Fifty Years of Maize Research in the CGIAR:
Diversity, Change, and Ultimate Success

Derek Byerlee & Greg Edmeades

CIMMYT
International Maize and Wheat Improvement Center

CGIAR
RESEARCH PROGRAM ON
Maize

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CIMMYT – The International Maize and Wheat Improvement Center – is one of the centers under the Consultative Group on International Agricultural Research (CGIAR) and is the global leader in publicly funded maize and wheat research and related farming systems. Headquartered near Mexico City, CIMMYT works with hundreds of partners throughout the developing world to sustainably increase the productivity of maize and wheat cropping systems, thus improving global food security and reducing poverty. CIMMYT leads the CGIAR Research Programs on Maize and Wheat and the Excellence in Breeding Platform. The Center receives support from national governments, foundations, development banks, and other public and private agencies. For more information, visit www.cimmyt.org.

The **CGIAR Research Program on Maize (MAIZE)** is an international collaboration led by CIMMYT and the International Institute of Tropical Agriculture (IITA) that seeks to mobilize global resources in maize R&D to achieve greater impact on maize-based farming systems in Africa, South Asia, and Latin America. The MAIZE strategy draws upon learning and experiences obtained through decades of extensive partnerships with national and international research and development partners, including both public and private institutions, and farming communities. For more information, visit www.maize.org.

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List of Abbreviations

AATF	African Agricultural Technology Foundation
ADP	Agricultural Development Project
AFRICA RISING	Africa Research in Sustainable Intensification for the Next Generation
AGG	Accelerating Genetic Gains for Maize and Wheat Improvement
AGRA	Alliance for a Green Revolution for Africa
AMBIONET	Asian Maize Biotechnology Network
BARI	Bangladesh Agricultural Research Institute
BMGF	Bill & Melinda Gates Foundation
BRAC	Bangladesh Rural Advancement Committee
Bt	*Bacillus thuringiensis*
CA	Conservation Agriculture
CAS	CGIAR Advisory Services Secretariat
CGIAR	Consortium of International Agricultural Research Centers
CIAT	Centro Internacional de Agricultura Tropical
CIMMYT	Centro Internacional de Mejoramiento de Maiz y Trigo
CML	CIMMYT Maize Line
CP	Colegio de Postgraduados
CRMA	Climate Resilient Maize for Asia
CRP	CGIAR Research Program
CSISA	Cereal Systems Initiative for South Asia
DFiD	Department for International Development (UK)
DNA	Deoxyribonucleic acid
DTMA	Drought Tolerant Maize for Africa
EV	Experimental variety
FAO	Food and Agricultural Organization
FAW	Fall Armyworm
GIZ	German Agency for International Cooperation
GMO	Genetically Modified Organism
HTMA	Heat Tolerant Maize for Asia
IARC	International Agricultural Research Center
ICRISAT	International Crops Research Institute for the Semi-Arid Tropics
IEA	International Evaluation Arrangement
IFPRI	International Food Policy Research Institute
IITA	International Institute of Tropical Agriculture
IMAS	Improved Maize for African Soils
IMIC	International Maize Improvement Consortium
INCAP	Institute of Nutrition of Central America and Panama
IPR	Intellectual Property rights
IRAT	Institute for Tropical Agronomy Research (France)
IRRI	International Rice Research Institute

MAB	Marker-Assisted Breeding
MAIZE	CRP on Maize AgriFood Systems
MAP	Mexican Agricultural Program
MasAgro	Sustainable Modernization of Traditional Agriculture
MDG	Millennium Development Goal
MLN	Maize Lethal Necrosis
MNC	Multi-National Corporation
MSV	Maize Streak Virus
MV	Modern variety
N	Nitrogen
NARSs	National Agricultural Research System(s)
NAFPP	National Accelerated Food Production Project
NGO	Non-Governmental Organization
NRM	Natural Resource Management
OFR	On-farm research
OPV	Open-pollinated variety
ORSTOM	Overseas Scientific and Technological Research (France)
PASS	Program for Africa's Seed Systems
PPP	Public-Private Partnership
QPM	Quality Protein Maize
R&D	Research and Development
RCT	Randomized control trial
RF	Rockefeller Foundation
SeeD	Seeds of Discovery
SG2000	Sasakawa-Global 2000
SIMLESA	Sustainable Intensification of Maize-Legume Systems for Food Security in Eastern and Southern Africa
SME	Small and Medium Enterprise
SMTA	Standard Material Transfer Agreement
SPTA	Seed Production Technology for Africa
SSA	Sub-Saharan Africa
STMA	Stress Tolerant Maize for Africa
TAC	Technical Advisory Committee
TSC	Tar Spot Complex
UN	United Nations
UNDP	United Nations Development Programme
USAID	United States Agency for International Development
USDA	United States Department of Agriculture
WEMA	Water Efficient Maize for Africa
WHO	World Health Organization

Foreword

Maize (*Zea mays* L.) is one of the most important crops globally; the crop is presently cultivated on over 197 million hectares for multiple purposes, including as food, feed, biofuel, and as a raw material for synthesis of various industrial products. Yet, it is fascinating that the needs, the desires, and the centuries of selections performed by the smallholder farmers in Mesoamerica, especially in Mexico, brought forth and shaped the genetic architecture of this amazing plant, before it was spread across the globe and formal institutional breeding activities were initiated. Thus, the first successful breeders of maize were undoubtedly the smallholder farmers! Over the centuries, for millions of farmers across Latin America, sub-Saharan Africa, and Asia, maize has gained—and retained—a very important place as a crop that provides energy and proteins, as a foundation of their sustenance and livelihoods, and as a part of the culture.

Established in 1966 in Mexico, maize's center of origin, the International Maize and Wheat Improvement Center (CIMMYT) has not only acted as a trusted steward of the maize genetic diversity developed by countless generations of farmers, especially in Latin America, but has always been at the forefront in developing and disseminating impactful germplasm. The aspirations of the maize-dependent smallholders remain the main force behind the continued and intensive maize improvement work undertaken by scientists at CIMMYT.

The CGIAR maize breeding programs bring the benefits of a vast tropical/subtropical germplasm (developed over the last five decades), cutting-edge breeding technologies, extensive partnerships with public and private sector institutions worldwide, and well-coordinated germplasm phenotyping/testing networks in the stress-prone tropical environments. The improved maize products developed by CGIAR Maize Program offer not only higher grain yields but also resilience to important abiotic and biotic stresses and improved nutritional quality traits relevant to the food and nutritional security, livelihoods and economic well-being of resource-poor farmers and their families in the low- and middle-income countries.

"*If you want the present to be different from the past, study the past.*" – Baruch Spinoza

A clear-eyed and unbiased appreciation of our past—both successes and missteps—can only enrich our efforts, make better progress, and effectively meet the challenges of the present and the future. The current volume is thus timely and necessary. The authors, Derek Byerlee and Greg Edmeades, are perfectly positioned to undertake the challenging task of tracing the evolution of CGIAR's maize improvement work over the last five decades. Both worked at CIMMYT through the 1990s and have forged careers as researchers par excellence, and are widely respected for their scientific wisdom and depth of understanding of the needs of agricultural R&D globally. This combination of the intimate familiarity of the CGIAR as former "insiders", and the independent and broader perspective of being the "outsiders", is one of the main reasons behind this captivating narration of five decades of CGIAR's maize legacy. It must be noted here that the authors conducted the historical review independently of CIMMYT, while CRP MAIZE provided support only for review, formatting, and online publication. The findings and conclusions are, therefore, completely those of the authors and may not necessarily reflect those of CIMMYT or CRP MAIZE.

The challenges to the maize-dependent smallholders in the tropics are far from over. Optimal, stable and long-term investment in international maize improvement efforts is critical.

I congratulate the authors of the present volume, and sincerely hope that this publication effectively informs and nourishes several more decades of impactful international maize R4D work undertaken by OneCGIAR and its partners!

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Preface

This paper builds on several antecedents. Both of us spent the best years of our careers at CIMMYT and were part of its history until the late-1990s. Our interest in maize as the world's most dynamic crop continued after we left CIMMYT's employment. Over the next 20 years we have both kept contact with CGIAR maize research issues as members of advisory panels, Boards of Trustees or reviewers of a number of projects involving both CIMMYT and IITA, mainly in sub-Saharan Africa. In 2015, Edmeades presented the history of CIMMYT maize research as part of CIMMYT's celebration of its 50th anniversary and was then lead author of a chapter, Tropical Maize (*Zea mays L.*) in *Genetic improvement of tropical crops*, Springer. Byerlee had reviewed the path to the creation of CIMMYT for the 50th anniversary and was the author of 'The globalization of hybrid maize, 1921-1970' in the *Journal of Global History* published in 2020.

The impetus for this paper arose from an invitation for us to prepare a chapter on the history of maize research for a book on the history of the CGIAR being edited by Helen Anne Curry and Timothy Lorek, to be published by Cambridge University Press. Given our interest and backgrounds the result has been a much longer and more in-depth paper than could be accommodated by the chapter. We have learned a great deal in the process on the achievements of CIMMYT in Africa since 2000 but also the broader context of maize research during our time in CIMMYT. We have also relied on comments and interviews with many people that substantially improved and corrected this version. We owe a debt of gratitude to Jock Anderson, Marianne Bänziger, Mauricio Bellon, Magni Bjarnason, Daniel Buckles, Helen Anne Curry, Joe de Vries, Olaf Erenstein, Bram Govaerts, Sarah Hearne, Paul Heisey, Thom Jayne, Jennifer Kling, Timothy Lorek, Abebe Menkir, Michael Morris, Sylvester Oikeh, Kevin Pixley, B.M. Prasanna, Robert Tripp, Steve Waddington, Pat Wall, and Martha Willcox.

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Executive Summary

Building on the experience of the Rockefeller Foundation in Mexico after WWII, maize was arguably the basis for the creation of the international center model of agricultural research that resulted in the establishment of the CGIAR in 1971. This paper traces the evolution of maize research in the CGIAR from its founding, focusing on CIMMYT with a global mandate but also recognizing the importance of IITA with a regional mandate in West and Central Africa and IFPRI with a mandate for policy research. Special attention is given to how the CGIAR centers interacted with other major players in the global research and development landscape—notably national research programs, the private sector, and farmers themselves.

Section 1 describes the major players at the time CIMMYT was established and introduces four major themes that frame the review. First, it addresses how the centralized research model of the international center was adapted to accommodate the huge diversity of maize growing environments, maize producers and uses of maize across the tropical and subtropical world. Second, the paper explores efforts to reach small-scale farmers often in marginal and risky rainfed areas through stress tolerant varieties and hybrids and sustainable crop and soil management developed with farmers and national research programs as key partners. Third, we explore the challenges of the CGIAR interacting with the private sector to deliver CGIAR maize products and to access new breeding tools and technologies, while maintaining its priority on resource-poor farmers. A final theme is how maize research has adapted to changing donor priorities and funding mechanisms while continuing to produce international public goods.

Section 2 provides a brief overview of the institutional and financial history of CGIAR maize research. This history starts by noting that the involvement of the CGIAR in tropical maize differs from rice and wheat, reflecting the legacy of programs that preceded it, as well as the diverse rainfed environments that maize serves. Networks and regional programs, existing at the time CIMMYT and IITA were founded, provided a template for center activities as well as extant germplasm collections that were the foundations for center breeding programs. With flexible and stable funding in the 1970s and 1980s, both CIMMYT and IITA created breeding populations and built large scale international testing programs to facilitate germplasm exchange and the development of open pollinated varieties (OPVs). From the mid-1980s, priorities were more systematically defined, and breeding products shifted toward inbreds and hybrids to be delivered through partnerships with the private sector. Over time, goals diversified from "increasing the pile of food" to a focus on poverty reduction and sustainable natural resource management. Priorities were further sharpened following a funding crisis in the 1990s that accelerated a pivot to Africa, supported through a series of large projects especially in the 2000s when the Bill and Melinda Gates Foundation became a major donor. This shift to Africa came at some cost to the traditional support offered by CIMMYT to Latin American and Asian national programs. In the past decade, the focus on Africa continued within the context of a CGIAR-wide maize program, MAIZE, that for the first time, built strong and sustained collaboration between CIMMYT and IITA. During this period there was ever more emphasis on "metrics" to define expected impacts of CGIAR investment in maize research, requiring strong downstream partnerships to reach smallholders. This further strengthened linkages between center breeding programs and the private sector especially small and medium sized seed companies (SMEs), but also large multinational companies.

Section 3 tracks the history of maize breeding over the last five decades that began by grouping the best landraces and synthetics and improving them as a diverse array of populations that were not based on any clear heterotic pattern. International testing of these populations in best-fitting target environments exposed cooperating national programs to an array of new germplasm, and allowed the populations to become more broadly adapted, although the rate of genetic improvement was slow. Experimental varieties formed from elite fractions of each were often retested, sometimes reselected, and released by national programs. Decentralization of breeding efforts to "hotspots" for diseases and pests, and where the populations were best adapted, quickly followed. The definition of mega-environment built around similar growing conditions, pest and disease complexes, grain type and color preferences across countries and sometime regions was a key step in prioritizing traits for more focused breeding. This allowed some populations to make faster progress and others to be retired. Regional and global networks were strengthened or established to facilitate faster genetic improvement and germplasm exchange.

Shifting the main thrust of the CIMMYT maize breeding program and its staff to Africa in 2000 improved operational efficiency and attracted considerable donor support. There was a concomitant and overdue increase in focus on hybrids rather than OPVs, leading to major changes in breeding methodologies, and increasing collaboration with the private seed sector. However, there was no escaping the effects of drought and low fertility, diseases, insects and Striga in depressing and destabilizing production, and breeding for stress tolerance quickly became the *modus operandi* in Africa. Progress towards stable and improved yields has been accelerated by using managed stress levels and new science—notably doubled haploids, marker-assisted breeding and more recently, genomic selection. Meanwhile, CIMMYT and IITA maize programs have proven agile and responsive to the new threats of maize lethal necrosis and fall army worm in Africa that has again demonstrated the value of coordinated international maize improvement initiatives backed by adequate funding.

Section 4 analyzes the large investment in Quality Protein Maize (QPM) with high lysine content that has waxed and waned over 50 years. The 1966 discovery of the *opaque-2* gene that significantly increased lysine content caused a great deal of excitement that maize could boost the nutritional value of protein worldwide. UNDP invested heavily in research on high lysine maize at CIMMYT for the next two decades to overcome low yield and soft dull kernel types. This substantial breeding effort produced varieties with a grain type indistinguishable from that of normal maize, but UN nutritional standards had by then shifted decisively toward energy rather than protein as the major challenge for ending hunger. Furthermore, success in creating a "normal" grain type negated the potential for markets to express a price premium needed for farmers to adopt QPM. With little effort to conduct nutrition educational programs for consumers to accompany the introduction of QPM varieties, adoption was limited, and the effort was halted in 1990. Meanwhile a highly successful QPM variety based on CIMMYT germplasm was identified in Ghana, and after local adaptation by Ghanaian breeders with Sasakawa Global 2000 support, was widely adopted in the early 2000s. When the breeding of QPM was recognized by the award of the World Food Prize in 2000, CIMMYT's efforts to scale up adoption of QPM were renewed with donor support, this time mainly as hybrids. Problems of demand for the product persisted and with limited evidence of improved nutritional outcomes from introducing QPM varieties, support for quality protein maize was again reduced to a trickle in recent years. However, many of the lessons from the QPM experience were incorporated into the CGIAR investment in biofortification in which maize grain with enhanced pro-Vitamin A and/or zinc are being developed. Improved pro-Vitamin A grain types are identifiable by their golden colour, though there is no visual marker for kernels with elevated zinc content. Both are promoted through public health messaging.

Section 5 reviews the evolving relationship of CIMMYT with the private sector from an initial lack of mutual trust to the present one of partnership and mutual dependence. For the first 20 years CIMMYT, and to a lesser extent, IITA, saw their role as working with public national research systems, often including public seed companies. An almost exclusive focus on OPVs whose seed could be saved by farmers from season to season provided a useful steppingstone on the road to supplying improved varieties to small-scale producers, but because seed sales were not required each season it was not an attractive product for the private sector. Instead, the gap was filled, albeit imperfectly, by farmer-to-farmer transfer of seed, community seed production, and parastatal seed suppliers with limited motivation for product improvement. Moreover, in the 1970s and 1980s the mounting evidence that smallholders were willing to grow hybrids and realize their benefits was often ignored by CIMMYT, effectively slowing investment in the seed industry. Our assessment is that CIMMYT's single-minded dedication to OPVs in the 1970s delayed the development of hybrids by the public sector and SMEs by about a decade. Still, population improvement in the OPV program contributed to the success of the hybrid program by increasing the average performance of lines extracted from those populations.

As CIMMYT and IITA steadily moved toward hybrids, research showed that the best hybrids generally out-yielded OPVs under stressed as well as high yielding conditions, and heterosis became recognized as a form of stress tolerance. These findings aligned with the transition by CIMMYT and IITA in the mid-1980s towards heterotic group identification followed by inbred line/hybrid development, moves that in turn provided SME seed companies with breeding materials they could easily exploit. The increased number and market share of SME maize seed companies in Mexico and sub-Saharan Africa in recent years are strongly linked to the availability of stable stress tolerant inbreds from CGIAR programs. The annual production (2020 figures) of over 130,000 tons of seed of CGIAR-derived stress-tolerant hybrids in Africa by SMEs through licences with exclusivity limited geographically has addressed an important gap in seed markets not being met by multi-national (MNCs). More recently, CIMMYT has used maize improvement consortia to support the R&D capacity of SMEs through access to inbreds during their development. At the same time, these partnerships have required CIMMYT to compromise somewhat on its original policy of unrestricted access to all of its products in the interests of quickly increasing the number of farmers it reaches.

CIMMYT judged that it could not compete with MNCs in R&D, especially for the transgenic technology. Instead, it took a bold although controversial step at the time to develop partnerships with the MNCs mostly by obtaining royalty-free licenses for use in specific geographies in Africa. These partnerships as well as similar agreements with advanced public research institutes, have played a key role by applying new technologies such as genomic selection, transgenes, databasing software, and doubled haploid generation in tropical maize. After two decades, transgenes employed by CIMMYT have struggled to get regulatory approval and have produced little impact. Insect-resistant transgenic maize, currently in commercial use in South Africa, is likely to be soon released in Kenya where fall armyworm is decimating maize crops.

Section 6 reviews investments by the CGIAR in maize agronomy. Recognizing that improved varieties would have only modest impacts unless accompanied by appropriate changes in crop and soil management, on-farm research (OFR) on crop management practices for improved varieties has been an important component of CIMMYT and IITA programs from the beginning. The public good element in this highly location specific research has been realized through development and demonstration of methods and then training and assistance to national scientists in their application. CIMMYT was a leader within the CGIAR in OFR that often went well beyond research on maize to address the management of complex farming systems with multiple objectives of food security, risk mitigation and income generation. Starting with the package approach focused on seed and fertilizer of the Puebla Project in the early years, these methods made a 180 degree turn in the 1980s and 1990s. Through collaboration of agronomists and social scientists, methods were developed for participation by farmers in all stages of design, experimentation, trial management and evaluation of results, drawing as well on farmer innovations and indigenous knowledge. By the 1990s, the type of technology tested had also changed to meet the evolving sustainability paradigm with due attention to rotation or intercropping with legumes and reduced or zero tillage and retention of crop residues, in what came to be known as "conservation agriculture". Nonetheless successful crop management in Africa is still dominated by nitrogen supply and nutrient use efficiency in soils that are often severely depleted.

Participatory OFR greatly increased scientists' understanding of the nuances of complex farming systems and their constraints and has helped to reshape research priorities. Many OFR programs provided important feedbacks to breeding priorities for varieties adapted to smallholder systems. The special focus by CIMMYT on the development of methods for OFR and associated manuals and training programs for national partners has been an enduring public good over many decades.

With the "impact culture" in play since 2000, major efforts were made to scale up conservation agriculture using innovation platforms in a number of large projects that ran for a decade or more. However, the widespread and impressive adoption of conservation agriculture by large-scale farmers in tropical Latin America has not been replicated in tropical regions dominated by diverse smallholder systems where crop residues for livestock feed is often a priority and appropriate planting machinery is not available. The introduction of new legume varieties and species in a range of settings, improved N use efficiency, refinements of tillage methods and control of problem weeds such as Striga have been the most notable achievements in Africa.

Onfarm research may also have overemphasized technological solutions versus research to improve the external policy and institutional environment in which farmers obtain inputs needed for successful adoption of crop and resource management technologies, notably for conservation agriculture. In recent years, IFPRI, CIMMYT and others have provided important insights on policy, reform of input subsidy programs and institutional innovations through panel household surveys and randomized control trials that experimentally test interventions at the household or village level.

Section 7 provides a summary of global impacts. The most important product has been the germplasm developed and disseminated by the centers. Although adoption in the early years of CGIAR-related maize germplasm was low, by 1998 it had reached 18 Mha or 28% of the maize area in the tropics and subtropics. At that time over half the total area sown to CIMMYT germplasm was in Latin America. In Africa, adoption was highest in West Africa, where IITA scored considerable success in developing varieties that enabled maize to expand rapidly in the savannahs. Adoption of CIMMYT-related germplasm in Eastern and Southern Africa has jumped in the past 15 years by mainstreaming stress tolerance in the breeding program and by the development of close working relationships with the private seed sector. In 2015 more than one third of the area in that region was sown to varieties and hybrids derived from CIMMYT germplasm, and adoption appears to have accelerated since then. Studies in both West Africa and Eastern and Southern Africa also document the high rate of return to investment in the CGIAR, with benefits in the past 25 years in the range of \$0.66-1.05 billion per year.

CIMMYT and IITA invested heavily in long-term in-service training courses up to the 1990s. Although not well documented, some evidence suggests significant payoffs in terms of building research capacity of national programs, including the private sector, as well as regional cooperative maize research networks. A brief review of three maize success stories from 2000, Ethiopia, Mali and Bangladesh suggest that while the impetus for the maize take off in those countries was home grown, training programs over many years have significantly contributed along with continued access to CGIAR personnel and germplasm.

We conclude in ***Section 8*** that our overall story is one of CGIAR maize research programs made up by a relatively small body of motivated and dedicated scientists that, with generally good leadership, strong financial support, and a vision that they could make a positive difference to the lives of smallholder families, were able to "punch well above their weight". The last five decades have seen the emergence of a truly global effort in improvement of maize-based systems through the international exchange of germplasm and people, and by being able to match rapid and significant changes in pests, diseases, and climate. Operating in the context of the CGIAR and the development community more generally the CGIAR's maize research programs have undergone profound shifts over the past 50 years, probably more than for any other CGIAR crop. The germplasm base, types of products, the geographical emphasis and the partnerships that emerged after 50 years of international maize research are now quite different to those in the first two decades of design and establishment of the program. We also document some unproductive detours and mis-investments, and the financial crises and reforms within the CGIAR that were at times disruptive. But in the end, the centers have made the hard decisions on priority traits and regions, notably the pivot to Africa where CIMMYT and IITA maize research has led CGIAR impacts in a region that until recently had been noted for stagnant productivity growth and rising food insecurity.

1
Introducion

In 2014 maize became the first crop to exceed one billion tons in global output, consolidating its role as the world's most important crop in terms of energy (calories) and protein supply. Originating in the tropics and subtropics of Mesoamerica it was spread by indigenous populations through much of the Americas, and then to the Old World from the 16th Century as part of the Colombian Exchange. However, its meteoric rise on the world stage began after WWII as global production rose over ten times its pre-War level (Jasny,1940). Much of this growth was for animal feed, and more recently for biofuel in the United States. However, maize remains the staple food crop in its center of origin, and in the first half of the 20th Century it became a staple in much of sub-Saharan Africa (McCann, 2005).

With the development and adoption of hybrid maize in the USA from the 1920s, maize was also the first 'Green Revolution' crop re-enforcing the US's position as the world's largest producer. US average maize yields now average 11 t/ha — more than double the average of maize yields in the rest of the world. In efforts to extend the US experience with hybrid seed, maize became the focal crop in early foreign assistance, private sector investment and international germplasm exchange around the world, beginning before World War II (Curry, 2017; Kass *et al.*, 2005; Byerlee, 2020). Indeed, it has also been argued that a proposal for an international research center on tropical maize by a Mexican government official in 1950 was the catalyst for the development of the international center model of agricultural research that resulted in the creation of the International Rice Research Institute (IRRI) in 1960, the International Maize and Wheat Improvement Center (CIMMYT) in 1966 and the CGIAR (formerly known as the Consultative Group on International Agricultural Research) in 1971 (Byerlee and Lynam, 2020).

Despite the early focus, maize research in the tropics was soon eclipsed by the Green Revolution in rice and wheat in the 1960s, and maize became an 'also ran' in the first three decades of the CGIAR. Up to the 1980s, the CGIAR emphasized Asia, driven by Cold War politics and Malthusian gloom. However, maize was not a staple food in Asia except for marginalized populations in the hills and tribal areas, and therefore not a 'political crop'. By 1985, only 6 M ha were sown globally to improved maize varieties using CGIAR germplasm compared to 50 M ha for wheat (Anderson *et al.*, 1985). Sub-Saharan Africa only became a priority for CIMMYT from the mid-1980s, two decades after its founding.

