WHEAT•PROGRAM•SPECIAL•REPORT

WPSR No. 5

Guide to Bread Wheat Breeding at CIMMYT

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International Maize and Wheat Improvement Center

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CIMMYT

International Maize and Wheat Improvement Center

CIMMYT® (www.cimmyt.org) is an internationally funded, nonprofit, scientific research and training organization. Headquartered in Mexico, CIMMYT works with agricultural research institutions worldwide to improve the productivity, profitability, and sustainability of maize and wheat systems for poor farmers in developing countries. It is one of 16 food and environmental organizations known as the Future Harvest Centers. Located around the world, the Future Harvest Centers conduct research in partnership with farmers, scientists, and policymakers to help alleviate poverty and increase food security while protecting natural resources. The centers are supported by the Consultative Group on International Agricultural Research (CGIAR) (www.cgiar.org), whose members include nearly 60 countries, private foundations, and regional and international organizations. Financial support for CIMMYT's research agenda also comes from many other sources, including foundations, development banks, and public and private agencies.

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Preface

This special report provides a detailed introduction to the three subprograms of the CIMMYT Wheat Program. First published in the late 1980s, the report has been updated regularly as the bread wheat breeding methodology has evolved. It addresses the breeding of bread wheat in the three subprograms: bread wheat for irrigated and high rainfall conditions, bread wheat for semi-arid and high latitude conditions, and hybrid bread wheat.

The report is designed to help colleagues, trainees, visiting scientists, mid-career fellows, and other interested persons acquaint themselves with the Program's philosophy, objectives, organization, structure, strategies, and specific activities.

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Guide to Bread Wheat Breeding at CIMMYT

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Introduction

The precursor of the present CIMMYT Wheat Program originated in 1944 under the sponsorship of the Rockefeller Foundation and the Office of Special Studies of the Mexican Ministry of Agriculture. In 1966, CIMMYT was established as a non-profit organization responsible to an internationally elected board of trustees. The Ford and Rockefeller Foundations joined Mexico as the initial principal supporters of CIMMYT. Presently CIMMYT has more than 74 individual donor agencies, including public and private foundations, and 33 individual countries, of which 16 are developing nations.

The CIMMYT Wheat Program currently distributes advanced bread wheat lines to more than 60 countries. Primary clients are the national agricultural research systems (NARSs, which include both the public and private sectors) of developing countries. Germplasm distribution and utilization are dependent upon their close cooperation. In our bread wheat breeding activities we have attempted to address the specific problems and limitations associated with wheat production in these countries.

In order to develop effective breeding strategies, various agro-ecological zones or so-called mega-environments (MEs) have been defined. Germplasm developed for a given ME will withstand the major stresses present within that ME, but not always the significant secondary stresses. However, an attempt is made to include genetic diversity for additional traits of importance within the ME. How these products are used and distributed within a ME to address the needs of specific agro-ecological niches is the responsibility of the individual NARSs.

Our primary goal is to develop broadly adapted, high yielding germplasm with high yield stability, durable disease resistance, and acceptable end-use quality within the context of each ME. While soil, temperature, and moisture factors influence crop stability and productivity, resistance to biotic factors (e.g., diseases and insects) and tolerance to abiotic factors (such as drought, heat, nutrient deficiencies, and soil acidity) can be critically important to maintaining high stable yields, and thus contribute significantly to the adaptation of a given variety over time and across locations. Emphasis is also given to the maintenance and expansion of useful genetic diversity within the germplasm targeted to each ME to help counter the potential negative effects of genetic uniformity.

To breed for wide adaptation and high yield potential, the respective breeding programs shuttle segregating material between alternate sites within Mexico, while pyramiding genes that carry durable resistance to the various pathogens. The final products are internationally distributed upon request through CIMMYT's International Screening Nurseries and Yield Trials. International multi-location testing of the International Yield Trials by our cooperators provides vital information for use in crossing and selection activities.

