID	S_0	ID	S_0	ID	S_0	ID	S_0	ID
	– cm –		——kg pl⁻¹——				– 0-1 –		– % –	
AM320	203	15.6	4.48	77.8	2.51	56.5	0.62	38.5	30.0	8.7
AM331	246	6.9	9.29	65.8	2.94	27.0	0.76	25.2	29.7	6.9
AM334	224	0.7	4.92	56.9	2.57	31.9	0.65	18.0	26.1	1.5
AM335	217	10.6	4.50	64.0	1.80	42.8	0.71	16.6	35.3	8.7
AM336	208	9.6	1.03	61.7	1.96	33.1	0.33	43.0	29.7	0.3
AM337	175	6.0	3.29	50.6	1.93	16.4	0.63	25.2	32.1	2.9
AM338	208	7.6	4.23	65.6	2.70	50.9	0.61	20.2	31.8	4.5
AM339	239	24.0	3.52	68.8	1.86	44.5	0.65	25.31	35.8	7.0
Avg.	215	10.1	4.4	63.9	2.3	37.9	0.62	26.5	31.3	5.3

†DMC, dry matter content.

$$ID = [(S_0 \text{ mean} - S_1 \text{ mean})/S_0 \text{ mean}] \times 100.$$

4) Develop technologies to **shorten crossing cycle** for inbreed development and trait introgression;

5) Implement **two-part strategy** to enhance population improvement and variety development.