This paper traces the evolution of maize research in the CGIAR from 1970 to 2020. The focus is on CIMMYT with its global mandate from the CGIAR for maize research, recognizing also the importance of the International Institute for Tropical Agriculture (IITA) in Ibadan, Nigeria, with a mandate for maize in West and Central Africa.[1] A brief summary of policy research specific to maize undertaken by the International Food Policy Research Institute (IFPRI) is also provided. The CGIAR was a relatively small player in terms of global investment in maize research, and even in the tropics and subtropics, CIMMYT estimated that it accounted for only about 2 percent of the total of 1300 maize scientists in 1998, including the private sector (Morris, 2002). Special attention is focused on how these centers interacted with the many other major players in the global research and development landscape—notably national research programs, the private sector, and farmers themselves.

The paper is built around four major themes. The first is to explore CGIAR maize research in light of the diversity of its target environments, countries and farmers. A logical focus at the onset was the 60 M ha of maize produced in the tropics and subtropics that in 1990 made up almost one half of the world's maize area (but only 30 percent of output), nearly all of it in low and medium-income countries. Even

[1] CIAT, FAO and the French food crop institute, IRAT also had important regional maize research programs (Byerlee and Lynam, 2020).

this subset included 53 countries that were significant maize producers (Hanson, 1974). Nearly all of this maize depended on rainfall with its inherent spatial and year-to-year variability of growing conditions. Grain type and color also varied widely, reflecting diverse uses for food in many forms from tortillas to porridges, green maize on the cob and snack foods, and for animal feed. Maize by-products were also highly valued in many regions for fodder.

This diversity challenged the development of international maize research as a coordinated and integrated program. The experience with rice and wheat over a decade had already established a model for international crop research built around a centralized breeding program linked through international testing with networks of public sector research systems at the national level (Byerlee and Lynam, 2020). A fundamental characteristic of the model was its 'open source' nature where countries were free to directly release varieties from the testing program or use materials as inputs into their own breeding programs. Nonetheless, the first international centers aspired to realize quick payoffs by developing widely adapted varieties that could be immediately grown on large areas by multiple countries (Anderson *et al.*, 1991; Baranski, 2015). Widely adapted and freely accessible germplasm would be the core of what came to be known as international public goods that could realize significant economies of scale and spillovers across countries through international crop breeding research.

While CGIAR maize research adopted the centralized breeding model it had to be substantially adapted to accomodate the huge diversity of maize producers around the world. This was even more so since tropical maize varieties retained a high level of daylength sensitivity and were not adapted across a wide range of latitudes. Pests and diseases were often region-specific, and these two factors generally resulted in tropical maize being locally adapted relative to the wide adaptation being experienced in wheat. In the early years, the broad diversity of maize systems and narrow adaptability of maize varieties was little understood, requiring considerable investment in defining the scope of agro-climatic conditions, the prevalence of pest and disease complexes and later the socio-economic context for maize production. It also raised questions about whether research should be concentrated in Mexico or decentralized to focus on region-specific problems.

The second theme also relates to the uniqueness of maize. Unlike other CGIAR crops, from the beginning public maize research programs such as CIMMYT and IITA had to deal with the reality of a growing role for the private sector. Hybrid maize, by requiring annual seed purchases to maintain yields, provided an inbuilt incentive for private firms to invest in the production and promotion of seed as well as in their own R&D capacity. By 1970 high income countries had almost completely switched to hybrid seed produced by private firms, some of which had evolved into large multinational corporations (MNCs). With further strengthening of intellectual property rights in the late 20th century a handful of private seed companies had emerged as major global players in R&D leaders in biotechnology and in investments that far exceeded those of the CGIAR (Duvick, 1998; Lopez-Pereira and Morris, 1994).

Morris (1998) has portrayed the private sector as passing through a number of stages in seed industry development from emergence to expansion to finally reach a mature stage where it dominates the whole seed value chain from upstream R&D to seed delivery. Within these evolutionary stages, the CGIAR had to continuously redefine its role as well as its target geographies and farmers, given the considerable heterogeneity across and within countries in seed industry development. In addition, interaction by the CGIAR with the private sector raised questions about the applicability of the original 'open source' model for CGIAR research. A recurring issue is how the CGIAR centers could balance their role in producing international public goods versus accessing proprietary technologies of value to smallholders and accelerating delivery of its products via private seed companies.

A third theme of this history was how an international center could reach the millions of small-scale maize farmers in stress-prone rainfed tropical environments, which were always risky, many with quite marginal growing conditions. This was not a new problem since the Rockefeller Foundation (RF) program in Mexico, from which CIMMYT was descended, had registered disappointing results after more than two decades of maize research—by its own analysis its impacts on poor farmers in rainfed areas in Mexico were minimal (Myren *et al.*, 1969). Edwin Wellhausen, CIMMYT's first director general and before that the first director of the RF maize program from 1943, was especially passionate about the need to reach smallholder farmers in order to redress past failures (Wellhausen, 1970).

The breeding programs thus had to respond to the specific needs of smallholders operating in risky rainfed environments. Indeed, maize became the first major crop for which the CGIAR departed from the prevailing paradigm of breeding and selecting under high input conditions to seek varieties with tolerance to drought and to low levels of soil fertility. Large investments were also made in maize research to improve the nutritional status of the poor, especially children and women, by incorporating a gene for high lysine to enhance protein nutritional quality. Both of these thrusts required long-term investments with potentially high but uncertain payoffs.

The focus on small-scale farmers was also a major impetus for the CGIAR investment in on-farm research led by maize agronomists and social scientists. Even so, scientists debated the merits of finding ways to develop and extend 'packages of practices' to transform rainfed agriculture following the Green Revolution model, versus building on farmers' existing practices, resource constraints, and food security needs while recognizing the role of indigenous knowledge and innovation. The huge number of smallholders also challenged the CGIAR to define the international public good elements of highly location-specific on-farm research.

From the outset the main impact pathway to reach millions of farmers in over 50 countries necessarily had to be through partnerships with public national agricultural research systems (NARSs) and later the private sector. Emphasis on cooperative research networks, technical assistance to NARSs, and training of young scientists was an integral part of the CGIAR research programs from the beginning. Maintaining support for such activities whose impacts could only be seen over the long term would prove to be an ongoing challenge to the CGIAR.

This leads to the final challenge of this review—maintaining financial support for international maize research over 50 years and the setting of priorities for the best use of those funds. This was, of course, not unique to maize research but within the CGIAR maize had to compete with other crops and an expanding portfolio of research on natural resources, policy and nutrition, among others. Donors in turn had to respond to their own political realities when deciding what to support. Balancing priorities of scientists, users (especially smallholders), and donors, is a recurring theme in this history.

In the next section we provide a brief overview of the evolution of the CGIAR maize research programs in the context of changing donor priorities, national demands, and evolving science. The following sections then explore the major themes in some depth through the lens of plant breeding and international testing (Section 3), the quest for quality protein maize (Section 4), and partnerships with the private sector (Section 5). Crop management research considered in Section 6, traces the evolution of multidisciplinary approaches to on-farm research and the products and impacts at each stage. Section 7 provides a brief summary of global impacts, leading to Section 8 this gives overall conclusions. Although we cover much of CGIAR maize history, the paper does not pretend to be comprehensive, leaving others to explore additional important themes and regional dimensions.

2

The Changing Institutional and Financial Context, 1971-2020[2]

1970: The Legacy of Tropical Maize Research

The story of the Mexican Agricultural Program (MAP) of the Rockefeller Foundation in 1943 is well known (Fitzgerald, 1986; Stakman *et al.*, 1967). Given its importance to Mexican diets and culture, maize was naturally the priority crop in the MAP, and wheat, the main imported cereal, was soon added. These two crops would become the focus of CIMMYT when it was created in 1966 in Mexico. CIMMYT is regarded as the second international center created after the International Rice Research Institute established in the Philippines in 1960. However, IRRI was built as a 'greenfield' center with a shiny new state-of-art research infrastructure and staff hired to fill specific disciplinary needs. In contrast CIMMYT was a 'legacy center' built on existing maize and wheat programs, mainly of the RF but also the Ford Foundation, FAO and USDA, located across the Americas, Asia and Africa (Byerlee and Lynam, 2020).

Within CIMMYT, wheat and maize each inherited a very different starting base that has major implications for understanding their histories. By 1966, when CIMMYT became operational, the wheat program was already a fully integrated global program under the leadership of Norman Borlaug with a strong central research program in Sonora in the northwest of Mexico as a focal point. It was also enjoying the early fame of the green revolution for which Borlaug would receive the Nobel Peace Prize in 1970. Maize was, by contrast, an *ad hoc* collection of regional and country programs without strong central leadership. In part this related to the nature of staffing since, unlike wheat, most RF maize staff outside Mexico had been hired independently of the Mexican program. It also reflected the nature of the crop with its highly diverse growing conditions across the tropics and subtropics, unlike the extensive irrigated areas of wheat for which direct transfer of technology from Mexico was possible – an important distinction. Further, after more than two decades, impacts of MAP maize research in Mexico were modest at best, and concentrated among larger farmers in irrigated and high potential areas. MAP maize research had very little impact on rainfed small-scale farmers in central and southern Mexico (Myren, 1969; Stakman *et al.*, 1967).

The transformation towards a CIMMYT maize program started when the Mexican National Institute for Agricultural Research (INIA) was created in 1961 and took over maize research for Mexico. RF maize staff were then placed under a newly created Inter-American Maize Improvement Program under the leadership of Edwin Wellhausen, who had led MAP maize research since 1943. The Inter-American program and later CIMMYT inherited some of the basic research on the evaluation of indigenous germplasm, heterotic patterns, cytology studies of chromosome morphology, and breeding methods, much of it in collaboration with the Mexican Colegio de Postgraduados (CP) and a number of US universities. One of CIMMYT's most important initial assets was the large germplasm bank of landraces from the tropical Americas collected by RF scientists and national partners under the auspices of the US National Academy of Sciences (Hallauer and Miranda, 1988; Curry, 2017). An important new initiative in 1967 was Plan Puebla in Mexico, managed collaboratively by CIMMYT and the CP to address the question of how to reach smallholder farmers in rainfed areas.

The Inter-American Program also included the Central American Corn *[sic]* Improvement Project that was the first network established for tropical maize research in 1954 with support from the RF. The program

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2 Much of this section is taken from CIMMYT Annual Reports published annually, and External Program and Management Reviews conducted each five years by TAC for each center.

facilitated collaboration among regional scientists in yield testing, germplasm exchange, agronomic trials, and annual meetings of scientists to review results and coordinate work plans. This regional networking model was extended to the Andean region, based out of the RF Colombian Agricultural Program and later CIAT when it was established in 1967.

The Inter-Asian Corn [*sic*] Program grew out of the RF program in India from the 1950s, while the African regional programs dating from 1963 were mounted in collaboration with USDA with funding from USAID. There were also country maize programs in Egypt and Pakistan supported by the Ford Foundation that were also included with CIMMYT when it was established, or soon after (Table 1).

Table 1. Regional and country programs inherited by CIMMYT, 1966/67. Source: Byerlee, 2016.

	Maize	Established
Rockefeller Foundation	Foundation maize staff in Mexico (Chapingo, Mexico)	1943
	Central America (San Jose, Costa Rica)	1954
	Andean Zone (Bogota, Colombia)	1961
	South & Southeast Asia (Bangkok, Thailand)	1963
USDA/USAID & Rockefeller Foundation	East Africa (Kitale, Kenya)	1963?
	West Africa (Ibadan, Nigeria)	1963?
Ford Foundation	Egypt	1966
	Pakistan	1967

In 1966, all these regional and country programs across Latin America, Asia and including East Africa were placed under the umbrella of the CIMMYT Maize Program. Transforming these legacy research programs and networks into an integrated and coordinated international program was challenging, more so since CIMMYT had two maize directors in its first four years. The regional programs continued to be quite decentralized, each with their own breeding centers and testing networks, and the Asian program had its own training program as well. Indeed, even after CIMMYT was legally established, each regional and country program outside of Mexico continued to report administratively to the respective Foundation's New York headquarters rather than to Mexico (E. Sprague, pers. comm.).

Meantime, two new international centers, CIAT and IITA, had been established in 1967 with a broad mandate to improve productivity of farming systems of the lowland tropics of Latin America and Africa, respectively. Maize programs in these new centers were envisaged as relay or testing stations for CIMMYT maize research. The regional maize network in the Andes was transferred to CIAT when it became operational, building on the maize research staff of the RF already in the region. Likewise, the regional program for West Africa (with USDA) was linked to IITA that became a strong maize breeding program in its own right when IITA hired CIMMYT's maize breeder for East Africa, Michael Harrison, to lead the program, after his success in breeding a widely adopted hybrid in Kenya.

CIMMYT's fledgling breeding programs in Mexico were focused around broadening adaptation and utilization of tropical germplasm through reduced plant height, improved pest resistance, training for the Americas, and *ad hoc* international sharing of germplasm. The first international testing of maize germplasm was organized only in 1970 as the International Maize Adaptation Nursery sent to 26 countries.

During these early years and indeed for the next two decades, CIMMYT enjoyed strong financial support from the two Foundations, joined by USAID after 1969. Their support was motivated by the prevailing Malthusian view of the world food outlook and Cold War politics (Perkins, 1997).

The Rockefeller and Ford Foundations had enthusiastically embraced the enormous challenge of accelerating world food production to meet population growth and fight communism. The initial mission of CIMMYT was to increase the "quantity of food produced", with quality (namely protein composition) added in 1970. However, CIMMYT along with other development agencies at the time, poorly articulated the pathway from increasing the 'pile of food' to reducing hunger. This narrow focus on increasing food production would dominate CIMMYT's narrative for the next 15 years.

1971-85: Organizing an Integrated Global Maize Program

The CGIAR was established in 1971 with CIMMYT as one of four founding Centers. The creation of the CGIAR within the unfolding context of the Green Revolution led to a period of rapid growth in funding by an increasing number and diversity of donors. During this period, maize research was well resourced, even though the contribution of the two Foundations had virtually disappeared by 1984 (only about 1% of the total budget) as USAID, Canada, and multinational financial institutions took the lead in supporting the CGIAR. Oversight of CGIAR funding was provided by a strong scientific body, the Technical Advisory Committee (TAC), that exerted considerable influence on donors in allocating funds across Centers and programs. In general, TAC endorsed a high priority to maize research within the CGIAR (TAC, 1987).

In 1970 the transfer of the leader of the Inter-Asian Corn Program, Ernest W. Sprague, to become Director of CIMMYT's Maize Program proved to be a significant turning point in the establishment of a well-coordinated global maize program. Under his leadership, CIMMYT hosted two international maize conferences—one to assess national demands for its products, followed by an internal review by all CIMMYT maize staff (CIMMYT, 1971; CIMMYT, 1974b). These efforts led to a systematic approach to developing and evaluating improved maize germplasm (Figures 1 & 2), structured around diverse germplasm pools and improved populations. International testing was introduced at scale more than a decade after the wheat program (Section 3). Both CIMMYT, and IITA developed an exclusive focus on open-pollinated varieties (OPVs) whose seed could be saved by farmers for a number of generations with only a mild reduction in performance. The centers saw their main clients as the public sector NARSs that also often included public seed enterprises.[3] Germplasm was supplied on request to the relatively modest private seed sector.

Figure 1. Ken Fischer (left) and Elmer Johnson beside Tuxpeño Plant Baja C15 (left) and C0 (right), El Batan, Mexico, 1976.

Figure 2. Maize seed preparation by the staff for trials (1974).

During this period, almost 40 percent of CIMMYT's staff were posted outside Mexico to cover the major maize producing regions of the world, and breeding was increasingly

[3] R. L. Paliwal, the deputy director of the CIMMYT maize program from the mid-1970s and later its director was recruited from his position as head of one of India's largest and most successful parastatal seed companies.

decentralized to address location specific disease challenges (Section 3). The maize program for the Andean region under CIAT was replaced by a CIMMYT program coordinated with CIAT. Meanwhile, the IITA maize program developed quickly and became independent of CIMMYT. The result was confusion in mandates in West Africa (for exam ple, CIMMYT took the lead in Ghana) and growing tensions in relationships between the two centers.

Underlining the high priority given to building NARS's capacity, CIMMYT staff were also seconded to provide technical assistance to seven national programs. Training was put on an equal footing with research and trainees from across the developing world undertook intensive practical courses of 3-4 months' duration in breeding and on-farm agronomy. The latter was linked closely to a major thrust in on-farm research involving economists and other social scientists that were being hired during this period. However, CIMMYT devolved responsibility for the flagship Puebla Project to the Colegio de Postgraduados in 1973. This together with dilution of the influence of the original Foundation staff as new staff from diverse backgrounds were hired, sharply limited interaction of CIMMYT with its Mexican hosts, a situation that would endure for several decades.

1985-96: Refining Priorities and Redefining Partners

In the late 1980s, CIMMYT undertook its first comprehensive strategic planning exercise that had profound implications for defining its priorities. Responding to trends in the development assistance community as well as a global food surplus, CIMMYT changed its mission from increasing food production to reducing poverty (CIMMYT, 1989). Further, the strategy gave greater emphasis to maize relative to wheat, mainly reflecting a perception by both CIMMYT and TAC of the potential to realize faster yield gains in maize, and that, comparatively, the task of improvement in wheat was well in hand (TAC, 1989). Importantly, the strategy also defined an approach to assigning priorities within maize across major 'mega-environments' (see Section 3). The plan also introduced the role of gender, natural resources management, and the growing challenge of hunger in Africa, that would all become major elements of CIMMYT's research until today.

This period also coincided with a sharp shift toward market-oriented approaches to development in what became known as "the Washington consensus". By 1985 both CIMMYT and IITA had independently recognized the slow progress in adoption of OPVs, and led by IITA, moved part of their breeding programs toward hybrids. This necessarily required them to work with the private seed sector and in some cases, support the development of private seed companies. CIMMYT added Donald Duvick, the Director of Research at Pioneer Hi-Bred International, to its trustees, and in the mid-90s hired its maize director, Delbert Hess, from the private sector to facilitate this process.

Another significant development in the 1980s was the rapid emergence of the science of molecular biology and biotechnology, and these were introduced to CIMMYT and IITA around 1990. A modest investment was justified to ensure access to new technologies that could accelerate breeding gains. Biotechnology and its growing privatization also put a premium on germplasm conservation and the recognition through international treaties of farmers' rights as the developers of this genetic heritage. A much-expanded germplasm bank facility was established and a Materials Transfer Agreement was introduced to govern the sharing and use of landraces. In 2006 the current Standard Materials Transfer Agreement (SMTA) was introduced to cover all germplasm shared by CIMMYT with national programs and private seed companies, under the terms of the International Treaty on Plant Genetic Resources for Food and Agriculture.

The Brundtland report on *Our Common Future* in 1987 followed by the UN Earth Summit in 1992 accelerated the mainstreaming of the sustainability paradigm for natural resource management (NRM), principally soil, water and major nutrients such as nitrogen (N). An updated strategic plan in 1996 endorsed a higher priority to NRM as well as increased emphasis on marginal areas and Africa through breeding for drought tolerance and subsequently, tolerance to low soil N. An NRM group was created within CIMMYT with a strong focus on principles of conservation agriculture (Figure 3) that was administratively separate to the Maize Program. Reflecting these changes, by the mid-1990s C IMMYT's mission statement was "to help the poor by increasing the productivity of resources committed to maize and wheat in developing countries while protecting the natural resources... through agricultural research and in concert with national research systems" (TAC, 1993).

Finally, CIMMYT's funding and staffing reached a peak around 1990 when seven regional programs were being supported. Crop research in the CGIAR faced a funding crisis in the mid-1990s as total funding stagnated and available funds were diverted to establish four new international centers with an environmental focus (Pingali and Kelley, 2007). Maize Program budgets and staffing were cut drastically by about half over the 1990s in both CIMMYT and IITA (Figure 4).

Figure 3. Conservation tillage plots (maize and sorghum) in El Salvador, 1993.

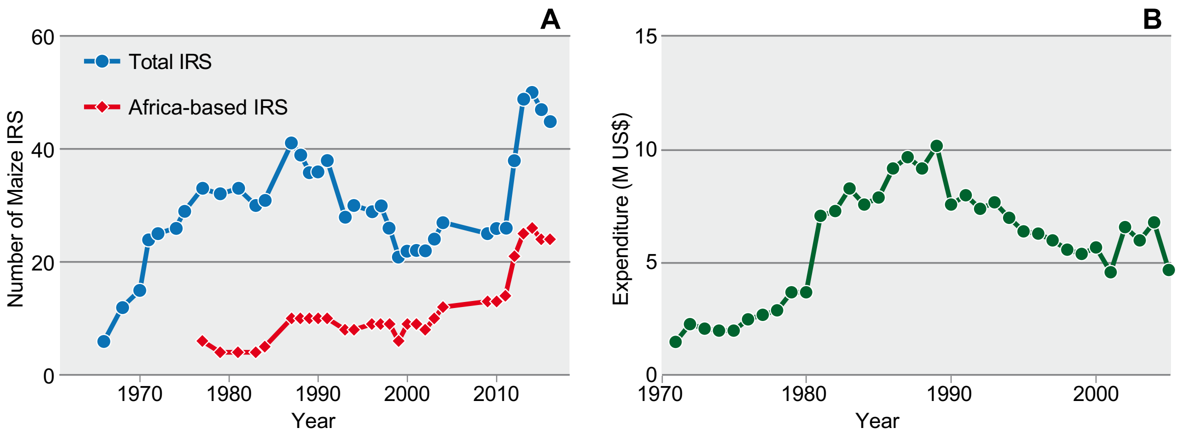

Figure 4: Panel A: Fluctuations in total CIMMYT internationally recruited maize staff (IRS) and those specifically based in sub-Saharan Africa, 1966-2016. Panel B: Fluctuations in IITA maize research budget 1971-2004, in 2000 dollars**.**

Source: CIMMYT Annual Reports; MAIZE Annual Reports; B.M. Prasanna, pers. comm., 2016. Alene *et al.*, 2009.

1996-2010: Pivot to Africa

The Millennium Development Goals (MDGs) formulated at the end of the 1990s gave new urgency and explicit targets to the global community for reducing poverty and hunger (MDG1), gender equality and empowerment (MDG3), and environmental sustainability (MDG6). The CGIAR made an effort to attract new funding through establishment of global challenge programs, including a significant investment in molecular genetics research on drought tolerance in maize that was based at CIMMYT. However, these new programs did not reverse the pressure on funding, resulting in a turbulent period with a near collapse in funding in 2003. As core unrestricted funding dwindled, financial support through specific projects became the *modus operandi*. In the case of maize, the Bill & Melinda Gates Foundation (BMGF) became a major new donor to large projects on stress tolerant maize for Africa that continue in various forms until today.

Other donors were also strongly favouring investment in sub-Saharan Africa where maize yields were extremely low and rising very slowly (about 1%, or 10 kg/ha per annum), while population growth remained high. Accordingly, in 2004 CIMMYT relocated its maize director, Marianne Bänziger, to Nairobi, and by 2010 CIMMYT's maize research effort was firmly centered in sub-Saharan Africa with over 50% of its staff located there. Meanwhile with continued difficulties in funding, CIMMYT's regional program in Asia, established in 1963, was closed around 2001 and breeding at its Mexican headquarter was de-emphasized.

During the 2004-2006 period, CIMMYT attempted to integrate breeding, crop management and socioeconomics into a cropping systems approach in a new program structure. For those years the Maize Program breeding effort was divided into two main programs, the Tropical Ecosystems and African Livelihoods, while agronomy was assigned to the Intensive Agroecosystems program. This reorganization failed at that time because of lack of funds, lack of focus and lack of identity with a specific crop, and in 2006 CIMMYT reverted to the Global Maize Program.

Figure 5. Abebe Menkir in a maize inbred line nursery, IITA, Ibadan, Nigeria, 2011.

CIMMYT's efforts during the 1996-2010 period were in addition to the continuing presence of a strong maize research effort at IITA for West and Central Africa (Figure 4) led by Jennifer Kling, Abebe Menkir (Figure 5) and colleagues. The prevalence of drought stress, infertile low organic matter soils that were often shallow and drought-prone, and low use of external inputs in much of Africa placed priority on breeding for stresses as well as on-farm research to develop management systems to reverse crippling soil degradation. Relationships between CIMMYT and IITA finally improved towards the end of the 1990s with the launching of their first major collaborative research initiative around maize stress tolerance.