Bread Wheat Breeding Staff

The three bread wheat breeding subprograms at CIMMYT Headquarters (in Mexico) currently have a staff of 23, comprising three international bread wheat breeders, two post-doctoral fellows, 17 support staff, and one secretary. Wheat Program directing staff provide major administrative support. Other non-bread wheat international staff at base and in Outreach also contribute to collaborative activities at base. All staff members who are involved in some way in our activities are listed below. Their country of origin is given in parentheses after their names.

International Bread Wheat Breeding Staff

- Maarten van Ginkel (The Netherlands): Bread wheat breeder with special responsibility for irrigated and high rainfall environments
- Richard Trethowan (Australia): Bread wheat breeder with special responsibility for moisture stressed and high latitude environments
- Karim Ammar (Tunisia): Bread wheat breeder with special responsibility for hybrid wheat (also Head, Triticale Program, as of April, 2002)
- Jiankang Wang (China): Post-doctoral fellow in computer simulation of bread wheat breeding
- Morten Lillemo (Norway): Post-doctoral fellow in breeding bread wheat for irrigated and high rainfall environments

National Support Bread Wheat Breeding Staff

I. Across all bread wheat breeding programs

- Maria Dolores (Lolita) Mir — Secretarial support
- Eduardo Hernández (M.Sc.) — Data analyst and assistant breeder
- Antonino Gutiérrez (M.Sc.) — Coordinator, El Batan spring wheat cycle
- Martín Rodríguez — Computerization of field-books
- José Terrazas — Seed storage, management of introductions

II. Irrigated, and High Rainfall Spring Wheat Environments

- Ramón Gil — Coordinator, Toluca spring wheat cycle
- Jorge Montoya (Ing.) — Coordinator, Cd. Obregon spring wheat cycle

• Armando Miranda (Ing.)	Hand-planting and data collection
• José Luis Coss	Field crossing, machine harvest, and Mexicali
• Leopoldo (Polo) Salazar	Field-book management, and crossing logistics

III. Semi-arid and High Latitude Spring Wheat Environments

• José Borja (Ing.)	Coordinator, Cd. Obregon and Toluca spring wheat cycles
• Salvador (Chava) Madrigal	All activities
• Alfredo Valencia	All activities

IV. Facultative and Winter Wheat Environments

• Mario Albarrán (Ing.)	Coordinator, Toluca winter wheat cycle
• Reyes Colín	All activities
• Valentín Ramírez	All activities

V. Hybrid Spring Wheat

• Gilberto Rodríguez (M.Sc.)	Coordinator, Cd. Obregon and El Batan cycles
• José Luis (Cinco) Jiménez	All activities

Supporting and Collaborating Staff

Director's Office

• S. Rajaram (India)	Wheat Program Director
• Tom Payne (USA)	Assistant Director
• Efrén del Toro (Mexico)	Administrative manager
• Arnoldo Amaya (Mexico)	Visitors coordination (consultant)

Agronomy

• Iván Ortiz-Monasterio (Mexico)	Nutrient efficiency
• Ken Sayre (USA)	Agronomic aspects of genotype by management interaction

Applied Biotechnology Center

• Alessandro Pellegrineschi (Italy)	Transformation
• Marilyn Warburton (USA)	Genetic diversity and fingerprinting
• Manilal William (Sri Lanka)	Molecular markers

Biometrics and Statistics

• José Crossa (Uruguay)	Biometrics and statistics

Crop breeding

• Karim Ammar (Tunisia)	Hybrid Wheat (Triticale, April, 2002)
• Flavio Capettini (Uruguay)	Barley
• Wolfgang Pfeiffer (Germany)	Durum Wheat

Genetic Resources

• A. Mujeeb-Kazi (USA)	Wide crosses and development of primary synthetic wheats
• Bent Skovmand (Denmark)	Germplasm bank