2010-20: Integration of CIMMYT and IITA Programs: MAIZE

The 2008-12 world food crisis resulted in a resurgence of interest by donors and countries alike in investing in agricultural research. In response to this opportunity, the CGIAR undertook an ambitious reform program to better integrate research programs across the CGIAR and reverse the trend away from unrestricted or core funding to funding of specific projects. The CGIAR Research Program on Maize Agri-food Systems (MAIZE), initiated in 2011, for the first time developed a CGIAR-wide integrated strategy for maize research and effectively placed both CIMMYT's and IITA's maize breeding efforts within one research program coordinated by the director of the CIMMYT Global Maize Program, B.M. Prasanna (Figure 6), also based in Nairobi. The strategy consolidated the focus on Africa and was much more explicit in targeting the poor for whom maize was a significant source of income or employment or source of food

Figure 6. B.M. Prasanna, Director of the CIMMYT Global Maize Program, 2010-present.

and nutrition—together estimated to total about 700 M people. The formulation of the UN Sustainable Development Goals during this period re-emphasized the goal of zero hunger, but also widened the scope of research activities to nutrition through biofortification, and to climate change, especially adaptation. The outbreak of new and devastating maize pests and diseases in East Africa in the 2010s demonstrated the continuing role of international research in responding nimbly to new threats.

The intention of MAIZE was to drive integration through unrestricted funding, but this was not realized as donors again reverted to project funding following a trend that had seen unrestricted funding decline from 67% of the CIMMYT maize budget in 1980 to only 8% in 2016. However, project funding did rise sharply until 2016 in response to the food crisis. Several large bilateral projects were focused on Africa, in particular to strengthen maize breeding and seed systems to develop and deploy improved maize varieties with tolerance to drought and low nitrogen conditions, besides other farmer-preferred traits. This breeding base was complemented by development and promotion of soil conservation technologies, rotations and intercrops, again by funding of large projects. Recent evaluations conclude that CIMMYT and IITA enriched each other through close working relations facilitated by MAIZE, and the uptake of maize technologies has accelerated (CAS Secretariat, 2020).

While its main focus was clearly on sub-Saharan Africa, in other regions CIMMYT was able to tap local funding sources to remain engaged. In Asia a new breeding program for hybrid maize was launched at Hyderabad, India that depended partly on private funding by a consortium of small and medium sized seed enterprises (Section 5). After decades of limited collaboration, Mexico also became one of CIMMYT's largest donors, initially providing about $20 M per year through the MasAgro project with about 80% of the grant promoting sustainable intensification, conservation agriculture and productivity growth in Mexico's maize-based agriculture, before terminating in 2020.

A significant development in this period was the emergence of an 'impact culture' by the development community that encouraged CIMMYT and IITA to strengthen partnerships with extension, the private seed sector, and NGOs, to ensure delivery and uptake of its products. However, unlike the early years of the program, the focus on short-term impacts left less time, resources and incentives for CIMMYT scientists to pursue longer-term research with more uncertain payoffs.

3

International Germplasm Development

The priorities that CIMMYT adopted in tropical maize research when it was established were largely governed by its prehistory, its assets, and its geographical location. History has been considered in Section 2. The assets included the skills and experience of staff assigned to the center, and the large collection of landraces that had been made by its predecessor organization from a diversity of environments in Latin America. Another asset was the geographic location of CIMMYT headquarters in the highlands of central Mexico that allowed its scientists access within a 250 km radius to growing environments ranging from sea level to 2600 masl. These spanned the humid lowland tropics, the mid-elevation subtropics and true highlands. In the lowland tropics and subtropical environments, maize grew well in winter and summer environments, while experiencing different disease pressures in each. In the subtropical location the clear demarcation between wet summer and dry winter seasons provided a unique opportunity to grow maize solely under irrigation and with few disease challenges, in order to express yield potential. These assets provided clear comparative advantages for CIMMYT to breed for the majority of tropical and subtropical environments from within Mexico.

Establishing a Global Maize Improvement Program

CIMMYT's two mandated crops, maize and wheat, were a stark contrast in terms of environmental diversity and research challenges (Table 2). Given the objective of rapidly increasing the amount of food, wheat research initially targeted the relatively uniform irrigated lands that accounted for over half of developing world wheat production. Maize environments were largely rainfed, and as a C4 photosynthetic plant maize was more sensitive to variations in available water, temperature, and soil fertility than a C3 crop such as wheat. Furthermore, daylength sensitivity, a major barrier to crop

Table 2. Comparison of characteristics of rice, wheat and maize in the tropics. Source: Fischer *et al.*, 2014.

Species	Rice	Wheat	Tropical maize
Photosynthetic system	C_3	C_3	C_4
Typical tropical/subtropical environment	Irrigated or flooded lowland tropics in summer	Irrigated lowlands in winter or spring, summer at > 1600 masl	Rainfed lowlands, mid-elevation or highlands, sea level to 3,000 masl
Proportion irrigated in tropics, area basis[a]	57%	51%	10-20%
Pollination[b]	Self pollinated	Self pollinated	Cross pollinated
Heterosis	10-15%	10%	15%
Feasibility of hybrids[c]	Moderate*	Low*	High
Day length sensitivity	Little	Little	High
Height reduction	One or few genes	One or few genes	Many genes with small effects

[a] The share of irrigated area has expanded for all three crops. The lower estimate for maize is for the 1980s as given by Dowswell *et al.* (1996).

[b] When maize is cross-pollinated (or "open" pollinated) the resulting seed will segregate or show characteristics of either parent. Maize can be self-pollinated but the resulting seed when grown out will show "inbreeding depression", and yield can fall by as much as 40%. This also occurs when inbred lines are created or when grain of hybrids is used as seed ("recycled"), caused by loss of heterosis and is a form of inbreeding depression.

[c] Hybrids in rice and wheat are often uneconomical because of low seed yields in the female parent of these normally self-pollinating crops.

performance across different latitudes, had already been largely nullified by the RF's Mexican wheat program, while tropical maize remained very daylength sensitive. Rice, the other major cereal crop, showed many of the same characteristics as wheat.

The variation in maize yields observed in initial wide area testing in tropical latitudes suggested that maize was narrowly adapted compared to the broad adaptation of wheat developed over two decades in the predecessor RF Program in Mexico. Many maize landraces had evolved in geographically isolated areas where they were well adapted but were susceptible to diseases and pests when sown in other locations. In fact, Paul Mangelsdorf, a distinguished geneticist at Harvard University and the senior adviser to the MAP maize program had argued against the idea of an international maize center noting that even within Mexico

> "it is simply not true that a good corn variety can be developed in one part of Mexico with the assurance that it will be successful in some other location, even though the micro-climate of the two seem to be largely similar. For one thing, different diseases always appear in different localities".[4]

An early goal of maize germplasm development was to expose breeding units (families, usually seed from a single ear) of each leading tropical maize population to many environments and select the best performing over sites for inter-crossing. Repeating this step should broaden adaptation, or alternatively identify specific lines and varieties that were locally well-adapted. Many of the barriers to broad adaptation in tropical maize were removed through 50 years of international breeding and testing but photoperiod sensitivity still remains an important source of genotype by environment interaction across latitudes.

As already noted, an initial asset of the CIMMYT maize program was the large collection of maize landraces. These were assembled by RF scientists, Paul Mangelsdorf and Edwin Wellhausen and their Mexican colleagues, especially, Efraím Hernández Xolocotzi who would become a distinguished ethno-botanist. As Wellhausen wrote, the "modern corn breeder …..had a responsibility to recognize, describe, and to preserve for future use the varieties and races which his own improved productions tend to replace" (Wellhausen *et al.*, 1952; p. 6). By 1970, 12,000 individual collections had been catalogued and stored under refrigeration and over 300 races of maize had been described, although subsequent analysis suggests only 130 are genetically distinct (CIMMYT, 1971; Wellhausen, 1978; Hallauer and Miranda, 1988). Today 59 of these races are identified as originating in Mexico alone (Willcox, pers. comm., 2020).

The task for CIMMYT breeders was to organize the germplasm collection and develop a systematic approach to improvement and international testing. The International Maize Adaptation Nurseries were conducted 1970-73 to identify key traits and populations, and breeding was organized into two main units. The Advanced Unit comprised the leading 28 "populations" for international testing that were selected to represent the diversity of maize grain types and adaptation to varying maize growing environments (CIMMYT, 1998). Each of these population was assembled from landraces of similar grain colour and adaptation that were intercrossed to form a composite. Most were legacies of the RF breeding programs in Mexico and elsewhere. A cycle of testing of 250 full-sib families at six international sites chosen for each population, and the recombination of the 40% best families within the population, took two years, since testing sites scattered across both hemispheres had planting dates throughout the year. An elite fraction of the families (4%) identified at each site were also intercrossed to create a site-specific experimental variety (EV) for further international testing and possible release by NARSs (Pandey and Gardner, 1992). These Advanced Unit Populations were supported by 34 pre-breeding 'Pools' within a second unit, the Backup Unit. The Pools were arranged systematically by combinations of grain colour (yellow vs. white), texture (dent, flint and quality protein), adaptation (lowland tropical, subtropical, highland and temperate), and maturity (early, intermediate and late). Pools were originally composed of landraces that were blended and improved through a mild half-sib selection system. In

4 Rockefeller Foundation Archives, Officer diaries, RG12, S-Z (FA394), Warren Weaver dairy, Oct 11, 1950.

practice the Pools were not prioritized for breeding specific traits and the flow of genes from the Pools to the matching Populations in the Advanced Unit proved modest at best. Arising from this large breeding effort was a comprehensive menu of germplasm at varying levels of improvement and trait expression available to national breeders and others (CIMMYT, 1998).

This breeding system aimed to allow national research programs to test and release OPVs directly or to undertake further improvement for local adaptation. These OPVs were usually the site-specific EVs that had been tested quite widely after their formation. . They were grouped into trials of 15-30 EV entries, local check varieties selected by cooperating programs were added, and each trial was planted at 10-30 locations. The best 30% of these EVs were retested in elite variety trials, and it was on the basis of these that national collaborators requested seed for further local testing, occasional reselection and possible release (Pandey and Gardner, 1992). Inbred development for hybrids using conventional pedigree breeding was added later to the program and a similar model of staged international testing was adopted as CIMMYT's program began to emphasize hybrids (Section 5). NARSs requested these trials, planted them with their own resources, returned data to CIMMYT or IITA, and in return received global data on performance as well as the right to use the germplasm. By 1980-82, an average of 665 trial sets were being sent annually by the CIMMYT Maize Program to 82 countries (CIMMYT, 1982). However most recipient countries lacked mature breeding programs, and response rates and quality of data returned varied widely (CIMMYT, 1989).

These testing networks accelerated the global germplasm exchange across the tropics and subtropics. NARSs gained access to an array of new tropically-adapted genetic materials and international testing helped to broaden the adaptation of these populations. Many smaller NARSs simply released the best of the varieties identified in CIMMYT trials, rather than using them as a breeding resource. However, overall progress was slowed by growing some trials in environments where they were not suited, the two-year cycle to receive results from both hemispheres, and the reality that many NARSs had limited capacity to conduct precise field trials. These difficulties, combined with genotype x environment interactions among test sites, slowed yield gains to a very modest 0.65% per year, much less than the measured gains of around 1% per year in temperate maize (Pandey and Gardner, 1992; Duvick, 2005). In summary, CIMMYT's international testing program was a well-structured way of exposing CIMMYT's germplasm to national scientists and vice versa, but was an inefficient means of effecting genetic improvement for yield and other traits. Despite this, several of the test sites consistently identified superior EVs or hybrids that have served national programs well.

Experience and feedback from NARSs indicated, however, that the large international testing program was not well targeted to appropriate testing sites, especially in the very diverse and often stressed environments in Africa (CGIAR, 1989; Kling, 2007). Priorities were sharpened in the 1980s through use of the concept of mega-environments — areas of more than 1 M ha of maize with similar plant performance, climate, soils and cropping systems, distributed over several countries and perhaps continents (CIMMYT, 1988). The more formal description of maize mega-environments in the 1990s, using advanced geographical information systems, led to changes in priorities to favour white maize populations and pools for the lowland tropics and subtropics. Analysis of genotype x environment interactions from the international testing data also helped to further define mega-environments and identify stable varieties.

By 1983 the integrated global program was paying off with 238 releases of CGIAR-derived maize varieties in 41 countries (Anderson *et al.*, 1985). Overall, from 1966-70 to 1986-90, direct releases from CIMMYT's international testing program increased from 10% to over 40% of all varietal releases in the tropics and subtropics, while use of its germplasm as parents in nationally-bred varieties increased from 10% to 45% of releases over the same period (Lopez-Pereira and Morris, 1994). In West Africa, IITA materials were initially combined with CIMMYT germplasm and dominated releases (Alene *et al.*, 2009). Thus, by the 1990s most newly released maize varieties in the tropics included CGIAR materials.

Some maize varieties or populations also proved to be quite widely adapted. Tuxpeño germplasm in various forms from the Mexican lowland tropics was used throughout the tropics, sometimes without further adaptive breeding. By 1990 some 255 varieties and hybrids selected from Tuxpeño or with Tuxpeño parentage had been released, as well as many of the very successful TZ varieties developed by IITA that spearheaded the Nigerian maize revolution (Lopez-Pereira and Morris, 1994; Section 6). The population 'La Posta', developed in lowland Mexico in the 1960s from Tuxpeño landraces and inbreds, performed well and was adopted in Central America and West Africa.[5] 'Suwan 1' developed for downy mildew resistance in Thailand in collaboration with CIMMYT proved to be very well-adapted to lowland tropical regions of other countries in Southeast Asia and the Americas, especially Brazil, becoming one the most widely grown varieties in the tropics (Sriwatanapongse *et al.*, 1993).

Assured funding in the early years allowed CIMMYT to pursue a number of exploratory projects with high but uncertain payoffs. One of these addressed the low harvest index (proportion of grain in total biomass) of tropical maize relative to its temperate counterparts. Especially when fertilized, tropical maize grew very tall to over three metres in height and lodged easily (Goldsworthy *et al.*, 1974). Efforts were made to replicate the Green Revolution approach of introducing a single dwarfing gene in tropical maize populations, but this was associated with low yields, very uneven heights in OPVs as the gene segregated, and other undesirable ear characteristics. In the late 1960s, CIMMYT started recurrent selection for shorter plants, essentially accumulating genes with small effects on height. After 15 cycles of full-sib selection over about a decade this procedure had spectacularly reduced plant height by a metre, sharply reduced lodging and increased harvest index and yield potential by 60% at the higher plant densities that were then possible (Figure 7). Concomitantly, barrenness was reduced, and tolerance to drought had increased (Johnson *et al.*, 1986; Fischer *et al.*, 1989). This study, led by Elmer Johnson who was a legacy of the MAP, provided basic directions for tropical maize breeding over the following three decades. Later, direct selection for shelled grain yield versus selecting on whole ear weights and assuming a shelling percentage, saw further gains from improved biomass partitioning to the grain (K. Pixley, pers. comm., 2021).

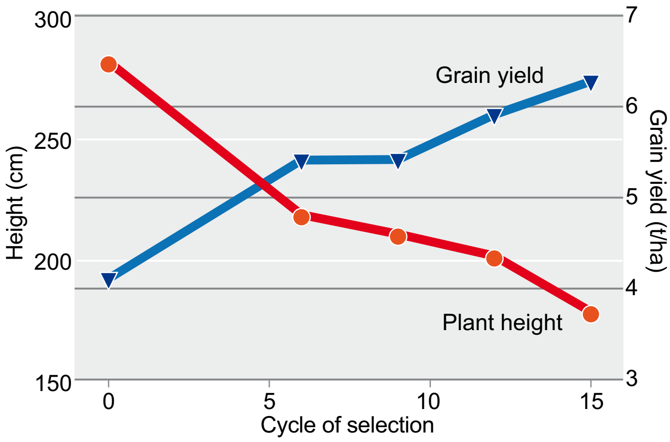

Figure 7. Changes in plant height and grain yield with selection for reduced plant height over 15 cycles in Tuxpeño I (Johnson *et al.*, 1986).

Decentralization for Local Adaptation

There were benefits from a centralized breeding program at CIMMYT but breeders quickly found that while broad adaptation and varietal stability remained key goals it was inefficient to expect one program to fit all regions (Hanson *et al.*, 1975). The Asian regional program, started in 1963, had maintained its own breeding program focused on downy mildew resistance — largely an Asian problem—that produced the successful Suwan varieties. IITA also maintained a strong and semi-independent breeding program for West African environments that initially drew on CIMMYT's shorter stature white grained germplasm. As in Asia, region-specific diseases were key reasons to focus breeding programs in specific regions—resistance to maize streak virus (MSV) and later gray leaf spot (GLS) and maize lethal necrosis (MLN) in sub-Saharan Africa, stalk rot resistance in the Middle East and South Asia, and resistance to corn stunt and tar spot complex (TSC) in Central America. Grain type was occasionally a dominant concern, as in the emphasis on floury maize in the Andean regional program.

[5] More recently inbreds derived from this population have been impressive in drought prone areas of southern Africa

Reports of MSV in Africa date back to 1901 (Monjane *et al.*, 2020), and the disease is now endemic in the lowlands and subtropics of Africa. Losses in susceptible varieties can be severe especially if infections occur in young plants. Beginning in 1975 IITA led the charge on developing streak resistant germplasm by rearing the vector of the virus, the *Cicadulina* leaf hopper, in the presence of MSV infected plants, followed by the transfer of infected leaf hoppers to the field for release in maize nurseries – an innovative step, well described by Yoel Efron, the Director if IITA's maize program at the time (Efron *et al.*, 1989). CIMMYT, recognizing the need for MSV resistance in germplasm suited to lowland Africa, posted a senior maize breeder to IITA in the early 1980s to convert CIMMYT's lowland tropical germplasm to MSV resistance, using techniques developed by IITA, and to assist West Africa national programs with the selection and conduct of trials (mainly OPVs) and training of staff. At the same time CIMMYT's subtropical germplasm suited to southern and eastern Africa was converted to MSV resistance in the CIMMYT station at Harare when it was established in 1985. IITA was awarded the King Baudouin Award in 1985, in recognition of the center's multidisciplinary teamwork in developing MSV resistance.

Grain texture, ease of shelling and flavour are important characteristics with strong local preferences that affect acceptance of new varieties, especially by women farmers and processors. For example, introductions of dented maize widely grown elsewhere in southern Africa into Malawi in the 1950s were rejected by farmers due to losses during hand processing for home consumption. However, locally bred semi-flint hybrids developed with CIMMYT's assistance in the 1980s were quickly accepted (Smale, 1995). Ease of hand shelling, though not often measured or included in selection, is frequently noted by women of the household as a positive characteristic for adoption.

Maize regional staff not only carried out local breeding programs but acted as a conduit to the NARSs of the region to improve the quality of international variety trials and to build local capacity more generally. These networks, based around regional cooperative trials and exchange of germplasm and information, aimed to strengthen local adaptation and improve efficiency of research especially in regions with many small countries that were a feature of maize economies. The basic model was developed through the regional maize program in Central America–started in 1954 and still continuing, albeit as part of a multiple crops and livestock network and with the addition of countries in the Caribbean (Byerlee and Lynam, 2020; Wellhausen, 1990). Similarly, in West Africa a maize network has been continuously supported by IITA and donors, especially USAID, for 50 years (Badu-Apraku *et al.*, 2012). Over time, the role of the IARCs in these networks has declined as selected national programs have taken over breeding for specialist traits on behalf of the region, and as member countries have been empowered through network governance, and/or financing mechanisms. The Asian regional network, for example, has become partly privatized as part of a maize improvement consortium (Section 5). Economic evaluations have shown a high rate of return to investment in these networks and enhanced research efficiency through sharing of research responsibilities and products, including in some cases, improved agronomic practices (Gomez, 1999; Badu-Apraku *et al*., 2012).

These moves to greater decentralization were still not sufficient to address the considerable micro-variation in many rainfed maize environments. The next step was to engage farmers in testing varieties under their own management and in participatory selection of varieties to fit their specific agroclimatic and consumer preferences. This practice was implemented in southern Africa through "mother-baby trials" where varieties are tested by male and female farmers under their management and then rated by farmers at harvest as a basis for varietal release decisions (Bänziger *et al*., 2006).

Mainstreaming Stress Tolerance

In the face of randomly occurring droughts small-scale farmers are naturally risk averse and hesitant to invest in external inputs such as fertilizers. As well, maize is often displaced by higher value crops and pastures to more marginal and risky areas where plant parasites like *Striga hermonthica* thrive and water and nutrient stresses are common (TAC, 2007; Ortiz, 2017). Varieties tolerant to such stresses and with more stable yields are particularly suited to small-scale farmers in marginal areas using low levels of external inputs.

In the 1970s, CIMMYT, especially its wheat program, emphasized breeding for yield potential in favourable environments, believing that high yielding varieties selected in these environments would also perform well in stressed environments. CIMMYT's maize physiologists were among the first in the CGIAR to challenge this approach in the mid-1970s when they began a pilot program of breeding for drought tolerance in Tuxpeño (Fischer *et al*., 1983). Given initial promising results, successive reviews of the CGIAR maize programs (e.g., TAC 1983; 1993; 2007) endorsed an increased focus on stress tolerance under managed stress environments at CIMMYT (Figures 8-10) and at IITA. In the late 1980s the pilot project was extended to five other populations and three of these continue to feature in the ancestry of the current cohort of stress tolerant inbreds (Edmeades *et al*., 2017). At the same time, methods for screening for tolerance to *Striga hermonthica* in the field were being developed by IITA scientists (Berner *et al*., 1996). This involved sowing Striga seeds uniformly along the row at the same time as maize rows were being sown, providing a repeatable screen for tolerance.

Screening for tolerance to low soil nitrogen (N) started in 1987 and soon confirmed a positive relationship between tolerance to drought and tolerance to low nitrogen (Lafitte and Edmeades, 1994; Bänziger *et al*., 1999). These projects showed that under drought stress levels that reduced yields to 2-3 t/ha, a 30-40% increase in yield could be

Figure 8. Leocadio Martinez measuring leaf chlorophyll under drought, Tlaltizapan, Mexico, 1987

Figure 9. Differences in drought and heat tolerance between maize lines in Cd. Obregon, July 1995.

Figure 10. Marianne Bänziger in high N and low N contrasts, Poza Rica, Mexico, 1994

achieved after a decade of selection (Bolaños and Edmeades, 1993). Conventional wisdom suggested such gains would incur a yield cost in well-endowed environments, but this has not been the case. Selected varieties when grown under stress had fewer plants without ears and exhibited better synchrony of male and female flowering (Bolaños and Edmeades, 1996).

Acid soils are a characteristic of otherwise suitable maize growing areas in large parts of South America and Africa. As soil pH falls below 5.5 free aluminum is released into the soil solution and damages plant roots, while soil phosphorus becomes less available. Although acidity can be remedied with addition of lime, this may be unavailable or too expensive. Following earlier work by Brazilian scientists (Magnavaca *et al.*, 1987), Shivaji Pandey of CIMMYT (and future director of its maize program) began developing acid soil tolerance (Figure 11) in broadly adapted maize populations in the Andean Region (Pandey *et al.*, 2007).

Figure 11. Shivaji Pandey harvesting acid soil-tolerant lines in Colombia, 1997. Pandey was the Director of the CIMMYT Maize Program from 1998 to 2004.

During the 1980s and 90s CIMMYT scientists developed sources of resistance to borers and leaf feeding insects, using innovative methods to rear larvae of these insects in the laboratory. Innovation extended to the means of introducing a known number of larvae onto young maize plants in the field using the hand-held "bazooka" that could be operated at scale (Mihm, 1989). Resistant lines were combined into multiple borer resistance populations to be used as genetic resources by breeders (CIMMYT, 1998). The emergence of single-gene transgenic insect resistance in the 90s in temperate maize slowed the momentum of conventional host-plant resistance studies, even though regulatory hurdles were to delay the use of tropical Bt hybrids except in a handful of countries (South Africa, Philippines and Egypt). However, the conventionally-bred source populations for insect resistance have recently provided a good basis for developing resistant varieties and inbreds in sub-Saharan Africa as fall armyworm has swept across the continent (Prasanna *et al.*, 2018).

Figure 12. Marianne Bänziger, Director of the Maize Program, 2004-2009

Research methods and products developed in Mexico proved valuable when CIMMYT shifted the focus of its maize research to Africa where infertile soils and drought are endemic and most smallholder farmers still use very low levels of fertilizer. By 1995 CIMMYT's stress breeding methods were judged sufficiently mature to be used in the mainline pedigree breeding program in eastern and southern Africa (Bänziger *et al*., 2000). This initiative was led by Marianne Bänziger (Figure 12), who later became the first female Director of the Maize Program. These efforts soon had a big impact as seed sufficient to so w 900,000 ha to one drought tolerant OPV variety (ZM521) was produced in five countries of southern and eastern Africa in 2004 (K. Pixley, pers. comm., 2021). The CIMMYT hybrids developed from such selections soon out-yielded commercial hybrids under low N and drought conditions (Bänziger and Diallo, 2004; Bänziger *et al*., 2006) (Figure 13). Screening for drought tolerance became routine in maize breeding in Africa and by 2020 over 230 varieties with drought tolerance plus other key adaptive traits had been released across Africa. Rapid adoption has shown that drought and low N tolerant OPVs and hybrids deliver value to smallholders (Fisher *et al*., 2005; Kosmowski *et al*., 2020; CAS, 2020; Krishna *et al*., 2021), and demonstrate an improved level of stability in performance (Setimela *et al*., 2017)

In West and Central Africa improved tolerance to *Striga* was a major target for the IITA breeding program under the leadership of Menkir and Badu-Apraku and their predecessors (Badu-Apraku, 2010; Menkir *et al.*, 2012).[6] Success with resistance to Striga as well as improved earliness and stress tolerance allowed maize to move north into the short season and climatically variable savannahs of the Sahel where 60% of improved maize area came to be derived from IITA germplasm (Ortiz, 2017).

The orientation of the breeding program swung ever more strongly to stress tolerance breeding from 2006 onwards, supported in Africa by several large BMGF-funded projects. Key developments were the experiment stations established at Chiredze, Zimbabwe in the mid-1990s and Kiboko, Kenya, and Ikenne, Nigeria, around 2010, where managed drought stress research under limited irrigation and low-N screening could be conducted on a large scale. This was accompanied by testing under random rainfall and fertility conditions at up to 60 locations scattered across Eastern and Southern Africa, and a smaller number across West Africa.

Figure 13. Greg Edmeades and Mandefro Nigussie selecting in drought plots, Tlaltizapan, Mexico, 1997.

External reviews of CGIAR maize research have highlighted research on stress tolerance as a major CGIAR success in Africa (CAS Secretariat, 2020). Yet stress tolerance alone cannot ensure adoption. A successful maize variety is made up of many traits including competitive grain yield and appropriate levels of resistance to diseases and pests, lodging, tight husk cover, etc. Gains in yield under any specific stress are clearly less when a number of traits other than yield are being improved simultaneously (Masuka *et al.*, 2017). However, the increased emphasis by both CIMMYT and IITA on combining tolerance to abiotic stresses, Striga and the major diseases resulted in the development of several improved varieties and hybrids that were stable and yielded well in smallholder farms across many of the key production environments in Africa. Forty years of sustained investment in research on abiotic stress tolerance had provided the basis for significant progress (TAC, 2007), and generated a number of genetic sources of stress tolerance and disease resistance that can be used as donors by national maize breeding programs (Cairns *et al.*, 2013; Das et al, 2018). In recent years, the focus has turned to scaling up adoption through strong partnerships with the seed sector (Section 5).

New Diseases and Pests, and New Science

Just as the spread of Southern leaf rust from the Americas to Africa in the 1950s led to an urgent global search for resistant germplasm from the Americas, maize smallholders in the tropics are continually challenged by the appearance of new diseases and pests. As previously noted MSV was endemic in Africa, but in 1990 Gray Leaf Spot (GLS) arrived in South Africa from the Americas (Ward *et al.*, 1999), and 95% of local lines and varieties were susceptible to it. For both of these diseases, progress towards resistant varieties owes much to the presence of CGIAR maize breeding programs at IITA and at

[6] In East Africa CIMMYT gained access to a naturally occurring maize gene giving resistance to the herbicide imidazolinone. Seed carrying this gene was coated with herbicide that killed Striga as it attached to the young plant (Kanampiu et al, 2007). This trait was released as inbreds and licensed to seed companies, and though effective, was not considered to be a commercial success (Bänziger, pers. comm., 2020).

CIMMYT's Harare station where germplasm introduced from Mexico provided new sources of resistance to GLS. In 2011 the first case of maize lethal necrosis (MLN), a combination of two viruses originating in South America, appeared in Kenya, and became especially devastating in Kenya, Ethiopia, Uganda and Tanzania (Prasanna *et al.*, 2020a). CIMMYT, in collaboration with the Kenya Agricultural and Livestock Research Organization (KALRO) established an MLN Screening Facility in 2013 at Naivasha, Kenya (Figure 14). This led to rapid success in breeding for MLN resistance and the release of 19 MLN-tolerant/resistant hybrids within a very short time frame (Prasanna *et al.*, 2020a).

Figure 14. MLN Screening Facility established by CIMMYT at KALRO-Naivasha, Kenya.

Then in 2016, Fall Armyworm (*Spodoptera frugiperda*; FAW), endemic in the tropical Americas, was observed in sub-Saharan Africa for the first time. This *Lepidopteran* insect pest, spread aerially by adult moths, has now been reported in all major maize producing countries in sub-Saharan Africa (Prasanna *et al.* 2018). It then made its appearance in India in mid-2018, and subsequently in over 15 countries across the Asia and Oceania. De Groote *et al.* (2020) estimated that maize losses to FAW in Kenya alone averaged 37% in 2017 and 33% in 2018. Legacy insect-resistant maize germplasm generated by CIMMYT in Mexico in the 1980s was used to identify the first set of three FAW-tolerant maize hybrids for eastern and southern Africa in December 2020[7] (B.M. Prasanna, pers. comm., April 2021). GMOs carrying a variant of the *Bacillus thuringiensis* gene will likely provide more promising solutions when eventually deregulated and released (Section 5). These examples demonstrate the value of an international center with access to global germplasm collections, collaborators in advanced centers of excellence, phenotyping capacity in the tropics, and breeding strength and networks that all contribute to providing a quick and coordinated response to new pest and disease outbreaks (CAS Secretariat, 2020).

Recently the centers have focused on accelerating yield gain at the farm level by making explicit the need for a clear product focus, an increased rate of varietal turnover, doubled haploids to speed the generation of inbred lines, and the use of molecular tools such as genomic selection to shorten breeding cycles (Atlin *et al.*, 2017; Chaikam *et al.*, 2018). The breeding team has demonstrated the benefits of marker-assisted recurrent selection and genomic selection over conventional methods for tropical maize improvement (Beyene *et al.*, 2016). Marker-assisted breeding is now being routinely deployed in CIMMYT's Africa breeding programs for key traits, such as resistance to MSV and MLN. During the last 5 years, CIMMYT's maize breeding programs have used genomic selection/ prediction extensively in biparental as well as multiparental populations with significant success (Crossa *et al.*, 2017; CAS Secretariat 2020).

[7] https://www.cgiar.org/news-events/news/announcing-cimmyt-derived-fall-armyworm-tolerant-elite-maize-hybrids-for-eastern-and-southern-africa/#:~:text=By%20leveraging%20tropical%20insect%2Dresistant,to%20fall%20armyworm%20in%20Africa).

Doubled haploid technology provides a direct route to creating inbred lines. Because successive generations of selfing are no longer needed, it shortens the time to generate genetically homozygous and uniform lines to just a year compared to three years using conventional inbreeding methods and is less subject to error. In collaboration with the University of Hohenheim, CIMMYT has developed "tropicalized" haploid inducer lines to employ the technology in tropical environments (Chaikam *et al.*, 2019). These inducers can be accessed by NARSs under license from CIMMYT and the University of Hohenheim. By paying a royalty to the University private seed companies can also use the technology. Trait-specific markers allow elimination of many double haploid lines before they enter the expensive process of multi-location testing for complex traits and heterotic combinations. For example, the technology has enabled breeders to screen for specific traits such as MSV and MLN resistance in doubled haploid lines that are currently being produced by CIMMYT, IITA, NARSs and seed companies in CIMMYT's maize doubled haploid facilities at Kiboko, Kenya (Figure 15) and Agua Fria, Mexico. Several of the elite inbred lines recently released by CIMMYT are doubled haploids with known heterotic response and tolerance to drought, low N and major diseases. These steps have accelerated the production of hybrids and are expected to increase the rate of genetic gain.

Figure 15. CIMMYT established a state-of-the-art Maize Doubled Haploid Facility at KALRO-Kiboko, Kenya in 2013.

The Seeds of Discovery (SeeD) Project funded by the Government of Mexico under MasAgro undertook to sequence and characterize the maize landraces held in CIMMYT's germplasm bank, as well as inbreds and varieties developed by CIMMYT and IITA, and this database is now publicly available. With these advances in genomics, phenotyping became a key constraint to applying the new science of genomics-assisted breeding. Phenotyping requires capacity for large scale testing for a diversity of traits, using uniform field sites. CIMMYT and IITA, through their private and public partners have access to 11 countries offering specialized field screening facilities (Prasanna *et al.*, 2021). Data from SeeD have been used to identify new sources of disease resistance, and for the first time, scientists have been able to evaluate diversity at the molecular level in the majority of landrace collection.

Progress in data management, an integral and essential element in modern plant breeding that depends on networks, has been less impressive and rather spasmodic. Over the period 1970 through 2010 the CGIAR maize programs lagged large private sector breeding programs in the management of both field and laboratory data (IEA, 2015; CAS Secretariat, 2020), and in the evaluation of historic trends in specific traits. It was not until 2015 that a fully-fledged breeding information management system was made available through the Integrated Breeding Program, developed under the Generation Challenge Program of the CGIAR. It is now also used by a number of national programs that collaborate with CIMMYT and IITA.

CGIAR Maize Breeding: A Story of Continuing Improvement

The history of the CGIAR maize improvement programs at CIMMYT and IITA is one of continuing improvement over the last 50 years, albeit with some delays linked to mis-investment or lack of funding. They built integrated global and regional programs by grouping the best landraces and synthetics and improving them as populations. International testing of these in best-fitting target environments exposed cooperating national programs to an array of new germplasm and allowed the populations to become more broadly adapted, though improvement was slow. Decentralization of breeding efforts to "hotspots" for diseases and pests, or where the populations were best adapted, quickly followed, with coordination being maintained through testing networks and strong program direction. The mega-environment analysis was a key step in prioritizing adaptation traits and grain types, and allowed some populations to make faster progress and others to be retired.

Moving the main thrust of the CIMMYT maize breeding program to Africa was a logical step that improved operational efficiency and attracted considerable donor support. There was a concomitant and overdue increase in focus on hybrids rather than OPVs, leading to major changes in breeding methodologies, but increasing the degree of collaboration with the private seed sector (Section 5). Breeding for stress tolerance quickly became the modus operandi to combat the multiple constraints to African maize production—drought and low fertility, diseases, insects and Striga. Today progress towards stable and improved yields is being accelerated by the use of managed stress levels, doubled haploids and marker-assisted breeding, while global coordination between CIMMYT and IITA has been significantly improved by joint projects and the operation of the MAIZE CRP. Meanwhile, the agile response by CIMMYT and IITA to the new threats of MLN and FAW, have demonstrated again the value of coordinated international maize improvement initiatives backed by adequate funding. Nonetheless, the focus on Africa reduced attention to the continuing and pressing needs of maize producers in marginal environments in other regions.

4

The Elusive Quest for Improved Protein Nutrition[8]

Over its entire history, CIMMYT's major quest to directly influence nutrition has been through the development and dissemination of maize with enhanced levels of the essential amino acids, lysine and tryptophan—so called quality protein maize (QPM). This effort has periodically waxed and waned over 50 years depending on breeding methods, nutritional guidelines, donor whims, and the influence of leading personalities. Two of the main architects of the QPM thrust, CIMMYT scientists, Surinder Vasal and Evangelina Villegas, were awarded the World Food Prize in 2000 (Figure 16). Although their scientific achievements were undoubtedly impressive, the overall impacts of QPM on nutrition have been modest in relation to the large investments that were made over many decades.

Figure 16 Surinder K. Vasal (left) and Evangelina Villegas (Right) were awarded World Food Prize in 2000 for their work on QPM.

The quest for QPM arose from an emerging consensus within the FAO and the WHO in the 1950s that protein malnutrition was the leading nutritional problem in much of the developing world (Carpenter, 1994). Accordingly, the UN formed a Protein Advisory Group that actively promoted targeted interventions with protein-dense foods for children (Brock and Autret, 1952; Carpenter, 1994, Ruxin, 1996). The 1960s became the 'protein decade' as FAO declared that "the greatest [nutritional] problem … results from inadequate protein in the diets of a large proportion of the population" (FAO, 1964, pp. 98).

It was in this context that crop scientists began to actively search for sources of genetic variation in protein quantity and quality of cereals, especially in maize where effective protein utilization was constrained by low levels of lysine. In 1963 scientists at Purdue University discovered the *opaque-2* gene that increased lysine content by 69 percent over normal maize (Mertz *et al.*, 1964). This discovery caused a great deal of excitement at the time that gave rise to visions of a single gene being incorporated into all new maize varieties to boost the nutritional value of protein worldwide. The introductory speaker at a conference of over 400 scientists on QPM at Purdue in 1966 enthused that "within the next five years millions of undernourished people.. would find their diets improved markedly due to the availability of high lysine corn" while US Senator George McGovern at the same conference called it "one of the great [scientific] breakthroughs of the 20th century" (Mertz and Nelson, 1966). Norman Borlaug, who specialized in wheat, also quickly endorsed the potential of QPM (Borlaug, 1966).

From their inceptions, both CIMMYT and CIAT had established programs to transfer the *opaque-2* gene to tropical maize germplasm (Harpstead, 1971). However, their varieties manifested undesirable traits associated with the *opaque-2* gene such as a pale lustreless grain type, soft endosperm, low yields and higher pest and kernel disease losses in production and storage. A CIAT economist (and future World

[8] We are indebted to Robert Tripp for access to unpublished data and memorandums for this section.

Food Prize winner) Per Pinstrup-Andersen (1975) presciently noted that the varieties may be suited to livestock feed but for food there were many issues on grain type, yields, storage and producer and consumer acceptance that would constrain adoption and utilization.

By 1968, a high-level UN report (UN, 1968), *International Action to Avert the Impending Protein Crisis*, provided a set of recommendations on the urgency of boosting protein supplies at the global level, including investing in "high lysine maize". After a meeting with Borlaug, UNDP's Administrator, Paul G. Hoffman, claimed that the modified protein "can make incalculable difference to hundreds of millions of children'" (Hoffman, 1971., p. 330; UN, 1971). UNDP then invested heavily in research on high lysine maize at CIMMYT for the next two decades ($64 M in today's dollars for 1971-84 alone). As in the 1966 Purdue conference, the vision was to transfer the gene to all maize varieties benefiting an estimated 200 M people that depended on maize as their staple (Hanson, 1974; Vasal, 1974). The priority was to increase the 'pile of protein' in the world rather than targeting it to specific population groups. Indeed, a follow up QPM conference at CIMMYT in 1972 discussed the benefits of saving land and reducing food protein prices by substituting QPM for higher priced livestock products and lower-yielding pulses in human diets (Altschul, 1975).

With the additional resources from UNDP, CIMMYT enthusiastically promoted the potential of QPM, lamenting high infant mortality rates and the prevalence of "stunted, often brain-damaged children" and projecting that, "mankind will have available a super grain which contains everything for complete human nutrition" (Wolf, 1975). Accordingly, in 1971 CIMMYT set out to convert the majority of its pools and populations to QPM varieties with hard endosperm and acceptable grain type, explicitly aiming to make grain of QPM indistinguishable from that of normal maize. This involved a long period of patient breeding, accumulating modifier genes for hardness combined with the development of rapid throughput laboratory methods to select lines that contained the *opaque-2* gene (Atlin *et al*., 2011). The program also included efforts to build national program capacity in breeding and laboratory methods used to monitor quality (Sprague, 1975). CIMMYT was optimistic that it could obtain quick results that would see "worldwide introduction in national maize programs by 1976 or 1977" (Wolf, 1975).

Even as the CIMMYT QPM work was accelerating, UN standards for minimum protein requirements were being revised downward. To be sure, there had never been unanimity among nutritionists around the size and extent of the protein gap even as the UN agencies and other donors had scaled up vast programs on protein concentrates for weaning and feeding young children (Ruxin, 1996). However, by 1973 recommended protein levels were being questioned by the FAO/WHO Expert Committee on Nutrition (FAO/WHO, 1973). Studies in India found no evidence of a protein gap nor deficiencies in specific amino acids (Sukhatme, 1970; Ryan, 1977). By 1975, the majority view had moved decisively toward energy intake as the major problem of hunger. John C. Waterlow, one of the most influential nutritionists at the time, firmly stated that "the concept of a worldwide protein gap is no longer tenable" and that the "protein gap is a myth" (Waterlow and Payne, 1975, pp. 117). Mclaren (1975) always a sceptic, coined the term "the great protein fiasco" and estimated that only five percent of malnourished children suffer protein deficiency, largely in areas where root crops were the staple.

UNDP and CIMMYT were aware of these changes in nutritional priorities, but as described by Robert Tripp, a CIMMYT social scientist with training in nutrition, "the train was already rolling down the track" and QPM breeding continued at full speed. The vision of converting all maize to QPM for all consumers and all uses was, however, modified to prioritize pregnant women, infants, and young children, although there was still no apparent effort to target specific regions, countries, or locations, or to link QPM with initiatives in public health messaging.

By the 1980s, UNDP was claiming that "producing varieties that have high yields, and kernels indistinguishable from those of normal, acceptable maize" (UNDP, 1980, p. 15) was a "spectacular achievement" (UNDP, 1984). The main problem "is how farmers can be persuaded to use the new varieties" (UNDP, 1980). In fact, after a decade of intensive breeding QPM adoption remained low because of reduced yields and insect and kernel rot susceptibility. On-farm trials in Ghana in 1981 at 12 sites showed that yields of QPM varieties were only 80% of the best normal check variety (GGDP, 1984). Although small clinical trials had been conducted on the value of QPM in nutrition, only one field trial on the nutritional impacts of introducing QPM varieties to farmers had been mounted by the Institute of Nutrition of Central America and Panama (INCAP) in Guatemala. Ricardo Bressani a nutritionist at INCAP, would claim that the data demonstrating the superiority of QPM over normal maize in human nutrition “are overwhelming” although the results were never published (Bressani, 1992, pp. 322).

In 1985, FAO and WHO again revised the recommended standards for protein, this time, upwards by 25 percent for adults and by 50 percent for young children (Carpenter, 1994). This gave a boost to the potential value of QPM especially for young children. The US National Academy then assembled an Ad Hoc Panel that although recognizing some of the challenges concluded “that QPM should benefit millions of poorly nourished people” (National Research Council, 1988, p. 35).[9] The report noted that while QPM was not vital for everyone, it should provide “a nutritional safety net”. Another conference on QPM in 1990 strongly endorsed QPM noting that the “potential advantages are enormous” and returned to a vision of a world with all maize converted to QPM (Mertz, 1992, pp. 6). At the same conference Borlaug highlighted the potential of QPM in Africa, specifically Ghana where the protein deficiency disease, *kwashiorkor,* had been first identified 60 years earlier (Williams, 1935; Borlaug, 1992).

By this time, there was growing recognition that even with a successful breeding program at least four practical problems seriously impeded successful uptake. The first was that as in all CIMMYT’s programs, the focus had been on OPVs and it would be difficult to maintain the nutritional value imparted by a single recessive gene under farmers’ seed management since varieties inter-pollinated and indeed, farmers often deliberately intermixed improved and local varieties (Bellon *et al*., 2006). Accordingly, the program began to work on QPM hybrids to create genetic uniformity that could be maintained through annual seed purchases (Villegas *et al*., 1992). Second, even with hybrids with equivalent yields to normal maize, a QPM grain type indistinguishable from normal maize negated any potential for markets to express a price premium needed for farmers to adopt QPM varieties (Tripp, 1990; Atlin *et al*., 2011). Farmers also lacked interest in growing QPM for subsistence since little effort was being made to mount nutrition educational programs to accompany its introduction (Tripp, 1990). QPM for animal feed, never a major objective of the CIMMYT program, also became questionable when the price of artificial lysine fell in the 1980s (Winkelmann and Listman, 1993; Krishna *et al*., 2014). Third, constraints on breeding capacity suggested that QPM was not a ‘free lunch’. Resource-strapped NARSs struggled to maintain breeding programs for normal maize and QPM in parallel, especially since substantial laboratory capacity was needed to detect protein quality (Winkelmann and Listman, 1993). Finally, there were questions of whether for a known protein deficiency, funds were better spent on QPM versus other ways of supplying protein, such as through investment in research on pulses and livestock.

On the nutritional front, the news was no better. CIMMYT had appointed a panel of nutrition experts in 1979 to advise the UNDP project that included quite diverse perspectives on the role of protein nutrition. These ranged from the enthusiasm of Bressani for QPM to the caution of Doris Calloway, Professor of Nutrition at the University of California, Berkeley. Calloway was soon to co-author an influential paper from field studies in Egypt, Mexico and Kenya that showed no apparent protein or amino acid deficiencies in children (Beaton *et al*., 1992). The panel also cautioned against field experiments to assess the effects of producing QPM on human nutrition at the village level given the state of methods at the time (Tripp, pers. comm.).[10]

All of these questions came together around 1990 as UNDP scaled back support to QPM after nearly two decades, and the CGIAR itself experienced a serious budget constraint. Donald L. Winkelmann, a CIMMYT economist who had questioned the resources allocated to QPM, took over as CIMMYT’s Director General and Calloway became a CIMMYT Trustee. Accordingly, CIMMYT halted its active QPM breeding program although it continued to make the QPM products it had already developed available to interested countries.

[9] All members of the panel were plant breeders except Bressani who was closely tied to the earlier ‘protein gap school’.

[10] A parallel story unfolded for breeding for high protein quality sorghum in ICRISAT. However, ICRISAT economists produced a series of papers based on consumer and nutrition surveys that indicated little need for protein quality (Ryan *et al*., 1977).

In the 1990s, the main QPM protagonist was Borlaug (Figure 17), who after his retirement from CIMMYT actively advocated for more investment in QPM, chastising participants at an international conference on QPM in 1994 for the slow progress to date (Borlaug, 1994). Borlaug had also joined with former US President Jimmy Carter and Japanese philanthropy to establish the Sasakawa Global 2000 (SG2000) program that invested heavily in technology transfer for maize in Africa. SG2000 strongly promoted QPM in Ghana supported by its President, Jerry Rawlings. A QPM variety 'Obatanpa' (literally 'good nursing mother') developed by S. Twumasi-Afriyie of the Ghanaian NARS and later CIMMYT, was widely adopted not only in Ghana but also in several African countries, notably Uganda (Sallah, 2003; Krivanek *et al.*, 2007). This reflected the success of Ghanaian and CIMMYT breeders in developing a QPM variety with excellent agronomic performance, that fitted local farming systems and was acceptable to consumers. However, there was no evidence that Obatanpa improved human nutrition. Although over half of Ghanaian maize farmers grew an improved variety, mostly Obatanpa, only 7% knowingly used a QPM variety as a weaning food (Tripp, 2001).[11] Of course, Obatanpa may have provided nutritional benefits to those who were not aware of its protein quality, but such potential benefits were not measured.

Figure 17. Norman Borlaug, with Tim Reeves, in a QPM field in China.

QPM received a new life and more importantly new funding when Vasal and Villegas jointly received the World Food Prize in 2000. The award reflected the scientific achievements and its future promise more than actual impacts on the ground. At the time about 0.5 M ha of QPM was grown, with most of that for animal feed (Lauderdale, 2001). Ironically, the award coincided with the release of a sobering assessment of QPM by Janet Lauderdale, a nutritionist working with CIMMYT's Socioeconomics Program. She concluded that the "extent of protein deficiency among humans is unclear" and cautioned that investment in QPM "runs the risk of once again being stymied and after great expenditure…failing to have any substantial impact on the nutritional problems of the developing world" (Lauderdale, 2000). Yet CIMMYT returned to some of the hype of the 1970s when it noted that "We believe we're witnessing a revolution unfolding" (CIMMYT, 2001a, pp. 7), followed by a glossy brochure in 2001, *The Quality Protein Maize Revolution* (CIMMYT, 2001b).

This resurgence of QPM was logically anchored in African countries where maize was the major staple and improving nutrition of infants and young children became the explicit target for QPM. In the new impact culture of donors, emphasis was finally placed on studies to assess nutritional impacts under field conditions (Krivanek *et al.*, 2007). This initiative was supported by QPM pioneer, Vasal, who argued that "there is a pressing need for a series of rigorous studies to determine the benefits of consumption of QPM to human nutrition" (Vasal, 2000, p. 450). In fact, since the 1990s, there had been several efforts to evaluate QPM's nutritional impacts. A meta-review by Gunaratna *et al.* (2010) found nine trials that complied with minimum methodological standards. Two of these trials evaluated the effectiveness of providing QPM seed to randomly selected communities or households in Ethiopia and found an impressive 15-26 percent increase in the growth of children (Akalu *et al.*, 2010). While these efforts were a welcome start, CIMMYT still lacked good data on the prevalence of protein malnutrition in maize-consuming populations that were needed to sharpen the targeting of QPM investments. This was demonstrated by another recent field trial with QPM varieties in Ethiopia that showed no significant effects on nutrition (Donato *et al.*, 2020). In any event, by 2019, only 1 percent of Ethiopian maize area in

[11] For a period, Ghana established a protocol of only releasing QPM varieties in anticipation of making all maize area QPM.

Ethiopia was sown to QPM varieties despite substantial investments in breeding and promotion of these varieties over two decades (Kosmowski *et al.*, 2020).

By 2020, QPM adoption had not exceeded 1 M ha globally, and over the past decade CIMMYT has largely halted investment in QPM, arguing that there are sufficient QPM hybrids and OPVs available to meet specific requests and that artificial lysine is widely available as a supplement for animal feed. Yet nutritional standards continue to evolve and some nutritionists now argue that in many situations, inadequate protein quantity and quality is a significant cause of child stunting (Semba, 2016; Moughan, 2021). With better targeting and complementary investments in nutritional education and evaluation, QPM may yet have a role.