Industrial Quality

• Javier Peña (México)	Industrial quality

Information Services

• Alma McNab (Honduras)	Editing and publishing

International Staff in Outreach

• Osman Abdalla (Sudan)	Breeder, Semi-arid Wheat, Aleppo, Syria
• Hans Braun (Germany)	Breeder, Winter/Facultative Wheat, Ankara, Turkey
• Etienne Duveiller (Belgium)	Pathologist, Katmandu, Nepal
• Arne Hede (Denmark)	Breeder, Ankara, Turkey (April, 2002)
• Peter Hobbs (USA)	Agronomist, Katmandu, Nepal (NRG)
• Man Mohan Kohli (India)	Breeder, Montevideo, Uruguay
• Craig Meisner (USA)	Agronomist, Dhaka, Bangladesh (NRG)
• Alexei Morgounov (Russia)	Breeder, Winter/Facultative Wheat, Almaty, Kazakhstan
• Julie Nicol (Australia)	Pathologist on root diseases (fungal & nematodes), Ankara, Turkey
• Guillermo Ortiz Ferrara (Mexico)	Breeder, Katmandu, Nepal
• Douglas Tanner (Canada)	Agronomist, Addis Ababa, Ethiopia
• He Zhonghu (China)	Breeder, Beijing, China

Information Technology

• Ed Brandon (Canada)	Information technology
• Carlos López (Mexico)	Software development

International Wheat Improvement Network

• Tom Payne (USA)	International Wheat Improvement Network

Natural Resources Group

• Jeff White (USA)	GIS

Pathology

• Guillermo Fuentes Dávila (Mexico)	Bunts and smuts
• Lucy Gilchrist (Chile)	Fusarium head blight, *Septoria tritici*
• Monique Henry (France)	BYDV and insects
• Julio Huerta (Mexico; INIFAP adjunct scientist)	Rusts
• Monica Mezzalama (Italy)	Seed Health Unit
• Ravi Singh (India)	Rusts

Physiology

• Matthew Reynolds (UK)	Physiology

Station Management

• Fernando Delgado	Station manager, Toluca
• Francisco Magallanes	Station manager, El Batan
• Rodrigo Rascón	Station manager, Cd. Obregon

Wheat Improvement Training

• Reynaldo Villareal (Philippines)	Training

Recognition is extended to associated NARSs and advanced research institutes (ARIs) for their cooperation.

Objectives within Each Mega-Environment

The total bread wheat growing area in the developing world is about 120 million ha. In order to address the germplasm needs of such a wide and diverse area it has been divided into 12 distinct mega-environments (MEs). ME delineation is based on water availability, soil type, temperature regime, production system, and associated biotic and abiotic stresses. Consumer preferences for grain color, and industrial or end-use quality are also considered. Such classification allows focusing on just those constraints and on requirements that are specific and of high priority within each mega-environment.

Six MEs define the environments for the production of spring wheats, three define the facultative wheat environments, and three the true winter wheat environments. These are described below.

Spring Wheat

ME1: Irrigated, low rainfall environment

ME1 represents the optimally irrigated, low rainfall areas of the world. The climate during the wheat growing period ranges from temperate to conditions of late heat stress. Representative temperate areas include the Gangetic Valley (India), the Indus Valley (Pakistan), the Nile Valley (Egypt), parts of Zimbabwe, irrigated river valleys in parts of China (e.g. Chengdu), and the Yaqui Valley (Sonora, Mexico). Kano (Nigeria) and Wad Medani (Sudan) are typical irrigated and hot locations. This ME encompasses about 36 million hectares spread primarily over Asia and Africa between 35°S - 35°N latitudes.

Breeding objectives include high yield potential, stable yield, semidwarf stature, input responsiveness, lodging tolerance, improved industrial- and end-use quality (medium and high quality), and durable resistance to the three rusts (leaf rust (LR), stripe rust (YR), and stem rust (SR)). Certain areas require resistance to Karnal bunt (KB), powdery mildew (PM), and fusarium head blight (FHB). Most areas require photoperiod insensitivity, but with a wide range of flowering dates. Some tolerance to late heat is also needed for certain locations. Greater emphasis will be given to tolerance to saline soils. White (amber)-grained types predominate in the vast majority of areas.