More generally, the CGIAR drew on the QPM experience as it invested heavily from the 1990s in biofortification of a number of crops with a strong focus on field evaluation studies that include complementary investments in nutritional education—key elements that were lacking until recently in the QPM venture. CIMMYT has been part of the CGIAR Harvest Plus program for biofortification with a focus on maize hybrids with a strong orange grain color for pro-vitamin A for sub-Saharan Africa and high zinc varieties being deployed in Latin America (Gannon *et al.*, 2014; CIAT & CIMMYT, 2019; Prasanna *et al.*, 2020b). High zinc varieties are not visually distinguished from normal grain types. Similarly, CIMMYT has promoted blue high-antioxidant maize that is grown by poor indigenous farmers in Mexico but commands a premium price in urban markets (Blare *et al.*, 2020). Building on the QPM experience, the keys to success of biofortification will be an easily identifiable indicator of quality (e.g., a different grain color as in Pro-Vitamin A maize), and a major initiative in messaging the health benefits of the biofortified grain over its conventional counterpart. These will be needed to overcome the expected but usually small yield penalty incurred when traits additional to yield *per se* are included in selection. The jury is out on how widely these will be adopted in future as healthy food options.

5

Working with the Private Sector

The discovery of heterosis and its resultant yield benefits in the early 1900s, followed by the development of practical methods to produce affordable seed of hybrids, led to the takeoff of hybrid maize and the private seed industry in the US in the early 1930s. Heterosis resulted in hybrids that yielded 15-20% more than OPVs. However, unlike OPVs whose seed can be saved and resown without significant yield loss—at least for a few years—seed saved from hybrids and resown the next season yielded 20-40% less than that of the parent hybrid. This provides a large incentive for farmers to buy fresh hybrid seed every season and for private companies to supply it. Moreover, breeders could maintain the parentage of hybrids as a trade secret, providing protection to private companies to invest in R&D when developing their own hybrids. Maize thus became the first major crop in which the private sector dominated all aspects of breeding, seed production and promotion in high-income countries.

The growth of the private sector has had important implications for defining the role of the public sector. Some argue that continued production of inbreds and hybrids by the public sector lowers the barriers to entry of small and medium firms and fosters a competitive seed industry. Historian Deborah Fitzgerald has chronicled these tensions in the early years of the US hybrid seed industry and the push by established private seed companies with their own breeding programs to discontinue public breeding programs (Fitzgerald, 1990). In the late 20th century, the development of the new science of biotechnology and the application of patents to biological interventions led to a surge in mergers and acquisitions among seed companies to access intellectual property that generated further debate about the role of multinational companies (MNCs) in controlling the seed sector (Kloppenburg, 2005).

Given this background, the roles of the public and private sectors in maize breeding for resource-poor farmers have generated ongoing tension in the history of CGIAR maize research, along with the search for effective public-private partnerships. That debate starts with the relative emphasis on OPVs versus hybrids and the role of the public sector in their development. With the advent of modern molecular science, the discussion centers on affordable and equitable access to proprietary tools and technologies that could potentially benefit the poor.

The Era of OPVs

The relative emphasis on hybrids versus OPVs was continually debated in Mexico long before CIMMYT was created. Although it is commonly stated that the RF's MAP aimed to transfer the US success with hybrid technology, Matchett (2002) shows that, in fact, the MAP favoured a range of products for different types of farmers. By contrast, an existing Mexican government program that continued parallel to MAP was narrowly focused on hybrids. The MAP initially released OPVs as well as synthetics that used limited inbreeding but allowed farmers to save seed without major yield losses. Over time, however, the MAP turned more to conventional hybrids when the Mexican government created a parastatal seed monopoly, Comisión Nacional de Maíz, that almost exclusively promoted hybrids (Matchett, 2002). Mexican regulations at the time also prevented use of public inbreds and hybrids by private seed companies. Given the perceived inefficiency of the Comisión and the lack of an extension program for rainfed areas, hybrid seed only ever reached 8-15% of the maize area of Mexico.

At the time that CIMMYT was founded, hybrids were widely believed to be unsuited to the situation of small-scale farmers producing maize in risky rainfed areas. The need for farmers to buy relatively expensive seed annually was the most important reason, especially in areas with low yields due to marginal growing conditions or the lack of complementary inputs such as fertilizer (Timothy *et al.*, 1988). Hybrids were also perceived (incorrectly as it turns out), to be narrowly adapted and unstable under stress. Finally, the resources and skills needed to produce hybrid seed successfully were considered major barriers to developing an effective hybrid seed industry (Heisey *et al.*, 1998).

Meanwhile, experiences in a few countries were revealing the value of OPVs to small farmers. In particular, the RF maize scientist, Ernie Sprague, posted to India in 1958 initially worked exclusively on hybrids (Sprague *et al.*, 1960). However, by 1964 Sprague was actively promoting OPVs (Sprague, 1964). It seems that his frustration with the slow pace of hybrid seed production in India together with his visits to Thailand to establish the Asian Regional Corn Program were important in this transition. Thailand had become a leading maize producer and exporter in the 1950s based on the successful and widespread adoption of an improved OPV imported from Guatemala (Byerlee, 2020).

Figure 18. Ernie Sprague (extreme left), Director of CIMMYT Maize Program, 1970-84, talking to visitors at the Poza Rica maize experimental fields. Ken Fischer (second from left) and R.L. Paliwal (third from left, wearing white hat) can also be seen in the photo.

When Sprague (Figure 18) moved to Mexico in 1970 to head CIMMYT's maize program, he vigorously championed the role of OPVs over hybrids, asserting that "none of the developing countries with small farm holdings should be working with hybrid development...fortunately, a number of countries with more advanced programs abandoned their work on hybrids" (Sprague (1974, p. 27). Sprague was pessimistic about the chances of developing hybrid seed systems to serve small farmers. Although his views prevailed in CIMMYT i n the 1970s, they were questioned by others. The distinguished maize geneticist, George F. Sprague of USDA and Iowa State University (no relation to E. Sprague), disagreed with this, citing Kenya as an example of successful smallholder adoption of hybrid seed (CIMMYT, 1974b). Private seed companies, not surprisingly, supported this assessment arguing that C IMMYT had a role to facilitate the development of the hybrid seed industry (Sehgal, 1977).

Throughout the 1970s, both CIMMYT and to a lesser degree IITA focused almost exclusively on working with the public sector to develop and promote OPVs. Given the close relations of NARSs with the Centers, especially through training of their scientists, most NARSs that did not already have a well-developed hybrid program followed this OPV policy. The share of OPVs among all public sector varieties released in the tropics and subtropics increased steadily, peaking at two thirds in the 1980s (Lopez-Pereira and Morris, 1994). However, by 1986, two decades after CIMMYT's founding, only 11% of tropical and subtropical maize area (excluding the large commercial farmers in Brazil) was sown to improved OPVs, compared to 16% to hybrids, mostly developed independently of CIMMYT (CIMMYT, 1987).

Ironically given one of the original motivations for the OPV policy, the slow spread of OPVs was largely due to the difficulty of developing a sustainable seed system. The private sector had little incentive to produce OPV seed since farmers were unlikely to buy fresh seed every season. A few companies did sell OPVs as a sideline to their main business of hybrid seed, as in Zimbabwe, or as an entry point for hybrid sales, as in Thailand. Further, unlike rice and wheat, seed of maize OPVs did not maintain its performance when transferred from farmer to farmer as varieties were gradually mixed due to the open-pollination characteristic of maize (Kim *et al.*, 1985). A handful of countries did produce and disseminate respectable quantities of OPV seed through the public sector, notably Thailand, but much of the OPV seed production was through *ad hoc* arrangements such as development projects, notably in Nigeria (see Section 6), and was of variable quality. Indeed, in addressing the slow adoption of QPM OPVs, Borlaug summed up the problem as "incompetent, bureaucratic and politicized [parastatal] seed organizations" that are the "bane of agricultural development" (Borlaug, 1994, pp. 400).

Partnerships With the Local Seed Sector for Hybrids

By the late 1970s, pressure was mounting in the CGIAR to begin developing hybrids. IITA had already broken rank, hired a hybrid maize breeder and started forming heterotic groups using two Nigerian composites. By 1979 it was extracting inbred lines and by 1982 it was testing hybrids (Ortiz, 2017; J. Kling, pers. comm., 2021). Useful heterosis was discovered between the population (TZB), formed by IITA from two Nigerian composites, and germplasm derived from CIMMYT's shortened version of Tuxpeño, named by IITA as TZPB. This led to the formation in 1984 of the first commercial seed company in Nigeria, though hybrid demand plateaued soon after, in part because of difficulties in attracting private seed companies. In Mexico, Wellhausen, now retired and looking back on his long career, concluded that:

> During my 32 years of promotion of maize production in the tropics, I have been unable to interest either the public sector or the private sector in the production of large volumes of seed of OPVs. Where it [OPV seed] is produced, it is produced by individual farmers or as a stopgap by commercial seed producers, until some kind of hybrid can be developed (Wellhausen, 1978, p. 81).

With the departure of Sprague in 1984, CIMMYT's breeders quickly began to develop hybrid breeding systems after a hiatus of 20 years. Re-enforced by CIMMYT's 1989 strategic plan, an estimated 35% of its breeding resources were devoted to hybrids by 1993 (TAC, 1993). Under the leadership of S. K. Vasal, CIMMYT's international testing program gradually converted to testing inbreds and hybrids, while the testing of OPVs, now being generated as synthetics formed by intercrossing inbreds, gradually declined in importance.

CIMMYT economists were among the most vocal champions of the move to hybrids, producing studies that demonstrated the willingness of smallholders to adopt hybrids and showing the superior performance of hybrids even under low input and risky conditions (Lopez-Pereira and Filippello, 1995; Heisey *et al.*, 1998). In particular, much of the extensive hybrid maize area in Southern Africa was sown by smallholders without fertilizer and subject to frequent drought stress. These experiences reflected a strong national program (Zimbabwe), and the development of an efficient private seed industry to produce affordable seed, supported by an effective public extension program to promote the initial adoption of hybrids. Later, CIMMYT breeders concluded that the best hybrids in southern Africa outyielded the best OPVs by around 18% across a wide range of yield levels (Pixley and Bänziger, 2001). Heterosis was becoming accepted as a form of stress tolerance as well as higher yield. Their findings also showed that while hybrids delivered greatest value to farmers when yield is consistently over 2 t/ha, they were also profitable when yields were as low as 0.5 t/ha provided an efficient seed system delivered low-cost seed (Pixley and Bänziger, 2001). The yield gain of improved hybrids over local varieties was assessed at over 50% and even more under drought conditions (Kathage *et al.*, 2012).

The switch from OPVs to hybrids was also driven by national demands. Thailand, the star in the adoption of OPVs, had by the 1990s become a leader in hybrid maize (Ekasingh *et al.*, 1999). Several MNCs had established research stations in Thailand, and CP Seeds, a home-grown company, became a major player. By the late 1990s, only hybrids were being released, 86% of Thai maize area was planted to hybrid seed, and yields increased from 2.5 t/ha in 1990 to 4.5 t/ha today.

Clear patterns of heterotic response took time to identify and consolidate, since CIMMYT's broad-based populations had not been assembled on any well-defined heterotic pattern. Early studies at CIMMYT focused on identifying heterotic responses among populations, but these rarely showed more than a

15% advantage over the yield of the best parent (Vasal *et al.*, 1992). Tropical heterotic groupings are still not as strongly defined as those in temperate maize, but two main groups are the Tuxpeño race, and a loosely defined non-Tuxpeño group that includes the Suwan OPV developed in Thailand as well as Caribbean flints (Section 3).

The first tranche of around 100 inbred lines from the leading CIMMYT populations was released in 1988 for breeders to use freely. These lines were not exceptional, but by recycling and testing inbreds derived from their progenies, later generations showed continuous improvement. By 1998 CIMMYT's program had released 366 inbreds as CIMMYT Maize Lines (CMLs) for use by public and private institutions in 80 countries and distributed 500 maize trials per year. Warburton *et al.* (2008) concluded that CIMMYT inbreds were a genetically "fixed" resource that represented the majority of the variation present in the entire tropical maize gene pool. By 1998, 58 percent of hybrids released by the private sector in the tropics and subtropics contained CIMMYT germplasm (Morris, 2002). By 2020, CIMMYT had made available more than 600 well-characterized inbreds (https://data.CIMMYT.org).

The shift to hybrids required the CGIAR centers to engage with the private sector in hybrid development, seed production and promotion. Pioneer Hi-Bred, then the world's largest seed company, began to invest in the tropics and subtropics from the 1960s and other US-based seed companies entered the market in the 1970s and 1980s. By 1985 MNCs worked at 29 stations in seven tropical countries (Pray and Echeverria, 1988). Other companies, including Kenya Seed Co in Kenya, SeedCo in Zimbabwe, Pannar in South Africa, Agroceres in Brazil, and CP Seeds in Thailand, were also major players in their respective regions. The era of trade liberalization and privatization from the 1990s further strengthened private investment in the seed industry, with MNCs buying several national and regional seed companies (Rusike, 1995). All these companies were involved in germplasm transfers between countries and sometimes regions, and most used CGIAR germplasm to some extent. By 2000, "the primary locus of maize breeding research [in Asia] had shifted from the public to the private sector" (Gerpacio, 2003, p. 328).

CGIAR scientists had limited experience in dealing with the private sector, resulting in a period of learning-by-doing while developing elite inbreds and hybrids, and sustainable partnerships. In 1989 CIMMYT established a policy of providing germplasm to private companies although it still treated public NARSs as its main client (CIMMYT, 1989). By 2003 CIMMYT clearly saw its role as serving markets that were not attractive to MNCs by offering inbreds and hybrids to small and medium sized (SME) seed enterprises to reduce their R&D costs (CIMMYT, 2004). This pattern followed the decades of continuing public development of inbreds for use by the private sector in the USA long after private companies had developed strong R&D programs of their own (Duvick, 1998; Kloppenburg, 2005).

Doubts were expressed regarding the pace of tropical hybrid development and its implications for the seed industry (TAC, 1993). Indeed, availability of competitive and well-tested hybrid combinations generally exceeded the capacities of countries to secure their release and of the seed sector to establish the marketing and supply infrastructure for seed delivery to farmers. As well, the introduction of new hybrids is costly especially for SMEs and this resulted in a very low rate of turnover of new hybrids in Africa (Abate *et al.*, 2017). Genetic gains in yields of hybrids are only of value if they reach farmers' fields through periodic hybrid turnover (Atlin *et al.*, 2017).

Accordingly, CIMMYT and IITA moved downstream in supporting seed production by providing limited exclusivity licenses for CIMMYT hybrids to SMEs restricted by geography and time, as well as technical support and training to SMEs for inbred line maintenance and hybrid production (e.g., MacRobert *et al.*, 2009). This was in line with the general surge in financing for private seed companies in Africa through NGOs such as the Alliance for a Green Revolution in Africa (AGRA, 2017) and donors such as the African Seed Investment Fund. With this support, the number of seed companies in Eastern and Southern Africa increased fourfold during 1997-2007 largely through the entry of SMEs, and this trend appears to have accelerated in recent years (Langiyintuo *et al.*, 2010; Erenstein and Kassie, 2018). It is noteworthy that less than half of these companies had developed some breeding capacity of their own (Kassie *et al.*, 2013).

Since 2000, a number of donor projects have supported a dramatic rise in production of seed of varietal releases based on CIMMYT and IITA maize germplasm and distributed largely through local seed companies. Certified seed production of CIMMYT/IITA-related stress-tolerant maize varieties increased from about 10,000 ton/year in 2010 to 111,000 tons in 2019, 75% as hybrids (Prasanna *et al.*, 2021; Krishna *et al.*, 2021). The Program for Africa's Seed Systems (PASS), part of AGRA, has actively supported the development of the seed sector as well as agro-dealers in 15 countries in sub-Saharan Africa, and PASS-assisted entities were responsible for 50,000 tons of certified maize seed in 2016 (AGRA, 2017). In addition, PASS trained over 100 PhD-level breeders, supported national breeding programs, SME seed companies, helped reform seed release policies and built networks of agro-dealers – all of which further enabled the development and adoption of maize hybrids and varieties. The introduction of input subsidies in many African countries after the 2008-12 world food crisis further stimulated uptake of hybrid maize seed and fertilizer (Jayne and Rashid, 2013).

The International Maize Improvement Consortium (IMIC) model (Figure 19) was a further step toward enhancing R&D capacity of SMEs to develop their own hybrids based on CIMMYT inbreds. Following a model developed at ICRISAT for hybrid sorghum and millet, CIMMYT initiated an IMIC in Asia in 2010 starting with a group of mostly SME seed companies (Ajanahalli *et al.*, 2014). Private sector members of each IMIC have access to early- and advanced generation inbred lines and trait donors from CIMMYT, besides a range of services to support hybrid development, in exchange for a modest annual membership fee to support the cost of CIMMYT's management of the IMIC. This model in Asia (25 companies) was subsequently copied in Mexico (69 companies) and in eastern and southern Africa (17 companies) (B.M. Prasanna, pers. comm., 2020). IMICs aim to help develop SMEs, to ensure that CIMMYT germplasm reaches new groups of farmers, and to enhance modestly the financial sustainability of CIMMYT's regional breeding activities.

Figure 19. IMIC partners during field days in India, Kenya and Mexico.

The growth of the number of nationally owned seed companies in Mexico from 20 in 1995 to 114 in 2015 suggests that the IMIC model is achieving its objective of developing a more competitive and diverse industry. In 1992 Mexico had one of the world's most concentrated seed industries with four MNCs controlling 83% of the market (Lopez-Pereira and Garcia, 1997). Most of the new entrants since the 1990s are SMEs and many are members of the IMIC (part of MasAgro) so that the share of national companies in maize seed sales has risen from 5% in 2009 to 31% in 2016. In addition, most of these companies serve farmers in rainfed areas where hybrid seed adoption has now reached 40% of the area, reversing the decades of failure to reach rainfed farmers in Mexico (Donnet *et al.*, 2020).

Hybrid seed remains a risky investment in marginal environments given that the added cost of purchased seed may not pay in some years. In addition, when seed supply chains are disrupted by political and economic instability, or farmers face acute cash shortage after a serious drought, they often revert to sowing seed harvested from hybrids (McCann *et al.*, 2006; de Groote, pers. comm. 2013). Pixley and Bänziger (2001) have shown that "recycling" hybrid seed saved from the previous harvest was the least profitable option since yields averaged 32% less than freshly purchased hybrid seed across all yield levels. Providing OPVs in marginal areas is still an important option for farmers, and CIMMYT has actively championed the development of community-based seed systems (Setimela and Kosina, 2006). Established seed companies, such as SeedCo, have also increased their supply of OPV seed in southern Africa (Kassie *et al.*, 2013).

In retrospect, the early CIMMYT dogma with respect to an exclusive focus on OPVs was well meaning but patronizing. It underestimated smallholder farmers' willingness to pay for higher yielding hybrid seed and countries' capacity to develop private seed industries. CIMMYT also overestimated the capacity of the public sector to deliver seed of OPVs. Our assessment is that CIMMYT's single-minded dedication to OPVs in the 1970s delayed the development of hybrids by the public sector and SMEs by about a decade. Still, population improvement in the OPV program contributed to the success of the hybrid program, since there is good evidence that the probability of extracting superior inbreds from a population increases with the average performance of that population (Hallauer and Miranda, 1981; Edmeades *et al.*, 1997). At the same time, with the development of hybrids and associated partnerships with the private sector, CIMMYT has had to compromise on its original policy of unrestricted access to all of its products in the interest of engaging the private sector to quickly increase the number of farmers it reaches.

Partnerships with the Multinational Sector to Access New Science

In partnerships with the private sector for commercialization of hybrid maize, the Centers were initially at an advantage given their access to and understanding of genetic resources, long experience in tropical maize R&D, and extensive networks of developing-country scientists. However, by 1990 private R&D on maize in the USA alone had grown from $8 M in 1955 to $110 M in 1990 dollars. This dwarfed US public sector R&D on maize of $35 M in 1990 and the $15 M annual investment in maize research in the CGIAR (Byerlee and Lopez-Pereira, 1994; Gryseels and Anderson, 1991). Pioneer Hi-Bred alone employed 250 scientists across 44 stations and invested $57 M in maize R&D in 1992 (Pioneer Hi-Bred Int, 1992).

During the next two decades, investment by the private sector in maize R&D skyrocketed, reaching an estimated $1.6 B in 2010 (Heisey and Fuglie, 2011). This was driven by breakthroughs in biotechnology and by stronger intellectual property rights on biological inventions, especially after court rulings allowed patenting of such inventions in the US. The need to gain access to patented technologies also stimulated a surge of mergers and acquisitions among seed, chemical and biotechnology companies. Today the top four companies are multibillion dollar operations accounting for an estimated 82 percent of maize seed sales in the USA, up from 52% in 1988 (OECD, 2018). By 2010, Monsanto (now part of Bayer) owned an estimated 85% of patents on GMO traits weighted by area planted (Heisey and Fuglie, 2011). The growing concentration of intellectual property ownership in the "Gene Giants" caused an uproar from non-governmental organizations (Fowler, 1994), academics (Kloppenburg, 2005) and international organizations (UNDP, 2001). Many argued that genetic resources were the result of millennia of selection and conservation by small-scale farmers who were their real owners (Fowler, 1994).

The CGIAR was concerned about its freedom to operate in a world increasingly dominated by patented tools and technologies, some of which were very relevant to solving intractable problems of poor farmers. It did not have the time, funds or laboratories to 'invent around' the technologies and had little choice but to partner with private companies to access the most relevant technologies for humanitarian purposes. As concluded by Michael Morris of CIMMYT, “the continuing relevance of the IARCs will depend critically on their ability to forge effective partnerships with the private firms that now control many critical technologies” (Morris and Ekasingh, 2002, pp. 223), a view that was echoed by stakeholder consultations for CIMMYTs 2003 strategic plan. Maize was the crop most affected by these developments and in 1999 CIMMYT arranged a small meeting with private companies and international agencies to agree on some common principles for such partnerships.[12] Beyond IPRs, the CGIAR had to wrestle with the merits of becoming involved in the acrimonious debate about the value and possible risks of genetically modified organisms (GMOs), and if so, how to develop an appropriate regulatory environment to make them safely available. The position CIMMYT has taken on the use of GMOs is one that sees a role for the technology, but respects the right of each country to make its own decisions about the technology provided appropriate biosafety regulations and stewardship procedures are in place and observed.[13] This position was extended in 2017 to cover the less controversial gene editing technologies in crops,[14] though the regulation of the products of gene editing is still unclear in most countries. Both GMOs and gene editing are being employed by CIMMYT in collaborations with technology providers to improve traits controlled by a few genes (See Table 3). The ethical reasons for CGIAR involvement with these technologies are well described by Pixley *et al.* (2019) who outline the importance of CGIAR monitoring and accessing new technologies on behalf of small-scale farmers in low and medium income countries who otherwise may be ignored.

Ironically, one of the first private-public partnerships (PPPs) was a serious attempt in the 1990s to develop apomictic tropical maize through a partnership with the then French Office for Overseas Scientific and Technological Research, ORSTOM, and three private multinational seed companies. Its ultimate goal was to introduce asexual reproduction (apomixis) that would allow the heritable transfer of heterosis thereby retaining the yield advantage of hybrids from one generation to the next even when farmers saved their seed (TAC, 1998). The project ran for around a decade before technical and funding issues led to its closure. However, it was an important learning experience for CIMMYT on balancing public interests in maintaining free access to any resulting technologies versus private interests in developing proprietary technologies for profit (Hodges, 2012).

From the 2000s, nearly all projects that involved partnerships with the private sector to access technology were funded by the BMGF with a special focus on Africa (Table 3).[15] The Water Efficient Maize for Africa (WEMA) project was executed by the African Agricultural Technology Foundation (AATF), with technical input from Monsanto, CIMMYT and NARSs in five countries. It was considered a bold step by Maize Director Bänziger to create this partnership between CIMMYT and Monsanto, but after a hesitant start the benefits to CIMMYT scientists and its NARSs clients in the five countries involved confirmed the wisdom of this collaboration. The project has invested over $100 M since 2008 and provided royalty-free access to five countries in sub-Saharan Africa to Monsanto’s commercial drought-tolerant transgene, MON87460, subsequently stacked with the insect resistance transgene, MON810 (Schnurr, 2019). The insect resistance work built on an earlier CIMMYT partnership with the Novartis Foundation in the late 1990s, but CIMMYT experienced significant problems in gaining access to intellectual property rights for commercial use of the technology (Mugo *et al.*, 2005; Mabeya and Ezezika, 2012). After switching to the Monsanto gene, the project has been subject to ongoing criticism (e.g., Schnurr, 2019).

12 https:/repository.cimmyt.org/handle/10883/3827

13 https:/www.cimmyt.org/wp-content/uploads/2015/05/Position-Statement-on-Genetically-Modified-Crop-Varieties_FV_Approved-by-BoT_Nov2011.pdf

14 https:/www.cimmyt·org/content/uploads/2019/04/CIMMYT·Position-Statement-on-Novel-Genome-Editing-Technologies-2017-12-17.pdf

15 Growing protection of intellectual property has also affected partnerships with advanced public sector institutes· An important development was the agreement with the University of Hohenheim to allow CIMMYT to use its technology to develop tropically adapted haploid inducer lines (Prigge *et al.*, 2011) (Section 3).

Table 3. Tropical maize germplasm projects operating since 2007 with significant public-private partnerships.
Source: CIMMYT Annual Reports. MAIZE Annual Reports; B.M. Prasanna (pers. comm., 2021); K.V. Pixley (pers. comm., 2021).

Acronym & technology suppliers	**Name** (names can alter as project evolves)	Donors	Main products, methods	Years
Downstream seed delivery focus				
DTMA CIMMYT & IITA	Drought Tolerant Maize for Africa 13 countries in SSA	BMGF; Buffet; USAID; DFiD	Drought tolerant inbreds, hybrids and OPVs, conventional breeding, MAB	2007-2015
STMA CIMMYT, IITA	Stress Tolerant Maize for Africa 11 countries in SSA	BMGF; USAID	Drought tolerant inbreds, hybrids and OPVs, conventional breeding, MAB	2016-2020
AGG-Maize CIMMYT, IITA	Accelerating Genetic Gains for Maize and Wheat Improvement 13 countries in SSA	BMGF, USAID, FFAR	Drought tolerant inbreds, hybrids and OPVs; conventional breeding, MAS, Genomic selection	2020-2024
IMIC CIMMYT, SME seed companies in South Asia; SSA; Latin America; NARSs	International Maize Improvement Consortium	Mexico GIZ SME seed companies	Improved inbreds, trait donors, and early generation inbreds; shared services (on cost-recovery basis)	Asia: 2010 Africa: 2018 Mexico: 2011 (MasAgro); IMIC-LatAm (2021)
CRMA Asian NARS and SMEs	Climate Resilient Maize for Asia 4 Asian countries	GIZ	Drought tolerant inbreds and hybrids; markers for drought tolerance	2016- 2019
MASAGRO Mexican SMEs	Sustainable Modernization of Traditional Agriculture Mexico	Gov of Mexico	Seed production of hybrids and varieties; conservation agriculture practices	2010-2020
Upstream access to technology focus				
WEMA AATF, Monsanto, CIMMYT, NARSs	Water Efficient Maize for Africa 5 countries in ESA	BMGF; Howard G. Buffet Foundation; USAID	Drought tolerant inbreds and hybrids (conventional & MAB); transgenic drought tolerance and insect resistance; regulatory compliance	2008 – 2018
TELA AATF, Bayer, CIMMYT, NARSs	7 countries in ESA	BMGF	Transgenic drought tolerance and insect resistance; regulatory compliance	2018-present
IMAS CIMMYT, Corteva	Improved Maize for African Soils 2 countries in ESA	BMGF; USAID	Low N tolerant inbreds and hybrids; *Ms44* male sterility gene for NUE	2010-2017
SPTA CIMMYT, Corteva, KALRO, ARC	Seed Production Technology for Africa. Kenya, South Africa	BMGF	Corteva's proprietary seed production technology system; Non-transgenic method of hybrid production without detasseling	2018 - present
HTMA CIMMYT; Corteva; Purdue Univ; NARSs; 20 SME seed companies	Heat Stress Tolerant Maize for Asia India; Bangladesh; Nepal; Pakistan	USAID	Heat tolerant inbreds and hybrids; MAB	2013 - present
MLN Gene Editing CIMMYT; Corteva; KALRO	MLN Gene Editing Project	BMGF	Using the CRISPR-Cas9 system to generate sources of resistance to MLN	2018 - present

To date none of these transgenic options has been released outside of South Africa because of delays in implementing national biosafety regulations. The jury is still out on the value added by Monsanto's drought transgene over conventionally bred drought tolerant varieties. Insect resistance transgenes have been very successful in other crops for small farmers, notably Bt cotton, (Kathage and Qaim, 2012). The effort by CIMMYT in East Africa on transgenic insect resistant maize, spanning two decades, while very costly and time consuming, may eventually pay off given high losses to insect pests and the recent invasion by FAW (Wesseler *et al.*, 2017). Even so, the multinational seed companies themselves have had limited success with GM maize for small-scale farmers, with only Filipino and South African smallholders adopting a significant area of GM maize developed by the private sector.

After an unsuccessful search for transgenes that increase nitrogen use efficiency in tropical maize it was concluded that non-transgenic technologies may provide quicker payoffs. Pioneer-Dupont (now part of Corteva) provided a non-transgenic maize male sterility gene, *Ms44*, used to create 50% of hybrid plants that are male sterile. Their smaller tassels have been shown to increase N use efficiency and drought tolerance (Fox *et al.*, 2017; Loussaert *et al.*, 2017), and *Ms44* hybrids are currently in field testing in Africa. In a separate endeavour, Corteva has also provided a technology to allow hybrid seed to be produced without de-tasseling, resulting in hybrids that are genetically pure (CIMMYT, 2020). This technology uses transgenes in developing male sterile inbreds, but the final hybrid is non-transgenic.

Overall, with more than two decades of experience, the partnerships with multinational companies to access new tools and technologies have yet to yield significant impacts for smallholders. Insect resistant GMOs hold the most promise and after two decades of investment should soon reach farmers experiencing high pest losses in East Africa. However, GMO approaches may soon be supplanted by new gene editing technologies that are less controversial and more cost effective. In the meantime, the conventional breeding component of the WEMA project with Monsanto (Figure 20) has yielded several hybrids for drought-prone environments that have accounted for around 2% of annual seed sales of drought tolerant hybrid seed of CGIAR origin (Marechera *et al.*, 2019; S. Oikeh, pers. comm., 2020). The opportunity for CIMMYT and IITA to upgrade their conventional breeding methods through such partnerships with the private sector has also been a significant benefit.

Figure 20. WEMA Product Development Team during a Field Day in 2015.

6

Maize Agronomy, On-farm Research and the Smallholder

It was recognized early on that crop management or agronomy would be as important, if not more important, than improved varieties in raising the productivity of rainfed maize production systems, and that such research would have to be carried out in farmers' fields to represent farmer conditions. Even more than for breeding, the CGIAR approach to on-farm agronomic research (OFR) on maize would have to recognize the inherent location specificity of crop management practices for small-scale farmers operating in heterogeneous and risky environments. Indeed, for this reason, an International Agronomy Trial sent out by CIMMYT in the early years was quickly dropped. Rather the centers saw their role as developing and demonstrating methods and approaches for OFR that could be applied across countries together with building capacity in national research systems through training to use those methods. Nonetheless, and especially with the 'impact culture' of the 2000s, the centers have been pressured to demonstrate adoption and impacts at scale of their investments in OFR.

The approach evolved in four distinct periods. Initial efforts starting in Mexico attempted to modify the Green Revolution 'package approach to technology transfer' to fit rainfed environments by increasing investment in OFR to better target seed-fertilizer recommendations. By the late 1970s, a second phase emerged of developing and demonstrating methods to explicitly engage farmers in the design and testing of technologies in what came to be termed "on-farm research with a farming systems perspective". By the 1990s, a third phase involved still more participatory approaches that were employed to empower farmers in OFR and the focus shifted from the standard seed-fertilizer technology toward more environmentally sustainable practices within diversified farming systems. Finally, in the most recent phase of the 2010s, donors and some countries have re-invested in OFR in large-scale projects and "big data" that shifted the balance from methods to enabling large scale adoption of practices for sustainable intensification and adaptation to climate change.

The Package Approach to Technology Transfer

The Green Revolution employed a package approach to transferring technology, an approach popularised from the 1950s by the government of India with support from the RF, Ford Foundation and USAID. This approach selected technological components from experiment stations, undertook limited testing in farmers' fields and combined components so that synergies between them were maximized. The best known such package was the combination of the semi-dwarf wheat and rice varieties with nitrogen fertilizer that yielded much more than the sum of the effects of using variety or fertilizer alone. Green Revolution packages also typically included other complementary practices to seed and fertilizer such as appropriate plant density and spacing, timely weeding and irrigation management to maximize yields.

Researchers typically worked closely with extension workers to demonstrate the package so that "farmers would be informed of the new recommendation and the necessity of using all components of the technology precisely to obtain maximum results' (CIMMYT, 1974a, p. 107). As expressed by one of its main architects, Norman Borlaug, the aim was to demonstrate a dramatic increase in yields so that "the farmer is shaken out of his old beliefs" (Borlaug, 1968. p. 100). The approach also explicitly aimed to synchronize the recommended technological package with input suppliers to ensure that the appropriate inputs were provided, with marketing agencies to assure a market at a known price, and with credit agencies to supply loans to purchase inputs—in each case mostly provided through public sector agencies (Wortman and Cummings, 1984).

While the Green Revolution initially took off in irrigated areas the package approach was largely unproven in rainfed areas. The MAP in Mexico had been established 23 years and by 1960, maize yields in Mexico had increased 34% over 1944 levels, but mainly on larger farms in irrigated or higher potential rainfed areas (Myren, 1969; Ardito-Barletta, 1970; Dalrymple, 1969). Delbert Myren, head of information services for MAP and later CIMMYT, identified the major problems in reaching small-scale farmers in rainfed areas—inefficiencies in producing and distributing maize seed through a parastatal company and paltry investment in extension and other support services in rainfed areas (Myren, 1969). Independent social scientists were highly critical of this unequal outcome as detailed in scores of studies (Hewitt de Alcantara, 1976;. Jennings, 1988; Freebairn, 1969). Even the main chronicler of the success of the green revolution, Dana Dalrymple of USAID, concluded that "the poor growers have largely been bypassed" and "the Mexican model is hardly a complete model for other less developed countries" (Dalrymple, 1969. p 26-27). The original architects of MAP, Stakman, Bradfield and Mangelsdorf, looking back on 25 years of experience, concluded that:

> "the great majority of Mexico's small farmers have not yet gained much from the agricultural research because they have not yet applied it….Such data as are available in Mexico indicate that the increased wealth produced by the improvement of agriculture in the past 20 years has gone largely to the upper income groups" (Stakman *et al.*, 1967, p. 214).

Wellhausen, the long-time leader of the maize program of the MAP, frequently agonized over the failure to reach small farmers and as the first Director General of CIMMYT passionately argued for the "urgency of accelerating production on small farms" by refocusing science on the "needs of the bottom half of the world's farmers that had not yet been reached" (Wellhausen, 1970).

It was against this background that Plan Puebla was launched with much fanfare in 1967 as a joint effort between CIMMYT (still nearly synonymous with the RF), and the nearby Colegio de Postgraduados, to redress past failures of MAP. Ironically, as Plan Puebla was initiated, smallholders in El Salvador and Kenya were already adopting hybrid maize seed and fertilizer (Byerlee, 2020). These successes were still not recognized, as CIMMYT, with support from the RF, chose to proceed with Plan Puebla aiming "to develop a technological package and apply it" in a rainfed area of 43,000 farm households (Felsthausen and Diaz-Cisneros, 1985). It almost exclusively focused on maize, although in the selected area of the Mexican state of Puebla that was well connected to towns with off-farm employment opportunities, maize accounted for only about one quarter of farm household income. A major objective of the project was to showcase an approach that could be replicated in other rainfed areas of small farmers.

Plan Puebla made two major adaptations to the package approach in order to accommodate rainfed areas. From the outset it recognized that 'highly precise agronomic information' would be important to tailor recommendations to the diversity of soil and climatic conditions characteristic of rainfed systems. Accordingly, the project invested heavily in on-farm experimentation, relative to the Green Revolution in India that focused largely on technology transfer (Turrent, 1971). Second, the project employed social scientists to understand adoption and evaluate performance. Project leaders were cognizant of the importance of risk in rainfed areas and involved CIMMYT economists in studies of risk analysis (Winkelmann, 1976. Moscardi and de Janvry, 1977). Mexican social scientists were also employed in extension to enhance sensitivity to local culture and power relations, and to undertake evaluation surveys to monitor progress and provide feedback to project management on meeting objectives (Redclift, 1983).

By 1973 when CIMMYT withdrew from the project, adoption had reached 26% of the maize area with yield increases of adopters of about 50%, mainly due to increased fertilizer use (CIMMYT, 1974a). Yet despite providing 16 different packages of recommendations based on soils and climate, less than 10% of farmers adopted the full package, raising questions about the relevance of a package approach (Winkelmann, 1976). A further telling result was that after 25 years of maize breeding in Mexico, project staff were unable to identify a variety or hybrid that was superior to the farmers' variety even under fairly high levels of nitrogen. Although the computed return on the investment in the project was high, it was nonetheless expensive in terms of resources (about $700 per farmer reached in today's dollar) and in terms of skilled human resources, employing five full-time Mexican staff with post-graduate degrees, and engaging considerable time of specialists from CIMMYT as well.

Still, much was learnt in the process, including the need for multidisciplinary approaches and close communication with farmers (Redclift, 1983). It was also an important initiation for the CIMMYT Economics Program that had started only in 1971 with the hiring of Donald L. Winkelmann from the Colegio de Postgraduados. The program quickly provided practical methods for analyzing on-farm experiments in terms of economic returns and risks that would become standard in the profession (Perrin *et al.*, 1976). However, by 1973 the role of CIMMYT, in what was essentially a national program, was questioned by donors and CIMMYT abruptly withdrew with some hurt feelings that paused relations with Mexican maize scientists for decades.

Unlike CIMMYT that focused on two crops, IITA was set up a year after CIMMYT in 1967 to address the challenges of intensification of farming systems in upland areas of the humid tropics, notably to find sustainable alternatives to shifting cultivation (Byerlee and Lynam, 2020). Nearly half of IITA's resources were assigned to developing such alternatives, largely through research conducted on its research station. One major effort was to develop alley cropping in which cereals were cropped in strips between rows of leguminous species, such as *Leucaena leucocephala* with cuttings from the leucaena providing feed and green manure, while the nitrogen fixed by the legume fed the maize crop. It failed to make an impact at scale, in part because of land tenure issues as well as its high requirements for labor (Ortiz, 2017). As described perhaps somewhat harshly by a senior IITA scientist, Bernard Vanlauwe, IITA "targeted a hypothetical new type of farmer who would integrate the research findings into an efficient, intensified, semi-mechanized operation....which had minor relevance for most existing farming systems in the humid area" (Vanlauwe *et al.*, 2017, p. 616).

Nonetheless, IITA also established a maize improvement program and quickly developed new varieties, building on the legacy of several earlier colonial and post-independent efforts in Nigeria and incorporating tropical germplasm from the Americas (Byerlee, 2020). By 1975, an OPV, TZB, had been released that was well suited for the savannah areas of Nigeria where maize was only a minor crop but had been identified as a crop with much potential (Kassam *et al.*, 1975).Meanwhile, based on recommendations of a team led by CIMMYTs' maize director, Sprague, and including also Winkelmann, the Nigerian government in 1973 established the National Accelerated Food Production Project supported by IITA in an effort to 'bring the Green Revolution to Nigeria' by extending new varieties such as TZB, fertilizer and complementary practices (Njoku and Mijindadi, 1985). However, the NAFPP was soon overshadowed by the much larger and more ambitious World Bank Agricultural Development Projects (ADPs) starting in 1975. These projects, totalling 12 by the early 1980s, promoted a package approach including the supply of needed inputs, notably highly subsidized fertilizer, and extension advice through the Bank's new Training and Visit System of extension (Smith *et al.*, 1994).

The TZB variety combined with modest doses of fertilizer was a catalyst for transformative change as it 'spread like a bushfire' through the savannahs (Mutsaers, 2007). Given its profitability maize was well suited as a cash crop and was increasingly used for subsistence food, often replacing sorghum, millets and legumes (Smith *et al.*, 1994). Unlike in Plan Puebla, adaptive OFR supported by the NAFPP and the ADPs was quite weak. Many of the components of the technological package relating to plant spacing and density were not adopted, and farmers' preference for intercropping was ignored (Mutsaers, 2007; Ega *et al.*, 1988). Even the extensive adoption of fertilizer turned out to be contingent on subsidies and maize area declined after structural adjustment programs reduced subsidies in the early 1990s (Igodan *et al.*, 1988; Smith *et al.*, 1994). Nonetheless, the expansion of maize production in Nigeria at 5 percent per year over the next 35 years exceeded that of wheat in the 35 years after the Green Revolution in India. Production growth was, however, based more on area than yield growth, as might be expected in the relatively land-abundant savannahs that were still characterized by extensive fallow periods.

Introducing a Farming Systems Perspective

On-farm research took a sharp turn in the late 1970s entering a second phase with the introduction of what was termed a 'farming systems perspective' into OFR methods. The idea was to start with an explicit effort to understand existing farming systems and practices, recognizing that farmers were rational decision makers that had developed complex and diverse systems to meet their needs. Even though the focus remained on maize, it was understood that optimal management of maize was often compromised by interactions with other enterprises in the farming system. These interactions included crop rotations and intercropping, the effects of livestock through fodder needs and provision of draft power, and balancing subsistence food needs and family labor use over seasons.

In lieu of 'rural development tourism'—that is, casual conversations with so-called 'progressive farmers' (Chambers, 1983)—that had been previously employed to design OFR programs, OFR now explicitly included an initial diagnostic step involving an interdisciplinary team of social scientists and agronomists. Employing individual farmer and group interviews and field observation, these teams systematically interacted with farmers to better understand constraints and opportunities as a basis for designing an experimental program to reflect farmers' priorities, and to define 'recommendation domains'—groups of farmers with similar circumstances that were expected to adopt the same technology (Byerlee *et al.*, 1981; Collinson, 1987). OFR in this phase also moved away from the package approach by seeking stepwise improvements to existing practices (Byerlee and Hesse, 1986). This stepwise approach required experimentation under farmer management, although this was hotly debated due to the tradeoff with statistical precision in measuring treatment effects. OFR still largely drew on technologies from the experiment station and like the package approach these were mostly built around improved seed, fertilizer and associated practices such as plant density and weed control (Figures 21-24).

Figure 21. Derek Byerlee in a maize and sorghum field, Northern Ghana, 1981.

Figure 22. Harvesting on-farm trials, Brong-Ahafo, Ghana, 1981.

Figure 23. Alex Violic and crop management trainees laying out an on-farm trial in the Tuxpan area, Edo. Veracruz, Mexico in 1975.

Figure 24. Don Winkelmann in a Plan Puebla maize plot, Mexico, 1973.

CIMMYT was in the lead in this movement, building on the experience in Plan Puebla and the hiring of economists and anthropologists with extensive field experience. CIMMYT rationalized its involvement in what was essentially location-specific research by the development of a series of popular manuals that were employed to support institutionalization of the approach in national research systems through training and technical support (Perrin *et al.*, 1976; Byerlee, *et al.*, 1981; Tripp and Woolley, 1989). In the early years, there was considerable debate between the social scientists and agronomists on their respective roles in OFR especially when social scientists sometimes took the lead in designing experiments. However, these tensions waned when CIMMYT appointed a new maize director, Ronald (Ron) Cantrell, in 1984, who had recently worked with a multidisciplinary team in Burkina Faso employing similar OFR methods (Matlon *et al.*, 1984).

The new-found respect for the role of farmers in OFR took center stage in most CGIAR centers and CIMMYT worked closely with other centers, notably CIAT and IITA, in methodology development and training (e.g., Tripp and Woolley, 1989; Mutsaers *et al.*, 1997). Donors enthusiastically supported large programs of capacity building for OFR in NARSs across the developing world, above all in Africa which became their focus in the 1980s. CIMMYT's largest OFR programs were in Africa, but significant investments were also made by regional programs in Central America, the Andes, South Asia and Southeast Asia.

CIMMYTs first nation-wide OFR effort was the Ghana Grains Development Project, focused on maize with IITA support on cowpeas, and funded by the Canadian International Development Agency. It began in 1979 and continued for 20 years emphasizing seed-fertilizer-weed control technology, including maize breeding and the conduct of some 6000 on-farm trials (Edmeades *et al.*, 1991; Soza *et al.*, 1996). The multidisciplinary research team initially co-led by one of the authors (Edmeades) integrated farmers at each stage. Traditional farming practices such as intercropping were gradually included in the experimental program and feedback from farmers such as the need for better husk cover to improve storability was incorporated into the breeding work (Russell, 1989). Differential impacts of the technology on men and women farmers were also analyzed in terms of implications for technology design and extension methods (Doss and Morris, 2000). A special feature was the graduate training of about 50 Ghanaian scientists that built local maize research capacity.

By 1998, more than half of maize farmers in Ghana had adopted improved varieties, fertilizers and planting methods. However, as in Nigeria the removal of the fertilizer subsidy caused a sharp drop in fertilizer use after 1990. Even so, over the past 35 years, maize production increased impressively by about 4.5 percent per year with about half of the gains from yield increases.

The high adoption rate in Ghana was also attributed to close links with the NGO, SG2000 (Section 4) that explicitly aimed at bringing the Green Revolution to Africa, building on the Asian experience. Ghana was the first country SG2000 selected, beginning in 1986 (Dowswell and Borlaug, 1995). Given Borlaug's leading role, SG2000 initially recruited its field staff from the Mexican cadre of scientists trained under the RF's MAP in the 1950s and 1960s. Using results from the Ghanaian OFR program, SG2000 worked directly with the public extension service by providing transport, training and inputs to transfer the technology. Engagement by Borlaug and former US President Jimmy Carter of SG2000 with Ghanaian President Jerry Rawlings enabled the project to gain high level political support and expand rapidly. Ghana became a showcase for SG2000 and in 1989 alone, it worked with the extension service to lay out nearly 80,000 one-acre demonstration plots, with the associated provision of seed, fertilizer, multiple extension visits, and credit. Problems soon arose in managing such a large program, especially with input supply and loan repayment. As noted by Tripp (1993, p. 2012) "probably the most serious flaw in the early years [of SG2000] was the lack of attention to strengthening local institutions". Other observers were more critical noting that such "magic bullet" approaches had consistently failed to deliver for Africa's 'complex, diverse and risk prone environments' (Jiggins *et al.*, 1996).

Meanwhile, an ambitious OFR program was launched in East and Southern Africa, eventually reaching all countries of the region where maize was the major food staple. Rather than working through maize research programs most of these programs aimed to establish local interdisciplinary OFR capacity for a defined area. There was a strong emphasis on training and institutionalization of OFR units within the research system, with special attention to using low-cost methods such as 'informal surveys' for diagnosing research priorities (Collinson, 1987; Tripp and Anandajayasekeram, 1990). The CIMMYT regional OFR project in southern Africa also emphasized on-farm experimentation, information exchange and shared learning. However, most OFR teams in Africa were supported by donors and they often became "orphans" when donor support ceased.

Retrospective reviews of this large effort in the 1990s noted that adoption was below expectations—of 53 research thrusts (specific intervention and area) in three southern African countries, only three resulted in widespread adoption (Low *et al.*, 1991; Waddington, 1993). Lack of useful technologies on the shelf, the variable quality of the research, weak links to extension, lack of attention to input supply and weak markets all contributed to low uptake of the recommended technologies. Where extension services existed CIMMYT agronomists played a significant role in developing technologies such as Striga management research in Kenya (Ejeta and Gressel, 2007) and reduced tillage as a means of advancing planting date in Zimbabwe (Shumba *et al.*, 1992). The OFR projects on maize also developed a strong human resources base and the emphasis on on-farm research became standard for countless subsequent projects and programs in NARSs and the CGIAR centres (S. Waddington, pers. comm., 2021). OFR also provided important feedback to maize breeding priorities**.** For example, diagnostic work consistently highlighted the need for early maturing varieties to accommodate farmers' seasonal food needs and delayed planting due to labor or draft power constraints or unfavourable weather (Haugerud and Collinson, 1990). Yet the OFR projects were also criticized because of their separation from maize research programs that inhibited mainstreaming of the findings in setting maize research priorities (Byerlee and Tripp, 1988).

Our final case illustrates a process of researchers understanding the rationality of small farmers in a maize-livestock system of northern Pakistan. From 1971, CIMMYT had been supporting extensive on-farm experimentation and demonstration of improved maize technology at over 600 sites in Khyber Pakhtunkhwa Province of Pakistan, where maize was the dominant summer crop and an important food staple. Yet in the fertile mountain valleys such as Swat, farmers continued to use a traditional system of broadcasting maize at a density of several times the recommended rate and then periodically thinning the maize over the growing season and using thinnings for forage. By 1980s, the importance of green maize for fodder was being recognized but scientists suggested that maize fodder and grain production be undertaken in separate fields. In the 1980s, a series of careful observation in farmers' fields over the growing season accompanied by interviews with farmers established that fodder accounted for about half the value of production. Further experimentation managed by farmers showed that the farmers' 'intercropping' of grain and fodder was in fact superior to the recommended technology in terms of profitability. Fortunately, maize breeders identified an excellent variety that performed well under high density and after testing with farmers was widely adopted in the area (Byerlee *et al.*, 1991). [16]

This second phase of OFR was undoubtedly a major step in involving farmers in technology selection and testing, as well as in advancing scientists' understanding of the many nuances of complex farming systems that influenced farmers' acceptance of maize technologies. It also challenged the package approach to technology transfer, but this was also a weakness. The OFR methods often treated the policy environment as 'exogenous' and research teams lacked engagement with input suppliers and other agents needed to achieve wide adoption of specific technological components (Low *et al.*, 1991). A notable exception was an explicit effort to use OFR to influence fertilizer policy in Haiti (Martinez *et al.*, 1991). Finally, for all the passion of this era, economists paid little attention to evaluating the impacts of their efforts (Low *et al.*, 1991).