ME2: High rainfall environment

ME2 is defined as those areas with average rainfall in excess of 500 mm during the cropping cycle. Representative areas are located in the West Asia and North Africa (WANA) Region, the Southern Cone and Andean Highlands of South America, the central highlands of Ethiopia (e.g. Kulumsa), the Mediterranean coastal plains of Turkey (e.g. Izmir), and the highlands of central Mexico (e.g. Toluca). Total area exceeds 8 million hectares.

YR, LR, *Septoria tritici* (ST), and pre-harvest sprouting are major production constraints. FHB is becoming more widespread and is a serious problem in many areas. Resistance to barley yellow dwarf virus (BYDV), bacteria, PM, and the root rots (RR) must also be considered in certain regions of ME2. Tolerance to lodging, shattering, and soil micronutrient imbalances are becoming more important. For high yield potential, semidwarf stature is essential. Photoperiod insensitivity is preferred but with a wide range of flowering dates. Red-grained wheat provides better sprouting tolerance than white-grained wheat, and is therefore generally preferred, with the exception of a few areas (e.g. Ethiopia). Demands for better industrial quality are increasing, and emphasis is given to the development of germplasm with high quality.

ME3: High rainfall, acid soil environment

Areas affected by low pH are mostly located in Brazil, the highlands of central Africa, and the Himalayas; the total estimated area is close to 2 million hectares. Disease and stress problems are similar to ME2. However, aluminum and manganese toxicities, plus phosphorus deficiency, are major constraints to production. Red grain is generally preferred, except in the Himalayas. High-level quality is demanded, especially in Latin America.

ME4: Semi-arid, drought environment
Three distinct types of drought have been identified based on the stage of plant development at which drought is most severe. These are:

- ME4A: Winter rain or Mediterranean-type drought associated with post-flowering moisture and heat stress typical of the West Asia and North Africa (WANA) region. Representative locations include Aleppo (Syria) and Settat (Morocco). Total estimated area: 6 million ha. YR, LR, SR, ST, RR, nematodes (NEM), and bunts are the key biotic constraints. Also late frosts may occur. Photoperiod insensitivity is preferred but with a wide range in flowering dates. White-grained wheat is preferred with good quality.
- ME4B: Winter drought or Southern Cone-type rainfall associated with pre-flowering moisture stress. Marcos Juarez (Argentina) is a representative location. Total estimated area: 3 million ha. Resistances to LR, YR, SR, and *Septoria* spp., *Fusarium* spp. and sometimes *Pyrenophora tritici-repentis* (tan spot (TS)) are requirements. Pre-harvest sprouting is also a common problem, due to the late rains; hence red seeded varieties are preferred. Photoperiod insensitivity is preferred but with a wide range in flowering dates. Good bread-making quality is demanded.
- ME4C: Stored moisture after monsoon rains results in continuous or Subcontinent-type drought under receding moisture conditions. A representative location is Dharwar (India). Total estimated area: 2-3 million ha, and probably decreasing, as irrigation facilities spread and/or other crop options are explored. LR occurs occasionally. Photoperiod insensitivity is preferred but with a wide range in flowering dates. Seed must be large, bold and amber in color to fetch a premium in the market place. Medium dough strength is required.

CIMMYT's breeding approach attempts to combine high yield potential with drought resistance for ME4. However, more specifically adapted germplasm with tolerance to early heat and a longer coleoptile is needed for ME4C. Breeding research for ME4A is carried out both at base in Mexico and by the CIMMYT Outreach breeder, Osman Abdalla, based at ICARDA, Aleppo, Syria. The base program provides the new and critical variability to the WANA region and the ICARDA based breeder recombines and screens the materials for local and regional adaptation. The combination of water-use efficiency and water responsive traits plus yield potential is important in drought environments where rainfall is frequently erratic across years. When rains are significantly above average in certain years, the crop must respond appropriately (water responsive) with higher yields, while expressing resistance to the wider suite of diseases that appear under more favorable conditions.