[16] CIMMYT eventually produced another manual to encourage more adoption studies (CIMMYT, 1993).

Participatory Research on Sustainable Intensification

With the budget cuts in the 1990s, OFR efforts were scaled back and were focused on Africa, Mexico and Central America. Ironically, it was the Rockefeller and Ford Foundations that had largely withdrawn from the CGIAR system that provided catalytic funding during this period for a re-orientation of research away from green revolution package technologies towards participatory engagement of farmers in developing so-called sustainable technologies.

This third phase of OFR methods responded to the challenge of 'putting the farmer first' (Chambers, 1983) by evolving from consulting farmers to engaging farmers as full partners in defining priorities, adapting technologies, managing experiments, selecting technologies for their own use, and farmer-to-farmer technology transfer. Farmers participated through novel methods such as transect mapping of village agricultural landscapes, participatory variety selection, the use of farmers' soil and climate taxonomies to frame recommendations, and understanding gender roles and responsibilities.[17] During this phase, OFR methods moved beyond the 'central source of innovation model' (i.e., the experiment station) to consider 'multiple sources of innovation', especially indigenous knowledge and farmer innovation (Biggs, 1990).

This stage also corresponded with a shift in the global agenda toward sustainable management of natural resources. This, together with the elimination of fertilizer subsidies under structural adjustment programs in the 1980s, stimulated the search for technologies that would reduce dependence on external inputs and at the same time build soil fertility and health, as well as reduce soil erosion. Along with developing participatory methods that could be widely applied, CIMMYT scientists in this stage also began to focus on a suite of technologies emphaizing reduced or zero tillage and continuous soil cover through crop residue retention and/or crop species diversification. These practices collectively came to be known as conservation agriculture (CA) that conserved both soil and soil moisture and could be employed across rainfed maize systems in many countries.

After a hiatus from Plan Puebla CIMMYT re-engaged in Mexico in the poorer south and in the west, and in marginal hillside systems in Central America. The major focus was on integration of legumes into maize farming systems to supply nitrogen and build soil organic matter, and experimentation on zero tillage with surface retention of crop residues. Much of this work drew on the results of farmer innovation. In Mexico and Central America, CIMMYT investigated how farmers developed and spread the *abonera* system of green manuring with *Mucuna*, a tropical legume, as well as the adoption and adaptation of CA by farmers in hillside systems (Buckles *et al.*, 1993, Erenstein, 1997; Buckles and Erenstein, 1996). Farmer-to-farmer learning networks were also built around green manures and conservation tillage for intensification of hillside maize systems (Buckles *et al.*,1998; Buckles, 1993). CAe was further tested in farmer's fields in Mexico in the 1990s but adoption was constrained by the need for herbicides and suitable machinery for direct planting without tillage (Jourdain *et al.*, 2001). Management of acid soils in the southeast of Mexico and in Colombia also emerged as major research priorities for OFR (Hibon *et al.*, 1992).

Similar approaches were employed by CIMMYT agronomists in Southern Africa through a Soil Fertility Research Network that supported local scientists to test a wide range of legumes—fodder trees, green manures, and grain legumes—through intercropping and crop rotations with maize (Waddington *et al.*, 2004). Emphasis was on providing options to groups of farmers to support 'farmer discovery' through their own experimentation and farmer-to-farmer learning. In lieu of standard soil and climatic information, this research also studied farmers' 'relatively sophisticated taxonomies' as a basis for refining recommendations (Bellon and Risopoulos, 2001). Network activities resulted in identification of ´best bet´ technologies that were widely promoted through extension to farmers**.** Adoption was generally modest with some exceptions where strong markets existed for grain legumes (Kamanga *et al.*, 2014).

[17] CIMMYT captured some of these methods in a further manual, Bellon, 2001

In West Africa, IITA had considerable success with participatory approaches to introducing green manures that led to the fairly widespread adoption of Mucuna in Benin, although more for weed control than for soil fertility improvement (Manyong *et al.*, 1999). This research was linked to similar work on green manures by CIMMYT and was heavily promoted by SG2000 in several countries.

Experimentation with CA in southern Africa introduced farmers to the practice, explained its underlying principles and then observed farmers' learning and adaptation (Wall *et al.*, 2013). The technology was largely transferred from Latin America but much adaptive research was required for its use in Africa. As described later by Giller *et al.* (2009), the requirements for inputs such as herbicides, machines and management skills, and conflicting demands for the use of crop residues, would constrain the adoption of CA by smallholders in the short term. CIMMYT agronomists, summarizing research in four countries in southern Africa, reported that 80% of responses to CA were positive. They noted that yield benefits were higher with increasing years of practicing CA, highlighting the need to gain experience to master critical management skills (Thierfelder *et al.*, 2015). Still, the prospects for wide-scale adoption of CA in Africa were and still are, vigorously debated (Wall, *et al.*, 2019; Giller *et al.*, 2009).

Finally, given the rich diversity of land races of maize in Mexico, maize's center of origin, Bellon *et al.* (2006) used participatory approaches to increase the understanding of farmers' management of germplasm in order to make farmers' selection of varieties and conservation of biodiversity more effective. His work also recognized farmers' purposeful hybridization of local and introduced varieties—termed *acriollamiento or* 'creolization' –to incorporate the best characteristics of each. In Southern Africa, mainstream maize breeding also involved farmers extensively in testing and selecting varieties and hybrids for drought-prone environments and providing feedback to the breeding program (Bänziger *et al.*, 2006).

By the 2000s, these approaches represented a 180-degree shift from the earlier seed-fertilizer package approach of the Puebla Project. Technological innovation now depended on multiple sources including farmers' own knowledge and experimentation. The package approach had essentially been abandoned with the emphasis now on farmers experimenting with a range of options. However, participatory research was costly in terms of time and skills of scientists and proved difficult to scale up. Further, as in the previous era, the methods became an end in themselves, often captured by NGOs that associated them with promotion of low-external input technologies even if these practices were not pro-poor in terms of adoption (Tripp, 2006). Nonetheless, the experiences across regions resulted in much "lateral learning" and increased awareness of the opportunity costs in the short term of CA in smallholder farming systems (Erenstein *et al.*, 2015; Hellin *et al.*, 2013)—experiences that were important in laying the basis for major projects on CA in the 2010s.

Scaling Up Impacts

The world food crisis beginning in 2008 reversed the flagging interest by donors and governments alike in agriculture, and spurred a resurgence of investment in OFR and technology transfer, and a fourth phase of OFR. In this new environment, funding was provided through a series of large projects with the clear objective of demonstrating impacts on the ground by reaching hundreds of thousands of farmers. Examples were Sustainable Intensification of Maize-Legume Cropping Systems for Food Security in Eastern and Southern Africa (SIMLESA), The Sustainable Modernization of Traditional Agriculture (MasAgro) in Mexico, Africa Research in Sustainable Intensification for the Next Generation (AFRICA RISING) (led by IITA) and Cereal Systems Initiative for South Asia (CSISA). These projects operated in the new context of 'development metrics' and set specific targets in terms of number of farmers reached and impacts on yields (Schurman, 2018). This emphasis on time-bound results forced the CGIAR centers into more downstream technology transfer activities, in part at the expense of producing international public goods, such as the further development of OFR methods.

In a departure from the participatory approaches of the previous era, scientists and donors largely selected the technologies to be tested and promoted with a strong emphasis on CA, building on the pilot efforts in the 1990s. In addition, they embraced the wider concept of climate-smart agriculture to build adaptation and resilience of smallholder farming systems in the face of climate change, although this was highly consistent with the use of CA (Campbell *et al.*, 2014). SIMLESA, for example, set a goal of reducing yield risk by 30%, in addition to the target of 30% higher yields (Figure 25). It is still early to evaluate the results of these projects but a brief overview of two of them, SIMLESA funded by the Australian Centre for International Agricultural Research and MasAgro, funded by the government of Mexico, illustrates their broad scope and initial impacts. A recent meta-review by CIMMYT of adoption of technologies for sustainable intensification of maize systems can be found in Jones-Garcia and Krishna (2021).

Figure 25. SIMLESA minimum tillage plots, Western Kenya, 2012

Recognizing the diversity of rainfed maize farmers and growing conditions, SIMLESA supported a large number of trials (over 2000) across different agro-ecologies in six countries in Eastern and Southern Africa. Recommendation domains also gave special attention to socio-economic status of farm households emphasizing those farmers who could 'step up' through successful commercialization, with some attention to improving the livelihoods of those who would 'hang in' for subsistence (Wilkus *et al.*, 2019). With an almost exclusive focus on CA, technological options included drought-tolerant maize varieties, tillage methods, legume species and crop rotation and intercropping ('best bets') preselected by researchers with little emphasis on precisely refining management practices to specific contexts (Wilkus *et al.*, 2021).

Research methods were necessarily adapted to the larger scale of impacts envisaged. Given the emphasis on metrics, economists organized large household surveys to track adoption of the selected technological components, somewhat reminiscent of the original Puebla project. However, these large surveys left little time for more in-depth and participatory interaction of interdisciplinary teams in the field to better understand farmers' decision making as in the earlier periods. The establishment of 'innovation platforms' in key locations became the main mechanism for linkage of engaging farmers with other stakeholders along the value chain, such as input suppliers, sources of credit, extensionists, and traders to coordinate efforts and jointly solve constraints to adoption. Priority was given to linking with seed producers to ensure sufficient supply of new varieties, and some innovation platforms undertook bulk buying of inputs, such as fertilizer, to obtain price discounts (Marenya et al., 2020).

The full impacts of SIMLESA are yet to be assessed but adoption of at least part of the package by 480,000 farmers (around 25% of farmers exposed to the technology) has been documented (Wilkus et al., 2021), with increased yields of up to 33% and increase in real incomes by adopters from 6-35% (Marenya et al., 2020). Adoption was highest for crop rotation and intercropping, although it is unclear whether this was due to 're-adoption' of practices traditionally used by farmers. Some progress was made in adoption of CA, especially in Kenya and Malawi. However, with the need for upfront investment in nitrogen fertilizer and herbicide, lack of suitable machinery for planting under zero tillage, and the use of crop residues for soil cover instead of animal feed, it was always recognized that adoption and performance would vary widely (Droppelmann *et al.*, 2017). In echoes of the package approach, the final report of SIMLESA noted that all the elements of 'improved varieties, timely planting, use of fertility amendments, weed control, and correct plant densities when applied correctly (as a complete set of practices), the yield and income benefits average 37-50% better than conventional methods" and therefore "should be promoted as an appropriate package, rather than as single components" (Marenya, 2020). In practice, very few farmers adopted the full package of six different technological components, and these were the larger more commercially-oriented farmers.

In sum, SIMLESA made a number of important advances in methods such as the definition of farm-household typologies and the use of innovation platforms. However, it had to revert to more supply-driven approaches to technology transfer, albeit for a more sustainable set of technological components and cropping system options. It also closely partnered with national research systems and invested significantly in building capacity that should have lasting impacts.[18] However, SIMLESA was one among several large projects in the region all aiming for sustainable intensification but often emphasizing different technological components and research approaches. Few national programs in the region had sufficient capacity and resources to integrate these projects to fit national strategies. Nor did they have the resources for the needed investment over the long term to scale out OFR to address the diversity of soils, climate and farmer resources and skills (Droppelmann *et al.*, 2017).

Over time more attention was given to design and advocacy of policies to enhance adoption, although this was largely centered on seed supply (Pengelly *et al.*, 2015). The development of efficient fertilizer value chains received little attention despite the need for increased fertilizer use and the notoriously high prices of fertilizer in Africa due to lack of competition, high transactions costs, weak infrastructure and small volume (Wilkus at al., 2021). There was also little research to explore policy and institutional options to overcome the upfront costs of using CA practices and incentivize their adoption.

The MasAgro project in Mexico (Section 5) also emphasized OFR for scaling up adoption of CA. The project aimed to change from a "push" technology transfer system (based on extension as in Plan Puebla) to a "pull" system (based on markets). As in Africa, MasAgro established innovation platforms to develop and spread adapted technology and to link to other actors in the value chain. MasAgro also developed and used a number of on-line and Smartphone tools to assist farmers and extension agents to more precisely tailor fertilizer recommendations to farmer circumstances. Although MasAgro has not published detailed evaluations, it claims that 500,000 smallholders in Mexico have adopted CA and now enjoy yields and incomes 20-25% higher than the non-adopting control (CAS Secretariat, 2020). However, it is not clear if adoption will be sustained over time and if adoption has reached resource poor farmers in Southern Mexico—major criticisms raised in the early stages of MasAgro by Antonio Turrent, one of the architects of Plan Puebla (Turrent *et al.*, 2014). Results also reflect a decade of sustained massive funding from the Government of Mexico that has now been terminated.

Finally, in this phase of OFR CGIAR scientists have recently turned to randomized control trials (RCTs) to test the potential of digital agriculture to transmit precision recommendations on input use for individual farmer, field and seasonal conditions. RCTs, using randomly selected households or villages rather than fields as the subject of experimentation, received a boost with the award of the 2019 Nobel Prize in Economics to pioneers in the field. Recent RCTs led by CIMMYT and IITA have validated nutrient response through a large number of on-farm trials in Africa, and used RCTs to explore the use and benefits of tailored recommendations delivered digitally to farmers. They found a significant impact on yields of 10-15 percent but mostly through fertilizing management practices rather than more precise dosage (Oyinbo *et al.*, 2021; Ayalew *et al.*, 2020). The growing ability to assess yields in small plots through remote sensing combined with other data bases such as nation-wide soil testing information offers promise that 'big data' may finally usher in a new era of precision farming for smallholders that will partly substitute for field-based OFR.

Complementary Policy Research

One reason why CIMMYT and IITA may have shied away from research on policy issues affecting maize technology uptake was the investment by the CGIAR from 1981 in the International Food Policy Research Institute (IFPRI). Much of IFPRI's research was related to exploration of broader issues of enabling policies for technology adoption related to prices, trade, regulatory issues, land tenure, science

[18] Over 50 post graduate scholarships were provided by SIMLESA

policy and so forth as well as providing leadership on gender in agriculture—all relevant to CIMMYT's and IITA's maize mandates. However, there has been relatively little IFPRI research related specifically to maize, and most of that understandably has been in eastern and southern Africa where maize is the major food staple.

Prior to 2000, the most important IFPRI contributions related to reform of input and food markets. Earlier work by Pinckney (1988) and Koester (1986) highlighted options for relaxing national marketing boards' control of maize prices and trade in the region as a means to stabilize prices, reduce state subsidies, and improve market efficiency. This was followed more than a decade later by a seminal review by Kherallah *et al.*, (2002) of the status of input and output market reforms in Africa that had been been promoted through structural adjustment programs. Their review had a particular focus on maize in several countries and highlighted the incomplete nature of the reform process along with the need to make complementary investments in infrastructure and market institutions.

The most significant policy research in recent years relates to fertilizer subsidies re-introduced after 2008 to stimulate intensification in sub-Saharan Africa, especially in maize. These subsidies were relabelled as "smart subsidies" to distinguish them from the earlier blanket subsidies since they were targeted at poor farmers and aimed to build private markets (World Bank, 2007). IFPRI, in collaboration with Michigan State University, showed that this new generation of subsidies resulted in large budgetary outlays amounting to about $US1 billion. These outlays were captured mostly by larger farmers with only modest impacts on total fertilizer uptake and maize yields (Jayne and Rashid, 2013; Jayne *et al.*, 2018). For example, in Malawi a focal country for the new generation of subsidies, maize yields still averaged less than 2 t/ha after more than a decade of heavy expenditures on subsidies. At the same time, there is evidence that subsidies undermined the adoption of integrated soil management practices needed to improve nutrient response and reduce risks (Morgan *et al.*, 2019). IFPRI's research has led to a redesign of subsidies as well as scaling back in favour of investment in research and infrastructure.

In the past decade, economists from IFPRI, CIMMYT and many other organizations, have employed RCTs to test a variety of policy and institutional interventions aimed to ease cash, information and risk constraints, such as crop insurance, cash grants, lay-away options for input purchases, and novel ways of providing extension advice, mainly in relation to fertilizer use. For example, extension messages delivered through videos were found to be more effective in adopting crop management practices for maize in Uganda relative to traditional extension (van Campenhout *et al.*, 2021). Many RCT studies have found that index-based insurance reduces risk of input use and increases fertilizer use in rainfed farming, but only if heavily subsidized (Hansen, 2019; Magruder, 2018). CIMMYT, for example, is currently collaborating on research to evaluate the combination of drought tolerant maize with weather indexed insurance to mitigate drought risk.[19] Based on these experiences, RCTs offer a means of identifying and testing ways to improve the policy and institutional environment for smallholder intensification that merits more investment in future OFR.

OFR Over the Long Term

This review of 50 years of investment in OFR on maize is sobering in terms of the paucity of results on the ground beyond the standard seed-fertilizer push that started with Plan Puebla in 1967. Yet we would certainly not go so far as to conclude as one ex-IITA agronomist has that "returns to small-scale farming from decades of expensive international research on agronomy have been next to zero" (Mutsaers, 2007, p. 202). Where there has been consistent long-term funding, efforts to involve farmers as full partners in the research process have greatly increased scientists' understanding of the nuances of complex farming systems and their constraints, and have reshaped research priorities accordingly. The special focus by CIMMYT on the development of methods for OFR, and the associated manuals and training programs for national partners, has been an enduring public good over many decades. However, OFR has largely

[19] https://basis.ucdavis.edu/project/bundling-innovative-risk-management-technologies-improve-nutritional-outcomes-africa

been a step-child within CIMMYT, funded opportunistically through specific donor projects that until recently were modest in size and did not provide long-term support for research on complex systems issues nor for building sustainable capacity in national programs.

Even so, OFR has also increasingly been linked to breeding, and there has been a gradual exploitation of positive interactions between variety and management practices. As examples we point to the use of higher planting densities with modern hybrids, the use of drought tolerant varieties with CA practices, and the slow but steady rise in fertilizer use as more nutrient-responsive and nutrient use-efficient varieties have been adopted. This, together with participatory testing of varieties, has aided the release of adapted varieties and hybrids and their diffusion over large areas. The introduction of new legume varieties and species in a range of settings has also been a notable achievement, especially in Africa (Marenya et al, 2020). However, the widespread and impressive adoption of CA by large-scale farmers in tropical Latin America has not been replicated in tropical regions dominated by diverse smallholder systems. This requires innovative and cost-effective approaches for scientists, extensionists, machinery manufacturers and farmers for experimentation, adaptation and mutual learning. Another imbalance may have been an overemphasis on promoting technological solutions versus research to improve the external policy and institutional environment in which farmers obtain information, inputs, capital and machinery needed for successful adoption of CA.

7

Assessing the Impacts of CGIAR Maize Research

CIMMYT has periodically estimated the use by national programs and the private sector of its germplasm products and adoption by farmers of varieties based on its germplasm. This has been standard practice for all crops in the CGIAR, although the number of global studies has declined sharply in the 2000s. Further, unlike rice and wheat, there have been very few efforts at the global or regional levels to assess returns to investment in CGIAR maize research (Alston *et al.*, 2021). In part this reflects the challenge of tracing maize germplasm in the genetically variable OPVs and the growing importance of the private sector who maintain trade secrets on the genetic makeup of their products and are reticent about sharing sales information. In recent years also, funding has constrained the implementation of large-scale impact studies. Most funding is tied to specific projects and impact evaluation necessarily requires several years after project completion. Further, methods for impact assessment have become more rigorous and costly, requiring larger sample sizes, panel household data over time, and more careful identification of varieties, now sometimes based on DNA fingerprinting (Krishna *et al.*, 2019).

Given these challenges, this Section only summarizes what is known about the global reach of CGIAR maize germplasm recognizing that are big gaps for Asia and Latin America in recent years. Then we turn to the Centers' substantial investment in supporting national programs through training and technical assistance, although the impacts of this effort are even less well documented. Finally, we look at countries where maize yields have grown fastest since 2000 and identify the role if any of the CGIAR in those countries.

Impacts Through the Use of CGIAR Genetic Products

Periodically, efforts have been made to assess use of CGIAR-related germplasm by estimating the extent of adoption of modern varieties as well as the intensity of use of CGIAR-related germplasm in those varieties. The first such effort in 1984 estimated that about 6 M ha of maize in the tropics and subtropics was sown to CIMMYT- and IITA-derived products, with the largest areas in Brazil, Nigeria, and Thailand (Anderson, 1985). By 1998, this figure had risen to 18 M ha (28% of maize in the tropics) for CIMMYT germplasm alone (Table 4) (Morris, 2002). About one third of the CGIAR-related germplasm area was in Brazil where most maize is grown by relatively large-scale commercial farms. Mexico and Central America continued to show low (21%) adoption of modern maize varieties (MVs) but CIMMYT materials were used on over 90% of that improved maize area (Figure 26). In South and Southeast Asia MV adoption was high (67%) but with somewhat less than half that contained CIMMYT varieties or lines. In terms of total area under CIMMYT germplasm, over half was sown in Latin America, but, excluding Brazil, the largest smallholder area was in Asia (Morris, 2002).

Figure 26. Hugo Cordova (right) played a major role in developing and deploying improved maize varieties in Central America.

Table 4. Estimates of use and adoption of CGIAR maize germplasm in the tropics and subtropics, 1984-1990. Modern varieties (MVs) are varieties released after 1970 from any source. Sources: Anderson (1985), Lopez-Pereira and Morris (1994), Morris (2002).

Year	Extension of MVs (% of total maize area)	Intensity of use of CGIAR germplasm (% of area under MVs)	Overall area in CGIAR-related germplasm M ha (% total maize area)
1984	NA	NA	6.0 (9%)
1990	43	55	13.5 (23%)
1998	47	59	18 (28%)

Note: Assumes all improved germplasm used in West Africa from IITA in this period has some CIMMYT parentage and is therefore included in CGIAR estimates.

Consistent with the pivot to Africa in the 2000s, the most comprehensive recent reviews of adoption have been in sub-Saharan Africa where there is a clear regional contrast (Table 5). Eastern and Southern Africa started with relatively high adoption of hybrid maize in some countries such as Kenya, Zambia and Zimbabwe based on a long history of breeding and strong seed systems established for the settler economies. Since CIMMYT did not initiate its African breeding program until the mid-1980s, use of its germplasm was minimal in this region. Use of CIMMYT materials increased by 1998 to account for a bit more than a quarter of the area under improved varieties. This was followed by a sharp jump in both the adoption of improved varieties and hybrids and in the use of CIMMYT materials in breeding programs to 2015, a trend that continued over the next 5 years (Krishna *et al.*, 2021).

Table 5. Estimates of use and adoption of CGIAR maize germplasm in sub-Saharan Africa, 1990-2015. Sources: Lopez-Pereira and Morris (1994), Morris (2002), Alene *et al.* (2008), Walker *et al.* (2014), Krishna *et al.* (2021).

Year	Extension of MVs (% of total maize area)	Intensity of use of CGIAR maize germplasm (% of area under MVs)	Overall area in CGIAR-related maize germplasm (M ha) (% total maize area in parentheses)
Eastern and Southern Africa			
1990	53	13	0.49 (5%)
1998	36	36	1.4 (13%)
2010	44	29	1.9 (13%)
2015	69	52	9.5 (36%)
West and Central Africa			
1990	22	71	1.5 (28%)
1998	37	66	2.2 (24%)
2005	60	68	2.9 (41%)
2010	66	80	5.3 (53%)
2015	68	45	3.5 (31%)

Note: All estimates combine use of CIMMYT and IITA germplasm. Modern varieties (MVs) are varieties released after 1970 from any source, except that Krishna *et al.* (2021) considered only those varieties released since 1995 as MVs. Inclusion of pre-1995 releases significantly affects estimates in West Africa where an additional 2.4 M ha or 20% of the maize area is sown to pre-1995 OPVs, such as Obatanpa in Ghana.

West Africa on the other hand began with almost no adoption of modern varieties, but adoption expanded rapidly in the 1980s accompanied by a dramatic increase in maize area. Varieties provided by IITA (with some having CIMMYT parentage) spearheaded this transformation, including early maturing varieties to allow expansion into the drier Sahel (Section 3). By 2021, half of the maize area in West Africa was sown to CGIAR-related varieties (Krishna *et al.*, 2021).

More recently, social scientists have mounted large studies to assess the adoption and uptake of drought tolerant varieties in Africa, indicating significant adoption in a number of countries (Fisher *et al.*, 2015; Abdoulaye *et al.*, 2018; Krishna *et al.*, 2021). The use of CGIAR-derived varieties and hybrids has sharply accelerated in the last decade in Sub-Saharan Africa where both CIMMYT and IITA have invested substantially to support scaling of seed production and delivery (Section 5). Certified seed of drought or low N tolerant maize varieties was estimated to be 135,000 tons in 2020, or enough to cover 5.5 M ha or about 30% of the maize area in Eastern and Southern Africa (B.M. Prasanna pers. comm.., 2021; Krishna *et al.*, 2021), although seed production may not always translate into sustained adoption.

In a recent meta-review of economic payoffs to CGIAR investments, only three studies covered maize breeding research (Alston *et al.*, 2020). Of these the most comprehensive (and credible) was conducted by Arega Alene and colleagues from IITA who estimated benefits of $100 M per year from 1981-2005 to CGIAR's annual investment of about $10 M at its peak in 1990—or a rate of return on the investment of 43% (Alene *et al.*, 2009). The same study estimated that maize breeding in West Africa had removed 0.75 M people from poverty. Very recently, Krishna *et al.* (2021), based on estimated cultivar adoption in 2015, have calculated aggregate benefits of CGIAR research in Africa to be US$ 0.66-1.05 billion and a benefit cost ratio of 22:1 to CGIAR's global investment in maize research. These estimates allow maize to join the club of nine studies of over $1 billion payoffs in the CGIAR included in Alston *et al.* (2020).

Estimates of adoption of MVs are dependent on data of variable accuracy, especially when the private sector's use of germplasm is being assessed. This and variation in country coverage probably explain the discontinuities in the use of MVs in different time periods in Tables 4 and 5. Nonetheless, the steady rise in use of CGIAR germplasm in Africa, and its rapid acceleration in the 2010s is impressive. The move to hybrids, the mainstreaming of breeding for stress tolerance, and the close partnership with a large number of seed companies have all contributed to this success.

Accelerated varietal turnover plays an important role in realizing genetic gains and protecting against diseases and pests the field. Based on a survey of maize cultivars grown in the 2013/14 crop season in 13 countries across sub-Saharan Africa Abate *et al.* (2017) estimated the area-weighted average age of maize varieties grown by farmers in sub-Saharan Africa as 14.9 years. Recent analysis estimates that the overall area-weighted average age of CGIAR-related improved maize varieties in 2020 was 11.2 years, suggesting some acceleration of varietal turnover (Krishna *et al.*, 2021; B.M. Prasanna, pers. communication, 2021). A more rapid rate of varietal replacement will be needed, however, as climate change accelerates the rate of change in rainfall, pests and diseases.

Finally, there have been dozens of recent household studies in sub-Saharan Africa to estimate impacts of adopting CGIAR related varieties and hybrids on yields and yield variability, as well as incomes and poverty (Krishna *et al.*, 2019). As already mentioned, some of these are linked to specific projects with insufficient data and time to assess impacts. Nonetheless, a careful synthesis of those studies with more complete data would likely identify important local level impacts of CGIAR maize research.

Building National Capacity

Dr. Ernie Sprague, architect of CIMMYT's maize program in the 1970s, argued that CIMMYT produced two products —improved germplasm and trained scientists—and ranked them of equal importance. Accordingly training programs were formally organized and scaled up in the early 1970s as a major component of both CIMMYT's and IITA's maize programs. Trainees worked for several months within the main breeding or production programs, usually in the lowland tropics of Mexico, emphasizing hands-on skills in the field through participation in laying out on-farm trials, selecting germplasm, and evaluating results. By 1982, CIMMYT had trained 650 maize scientists from 61 countries (CIMMYT, 1982). Former trainees became major collaborators in the international testing network as seen in the close correspondence in the regional origins of trainees and the location of trials (Table 6). From the late 1980s, long term in-service training was increasingly decentralized to the regions – Suwan, Thailand for Asia, Sete Lagoas, Brazil for Latin America and Egerton University, Kenya for eastern and southern Africa.

Table 6: Proportion of CIMMYT-sponsored field trials in the early 1980s vs. proportion of trainees attending courses in CIMMYT from 1971-82, by geographical region. Source: CIMMYT, 1982.

	Percent by Region	
	% Trials, 1980-82	**%Trainees, 1971-82**
Mexico, Central America and Caribbean	26	28
South America	16	14
North Africa & Middle East	6	6
South and Southeast Asia	16	25
Sub-Saharan Africa	34	26
Other	2	1
Total %	**100**	**100**
Total Number	665	653

CIMMYT also invested in intensive training in OFR methods, sometimes using several return visits ("calls") by trainees over the season, especially in Africa (Anandajayasekeram, 2000).

As budget pressures mounted in the 1990s training was cut sharply, accounting for only 5% of CIMMYT's operating budget in the mid-2000s (Cooksy and Arellano, 2006). This essentially ended the season-long courses in crop management training. Short in-service and more specialized and decentralized training sessions funded by individual projects became the main vehicle for training. Only 10% of the 44 courses offered from 2000-2004 were longer than a month, mostly conducted at training facilities in Mexico, Brazil, Zimbabwe and Kenya (TAC, 2006). However, in the past decade, support to graduate training has again increased. In 2019 a total of 93 maize scientists at MS and PhD level were being supported by funding channelled through the CGIAR (CAS Secretariat, 2020). IITA also reduced technician training sharply in the 1990s, but maintained sabbatic-type opportunities for national scientists at its own headquarters.

The investment in training by CIMMYT and IITA has yielded mutual benefits. Aside from stronger NARSs and improved quality of international testing, trainees have frequently caught the vision that motivated the founders of the Maize Program – that through improved maize varieties and practices they could make a positive difference in the lives of small-scale farm families and their communities. The feeling of identification with CIMMYT and IITA among trainees resulted in a cadre of scientists who have welcomed close and effective collaboration with both centers. Understandably these changes in orientation, research philosophy and institutional loyalty were partly a function of the length of the courses in which the students participated. Over time, the regional networks initially created through the CGIAR centers have built on this social capital to help develop self-sustaining and governed networks (Section 3).

Is there evidence that improved germplasm, staff consultation, and national and regional training by CIMMYT and IITA staff have strengthened the research capability of NARSs? A formal external assessment of CIMMYT training activities in 2006 based on surveys of former trainees and their employers indicated that training was achieving many of its goals (Cooksy and Arellano, 2006). Trainees brought new approaches, new germplasm and additional research skills to their institutions, resulting in the development of superior stress-tolerant varieties, efficient growing practices and higher quality seed. An evaluation of the Asian Maize Biotechnology Network (AMBIONET) led by CIMMYT, found that it had fostered the use of new biotechnology tools, especially molecular marker applications for maize improvement, with benefits that far exceeded its cost (Pray, 2006).

The strength of NARSs depends on many factors, such as policies, budgets, facilities, staff recruitment and incentives for performance. Many of these are still lagging in Africa, where maize research programs undergo cycles of capacity weakening followed by donor-supported efforts to rebuild capacity (Lynam, 2011). Within the private sector, however, significant progress has been made in management of large numbers of plots, mechanization of research, data collection, research planning and in the management and design of breeding programs. Some of the credit for these changes can be attributed to CGIAR training courses that staff attended, often before being employed in the private sector. We conclude that training has been an excellent long-term investment in human capital and networking that has generally been poorly supported in this millennium.

Revealed Success Stories of Intensification in the 2000s

An alternative approach to assessing impacts, is to review success stories of intensification narrowly measured in terms of maize yields and then look for evidence of the role of CGIAR centers in maize research and development in that country. We have already reviewed the role of CIMMYT and IITA in rapid expansion of maize area and yields in Nigeria, Ghana, and Thailand up to the 1990s. Here we have looked for recent successes since 2000 by identifying countries where maize is grown largely by smallholders and that have achieved maize yields above 2.5 t/ha by 2016-18 with a yield growth rate of at least 2.5 percent annually in the period 2001-18 (Table 7).

Three sets of countries stand out. First, in Eastern and Southern Africa, Ethiopia is the star performer. In what has been described as a 'green revolution" (Rohne Till, 2021), maize yields have grown at 5.3% annually and maize has been converted from a secondary crop to the most important food crop in Ethiopia. One estimate is that research that led to the maize takeoff in Ethiopia lifted 800,000 people out of poverty (Kassie *et al.*, 2018). Facing severe food insecurity and acute land scarcity, Ethiopia

Table 7. Countries with best yield performance for tropical and sub-tropical maize this century. Source: FAOSTAT.

	Maize yield, 2016-18	Yield growth, 2001-18	
	t/ha	%/yr	kg/ha/yr
AFRICA			
Ethiopia	3.57	5.30	135
Mali	2.74	4.80	93
Uganda	2.51	3.16	65
ASIA			
Bangladesh	7.76	4.33	241
Bhutan	3.45	3.44	82
India	2.92	2.94	69
Pakistan	4.68	5.52	176
Sri Lanka	3.71	8.33	185
Cambodia	4.80	3.50	128
Indonesia	5.29	3.85	157
Laos	5.89	5.11	216
Malaysia	6.95	6.48	315
Myanmar	3.80	3.31	100
Philippines	3.03	3.20	78
Viet Nam	4.64	2.60	101
LATIN AMERICA			
Colombia	3.37	2.53	73
Ecuador	3.73	6.91	161
Brazil[a]	5.00	3.39	142
Paraguay[a]	5.28	5.66	200

[a] Countries with mainly larger scale production

began to give high priority to agriculture after the fall of the *Derg* (communist) regime in 1990. Ethiopia also became a focus country of Sasakawa Global 2000 that mounted a massive program of on-farm demonstrations. This program reached about 40 percent of the roughly 10 million farm households in Ethiopia over the period 1993-2003, and emphasized maize. SG2000 showed that the adoption of seed–fertilizer technologies could more than double maize yields, but the collapse of maize markets in 2003 and problems with input supply dominated by the public sector curtailed impacts (Spielman *et al.*, 2010). In the 2000s an Ethiopian Government-led effort based on the release of well-adapted hybrids, improved fertilizer distribution, credit provided through cooperatives, a massive extension program, growing private sector participation in input markets, and better infrastructure, enabled varieties and hybrids to reach two-thirds of maize area along with substantial increases in fertilizer use (Abate *et al.*, 2015; Yirga *et al.*, 2017). Notably, Ethiopia devotes 16% of its public expenditures to agriculture, the highest in Africa. This supports one of the strongest research systems in Africa and a very large public extension program that has been identified as key to the high adoption rates (e.g., Yirga *et al.*, 2017).

Reviews reveal that CIMMYT provided a critical role in Ethiopia's success. A recent analysis based on large-scale DNA-fingerprinting of a national sample of 450 maize fields found that 43% of the fields were planted with varieties containing CIMMYT germplasm, over half of them as hybrids. Notably the most popular hybrid (BH661 released in 2011) was developed from CIMMYT germplasm and is noted for its drought tolerance (Kosmowski *et al.*, 2020). CIMMYT stationed maize breeders in Ethiopia from 1998 who worked closely with the Ethiopian scientists and some 58 Ethiopian scientists received short- or long-term training in Mexico (Zegeye, 2001). CIMMYT also had decades of cooperation and capacity building in on-farm research that may have played a role in improved crop management. Since 2000, much of that work focused on conservation farming, and there is good evidence of adoption of minimum tillage but not of the other pillars of conservation farming—rotation or intercropping with legumes and retention of crop residues as soil cover (Tesfaye *et al.*, 2020). Other studies suggest that in the higher rainfall areas where maize is grown, most of the yield increase was due to improved seed and fertilizer. An IFPRI study demonstrating the benefits of direct marketing of seed through the private sector also contributed to greater private sector involvement, including significant adoption of private sector hybrids (Komowski *et al.*, 2020).

In West Africa, maize intensification has occurred across the Sahelian countries in what has been termed a 'silent revolution' in Mali (Foltz *et al.*, 2016). As in the Nigeria and Ghanaian savannahs described earlier, maize expanded rapidly in the 1980s with the release of suitable early maturing varieties developed by IITA. Initially maize was a rotation crop with cotton, but became an important food crop (Boughton and de Frahan, 1994). Similarly, maize production stalled with structural adjustment that reduced input subsidies to maize, but farmers quickly diverted fertilizer supplied on credit by the parastatal cotton corporation toward maize. Unlike elsewhere in Africa, fertilizer use on maize in Mali continued to rise in the early 2000s, albeit at the expense of cotton yields (Foltz *et al.*, 2016). A new generation of improved OPVs supplied by both IITA and local researchers, and seed production organized through innovation platforms, also contributed to the more than doubling of yields from 2001-2018 (Alene and Mwalughali, 2012; Sanyang *et al.*, 2014). With earlier maturing varieties from IITA maize area has expanded rapidly into the drier savannahs of other Sahelian countries as well.

Finally, maize yields have grown rapidly in most countries in South and Southeast Asia in the 2000s driven largely by the burgeoning demand for animal feed (Erenstein, 2010). The most spectacular example is provided by Bangladesh where maize, although a new crop, is now grown by over one million households in the winter season who produce 3 M t of maize and boast the highest maize yields in the developing world of around 8 t/ha (FAOSTAT, 2020; Mottaleb *et al.*, 2018). Private sector hybrids from neighbouring countries, especially the Thai CP Group, as well as dozens of seed companies from SMEs to multinationals, stimulated this take off (Mondal *et al.*, 2014). More recently maize has been introduced on land that is underutilized in the spring and summer seasons, although with a lower yield potential.

NGOs also played an important role in disseminating the technology. The Bangladesh Rural Advancement Committee (BRAC) has its own breeding program and hybrid seed business while a donor-supported NGO, Katalyst, provided training to farmers, mounted demonstrations and facilitated contract farming to supply feed mills.[20] Farmers too have been innovative in developing a range of new cropping systems that include maize (Ali *et al.*, 2008). CIMMYT and the Bangladesh Agricultural Research Institute (BARI) provided support through 'whole family training' of trainers from the public and private sectors, including both husband and wives, that covered the complete value chain from farm to fork, and reached thousands of farm families. CIMMYT-based hybrids have also been released by the public sector but command a very small share of the seed market to date (Hasan *et al.*, 2007).

The fact that maize in Bangladesh is still mainly grown in the dry winter season under irrigation, free of pests and with an assured market for feed, makes it a very low risk crop. Under these conditions and with appropriate support, even very poor farmers have been able to adopt a full package of practices and achieve extraordinarily high yields. Several other Asian countries in the region have made impressive gains in maize yields sometimes under rainfed conditions. Examples are Myanmar that has emerged as an exporter to China, and Vietnam, Indonesia, India, and Pakistan that supply local feed markets. A variety of formal and informal contract farming arrangements with traders and feed mills have also emerged to supply inputs and assure markets. CIMMYT through IMIC-Asia has provided some of the germplasm to develop locally-adapted hybrids (Section 5).

These examples all point to the role of strong markets, well-adapted varieties and hybrids, and diversified institutional arrangements involving the public, private and NGO sectors, in disseminating the technology and extension advice. The cases reviewed are all 'home grown', although the CGIAR Centers have continued to be important sources of improved germplasm, probably even for private companies that do not disclose the pedigrees of their hybrids. Investment by the Centers in capacity building and OFR have also likely played a role, especially in Ethiopia and Bangladesh.

All of these cases are a continuation of the seed-fertilizer approach to intensification that was the original focus in 1970. They are more sustainable in the sense of being relatively free of subsidies, and show growing private sector participation. However, they face challenges of sustainably managing soil fertility and soil health, given the narrow focus on inorganic fertilizer containing a limited range of plant nutrients. Adoption of a wider set of intensification practices such as CA has been generally low, although it is recognized that such practices will be important going forward (Yirga *et al.*, 2017).

[20] http://katalyst.com.bd/archivephasethree/maize/

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Conclusions

The CGIAR was founded on the three big food staples, rice, wheat and maize. Maize and wheat research at CIMMYT were the legacy of pre-existing program of the US Rockefeller and Ford Foundations, USDA and FAO. However, unlike wheat that was established in 1961 as a well-integrated international research program headquartered in Mexico, maize inherited a fragmented portfolio of relatively independent regional and country projects. International research on maize at CIMMYT therefore required a longer period to organize and reach maturity. Still, CIMMYT through its location in Mexico, its extensive germplasm collection, and its staff with experience in tropical maize improvement had a clear comparative advantage to lead maize research. It was soon joined by IITA that quickly built its own maize program and established a leadership role in West and Central Africa. Overlapping and unclear mandates were sometimes a source of tension between the two centers that was finally resolved through joint donor projects and by the CGIAR reforms of 2011 when the two breeding programs functionally came under one platform and leadership.

Although CIMMYT's Maize Program got off to a slow start, it quickly built a global presence in the 1970s through a system of international testing, germplasm exchange and training of national scientists adapted to maize. International breeding and testing had to be designed to cover the great diversity of maize ecologies and grain types across the tropical and subtropical world. It was a key step in creating awareness and demand but was less effective as a method for realizing breeding gains. There was considerable doubt about the broad adaptability of tropical maize germplasm, although some varieties and landraces from the Americas proved surprisingly well suited to the tropical regions of Africa and Asia. However, mainly due to regionally specific diseases, global maize breeding has been steadily decentralized away from Mexico to other regions, most notably to Africa that is today the major focus of CGIAR maize research. International testing, training and regional activities in turn created strong networks of maize researchers in the tropics and subtropics, globally and regionally that were an outlet for CIMMYT's and IITA's early products, and provided feedback to improve center performance.

Beyond germplasm, CGIAR maize scientists especially in the early years of stable and flexible funding, had significant freedom to explore novel breeding methods. A sustained effort to shorten tropical landraces resulted in more efficient, higher yielding and lodging resistant plants that became the bedrock of improved varieties in the tropics. CIMMYT has also been a global leader in developing methods for breeding for stress tolerance notably to drought, nitrogen deficiency and acid soils - an effort that has been sustained over nearly 50 years. The payoffs are seen today in the recent impressive adoption by smallholders of stress tolerant varieties in sub-Saharan Africa where in 2019 seed of stress-tolerant varieties and hybrids sufficient to plant 5 M ha was produced (Krishna *et al.*, 2021). For IITA the equivalent has been breeding for earliness and for biological stresses— resistance to MSV and tolerance to the Striga parasitic weed, in particular—that have been incorporated into many varieties that are now widely grown in Africa. Fortunately, these high priority activities could successfully transition from long-term core funding to long-term funding through a sequence of large projects in Africa, many of which were jointly executed by the two maize programs. The CGIAR has recently recognized climate-smart maize with tolerance to several stresses as one of its top 50 innovations as it celebrates its 50th birthday.[21]

[21] Drought-tolerant maize project pioneers a winning strategy for a world facing climate change - CGIAR.

There were also significant mis-investments of resources, or at least some priorities were maintained well after the evidence had shown otherwise. The exclusive focus on OPVs for almost two decades was well intended but underestimated the capacity of small-scale farmers and ignored mounting evidence of large-scale adoption of hybrids by smallholders in countries as diverse as El Salvador and Kenya. The large investment in QPM sustained over several decades also yielded disappointing results as it faced changing nutritional guidelines, and failed to address market incentives to produce it and nutritional education to consume it. The weak data management system supporting the maize breeding program and the lack of plot mechanization persisted until recently and reduced the efficiency of the research process.

The CGIAR was building its research capacity and networks at the same time that the private sector, including large multinational companies, were moving into seed markets in the tropics. The private sector quickly "harvested the low hanging fruits"—market-oriented farmers producing maize for feed in areas that were relatively favored in terms of soils, climate and infrastructure. By 2000 these conditions characterized much of Asia and Latin America. Logically, CIMMYT and IITA did not try to compete in these markets, leaving them with the more difficult and poorer areas, and re-enforcing their priority on breeding for stress tolerance for maize growing in more marginal areas and by risk-averse farmers.

After a slow start, the Centers eventually developed effective partnerships with emerging regional seed companies. However, the major focus has been in building SMEs in the seed industry either directly through limited exclusivity licensing agreements or through collective action in the form of research consortia (i.e., the IMICs). Today CIMMYT and IITA seem to have found a happy niche in supplying inbreds to the emerging private seed market made up of a diversity of SMEs and regional seed companies that together with OPVs address areas, farming systems and markets that the MNCs consider unprofitable. The availability of inbreds from the CGIAR also reduced the cost of entry of new companies and has made the seed industry more competitive and more diverse. CIMMYT also developed a number of partnerships with the MNCs to access proprietary tools and technologies, and although these have considerable promise they have had limited impacts to date. More important have been agreements with public advanced research institutes to license intellectual property for humanitarian purposes that have yielded critical new tools such as doubled haploid technology. Yet these public-private partnerships have had a cost in moving CIMMYT away from a purely 'open source' system in the earlier decades to one that is more constrained by intellectual property and access to its products.

CIMMYT and IITA recognized that breeding could only very partially address the challenge of increasing maize productivity of smallholders in less-favoured environments, and accordingly invested strongly in on-farm research to improve crop and soil management. To enhance the international public good element, the Centers emphasized the development and demonstration of appropriate methods and building the capacity of national programs to scale up OFR. Indeed, the Centers became known for their leadership in this area. OFR involved considerable learning and experimentation and the approaches underwent rapid evolution. Starting with the relatively top-down adaptation of the seed-fertilizer technological package, as in the showcase Puebla project, the Centers moved toward engaging farmers in participatory technology design, testing and shared learning. Social scientists for the first time also became full partners, and in many cases led the work. Over time, the technological focus shifted to a growing appreciation of maize within a farming system that included other crops, especially legumes, and livestock.

Although OFR scored some notable successes in terms of feedback of farmer priorities to breeding research and to extension, overall impacts in terms of adoption were modest. The impact pathway for germplasm improvement was clear, via varietal development to varietal release to seed production, marketing, and adoption. The delivery and scaling of the results of OFR, on the other hand was much more complex, required considerable local adaptation depending on existing extension services, input supply, prices and marketing systems, and recently, the availability of information technologies. In short, the adoption of improved growing practices had many more components that depended on many and diverse actors. In the past decade large projects have attempted to reach scale through OFR, although this necessarily required some compromise in employing participatory methods developed earlier. In retrospect too, the technological focus of the maize research centers also resulted in underinvestment in research on policy and institutional innovations required to realize the potential of crop management research. This has been partly redressed by policy research at IFPRI, some of which has tackled policy issues specific to the maize sector, notably in Africa.

Although the most recent assessment of the global impacts of the CGIAR's maize efforts have been limited to sub-Saharan Africa (Krishna *et al.*, 2021) they appear to be significant and now rival the earlier impact history of wheat and rice. It was not always so. Maize faced a harder challenge than wheat in terms of diverse and risky target environments and maize farmers that were generally poorer, and the more so as the private sector took over the more favoured environments. Measured conventionally by the area reached through CGIAR germplasm, maize ranked third among the CGIAR crops after rice and wheat in a global study in 2000, and that ranking is unlikely to have changed (Evenson and Gollin, 2003). What has changed is the sharp rise in the number of farmers reached in Africa where maize research has become the CGIAR's star performer in terms of the area and number of smallholders who benefitted (Walker and Alwang, 2015). IITA led the way in the 1980s in West Africa, and as CIMMYT pivoted to Africa in the 1990s it laid the basis for reaching about half the maize area of Eastern and Southern Africa in the past decade. Indeed, after some false starts, Africa may finally be realizing its "maize revolution" projected some 25 years ago (Byerlee and Eicher, 1997).

Of course, the IARCs were only one link in the maize improvement chain and in the end, the national programs along with the private sector have been the major players. In the first two decades, the Centers invested heavily in developing capacity of national programs through training and technical assistance, although sometimes more in the role of a patron-client relationship. Anecdotal evidence such as in Ethiopia where the government has provided sustained support to agriculture since the 1990s suggest that such training has paid off. Our own experience as well as recent external reviews of maize research suggest that since the 1980s the CGIAR has underinvested in capacity building especially in the multitude of small countries where maize for subsistence remains important. However, other actors, such as the West African Centre for Crop Improvement supported by AGRA, are now contributing many of the graduates in maize breeding to re-staff national public and private breeding programs in the region.

This review of CGIAR maize research over the past 50 years, points to an ongoing role of the CGIAR in maize improvement. Even as the growth of the private sector has narrowed the space for the CGIAR, international research and cooperation continues to be imperative to respond rapidly and in a coordinated fashion to new transboundary diseases and pests, and to new challenges such as climate change. Especially in regions of small countries, it has a proven track record of acting as a neutral broker in mobilizing teams of scientists and resources to address emerging issues. International assets such as the germplasm banks are likely to increase in value as new gene tools facilitate their practical utilization—an area where the CGIAR has a clear comparative advantage as well as a continuing obligation to the global community for sound stewardship. Our history has shown CGIAR research to be at its most effective when financial support has been sustained, since research to develop solutions to new challenges often takes decades.

Our overall story is one of CGIAR maize research programs made up by a relatively small body of motivated and dedicated scientists that, with generally good leadership, strong financial support, and a vision that they could make a positive difference to the lives of smallholder families, were able to "punch well above their weight". Operating in the context of the CGIAR and the development community more generally the CGIAR's maize research programs have undergone profound shifts over 50 years, probably more than for any other CGIAR crop. The type of product, the geographical scope and the partnerships that emerged after 50 years of international maize research are now quite different to those in the first two decades of design and establishment of the program. Financial crises and reforms within the CGIAR were at times disruptive but in the end forced hard decisions on priority traits and regions, notably the pivot that resulted in impressive impacts in Africa.

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