ME5: Warm humid tropical environment
These areas are generally located at low altitude (< 1000 m), with a mean minimum temperature during the coolest month greater than 17^{0}C. As a result relative humidity tends to be high. Representative locations are Pusa (Bihar, India), Jessore (Bangladesh), Chiangmai (Thailand), and Encarnacion (Paraguay). The estimated area is about 9 million hectares. In these warm, humid locations, resistance to helminthosporium leaf blight (HLB; caused by *Bipolaris sorokiniana*), and LR, plus tolerance to sprouting are major objectives. Photoperiod insensitivity is preferred with an emphasis on medium to early maturity. Quality demands vary from rather moderate to high.

ME6: High latitude environment
The higher latitude (> 45^{0}N or 45^{0}S) requires materials that have a degree of photoperiod sensitivity, which is different to other spring MEs. Wheat is spring-sown in this ME, as winters are too severe for survival.

Harbin (Heilongjiang, China) is a representative location, with pre-anthesis drought followed by rainfall during flowering and grainfilling. Resistance to *Fusarium* spp., TS, YR, LR, SR, and tolerance to sprouting are breeding objectives in this environment.

However, very dry representative ME6 locations also occur in central and northern Kazakhstan (10 million ha) and the southern Siberian wheat belt (8 million ha). The major diseases are LR and RR. In addition, drought tolerance specific to the rainfall pattern in the region is needed. Taller wheats generally do better under these conditions.

The total estimated ME6 area in developing countries is 20 million hectares. Wheats with high protein and strong dough are required.

Facultative Wheat

ME7: Irrigated, moderately cold environment
In these irrigated regions temperatures vary from 0^{0}C to 5^{0}C. Yield potential and disease resistance are the main breeding objectives.

- ME7A: Fully irrigated. The major diseases are YR, LR and PM. A representative location is Zhenzhou, Henan (China).
- ME7B: Supplementary irrigation. Representative countries are certain regions in Turkey, and Iran with YR, and bunt as the major diseases; and in the Central Asian Republics with LR, common bunts, YR and loose smut (LS; caused by *Ustilago tritici*) as the main diseases.

ME8: High rainfall, moderately cold environment
Rainfall on average exceeds 600 mm per crop cycle, with temperatures varying between 0^{0}C and 5^{0}C.

- ME8A: Photoperiod-sensitive varieties are cultivated. The major diseases are YR, LR, *Septoria* spp., PM, *Fusarium* spp. and RR. A representative location is Temuco (Chile).
- ME8B: Photoperiod-insensitive varieties are cultivated. Representative regions are the transitional spring/winter wheat zones in Turkey with YR and common bunt the major diseases, and Thrace (Turkey) with LR, RR, PM and common bunts as the main diseases. Other representative areas include certain regions in the Central Asian Republics where YR, LR, RR, PM and common bunt are the main diseases.

ME9: Semi-arid, moderately cold environment
Rainfall is moderate to low (<400 mm), and temperatures are in the range of 0^{0}C to 5^{0}C. Drought tolerance is required.

- ME9A: Heat stress at grainfilling. Mainly non-semidwarf varieties cultivated. Areas in West Asia and North Africa are representative with YR, common bunt and LR the major diseases. Other areas include the Central Asian Republics where YR, common bunt and LR are the main diseases.
- ME9B: Mainly semidwarf varieties cultivated. The major disease is LR. Representative locations are certain regions in China.
- ME9C: Less cold tolerance required than in 9A and 9B. Mainly semidwarf varieties cultivated. Areas in South America and South Africa are representative with LR and Russian wheat aphid (RWA) (in South Africa) the major biotic stresses.

Winter Wheat

ME10: Irrigated, severely cold environment
These irrigated areas experience very cold conditions with temperatures dropping to between 0^{0}C and -10^{0}C. High yield potential and disease resistance are requirements.

- ME10A: Fully irrigated. The major diseases are YR, LR, PM and BYDV. A representative location is Beijing (China).
- ME10B: Supplementary irrigation. Specific locations in Turkey, and Iran are representative where YR, common bunt, RR and NEM are the major diseases. Areas in W- and NW-Iran (YR and common bunt predominant) and in the Central Asian Republics (LR, common bunt, LS and PM are key diseases) are also representative.

ME11: High rainfall, severely cold environment
Rainfall on average in excess of 600 mm is common, while temperatures are low, between 0^{0}C and -10^{0}C.

- ME11A: Photoperiod-sensitive varieties cultivated. The major diseases are YR, LR, PM, *Septoria* spp., *Fusarium* spp., BYD and RR. No representative locations occur among the

developing countries. However, other example locations are Martonvasar (Hungary), Krasnodar (Russia) and Odessa (Ukraine).
- ME11B: Photoperiod-insensitive varieties cultivated. The major diseases are LR, *Fusarium* spp., *Septoria* spp., RR, BYD, and YR. A representative country is North Korea.

ME12: Semi-arid, severely cold environment
Conditions are harsh, with little rainfall (300-450 mm); temperatures vary from 0^0C to -10^0C. Drought tolerance is needed.
- ME12A: Heat stress at grainfilling. Mainly non-semidwarf varieties are cultivated in certain representative regions in Turkey, Iran, and Afghanistan. In these areas YR, common bunt, RR, NEM, and zinc deficiency are the major biotic and abiotic stresses. In the Central Asian Republics YR, common bunt, and LR are the main diseases. In representative areas of China, semidwarf varieties predominate, with YR and PM the key diseases.
- ME12B: Medium heat stress at grainfilling. Mainly non-semidwarf varieties are cultivated in certain representative regions in Turkey, and Iran with YR and common bunt the major diseases. In representative regions of China semidwarf varieties are generally cultivated, and YR and common bunt are the main diseases.

Nomenclature of Breeding Materials

Coding
All breeding materials, whether fixed lines or segregating populations, are assigned a standardized alphanumeric code of up to 12 characters that aims to uniquely identify the genetic material and indicates the flow of the germplasm through the breeding generations.

Nursery/Generation
The first two or three alphanumeric characters indicate the nursery type (e.g. parental breeding stock, segregating generation, fixed line or yield trial). The three characters may also designate the country from which the germplasm was received. Some examples are given below. The remaining cases are discussed in the subsequent text.
- CB: Crossing Block coded by ME with popular parents for crossing
- ON: Observation Nursery with potential parents for crossing
- F1, F2, F3, F4, F5, F6, F7, F8: Filial breeding generation
- F1T: F1 Top Cross (= three-way cross), which will segregate
- AL: Advanced Lines with high level of homozygosity, generally bulked following the F7 or F8
- PC: Small plot (*Parcela Chica* in Spanish) of advanced lines, that have subsequently been entered into first-time preliminary yield trials (PYT), and are

grown at the same time as the PYT in an artificially inoculated high disease pressure area
- EAL: Elite Advanced Lines that have been promoted following superior performance in the PYT
- EPC: An Elite PC of elite advanced lines that, following acceptable performance in the PYTs and EALs, have now been entered into second-year yield trials (YT), and are grown at the same time as the YT in an artificially inoculated high disease pressure area
- HS: Head (spike) selections made from (elite) advanced lines that showed promise but still expressed some heterogeneity
- IND: Material from India
- CHK: Checks
- M: Multiplication

Sometimes "S" and "W" are added to distinguish spring and winter wheat nurseries that are not intended for any specific ME but are probably relevant across several MEs.

Mega-environment or researcher
The second group of three or four characters (two letters and one or two numbers) in the internal coding system defines the intended target mega-environment: ME1, ME2, etc. The second group of spaces may also identify a specific CIMMYT researcher, student or visiting scientist involved in research with CIMMYT:

- AH: Arturo Hernández (ICAMEX, Toluca, Mexico)
- BS: Bent Skovmand
- ED: Etienne Duveiller
- EVM: Eduardo Villaseñor Mir (INIFAP, Chapingo, Mexico)
- GOF: Guillermo Ortiz Ferrara
- GS: Given Sikasote (student, Zambia)
- HJ: Hwang Jong Jin (visiting scientist, South Korea)
- IOM: Iván Ortiz-Monasterio
- JLC: José Luis Coss
- JM: Jorge Montoya
- JN: Julie Nicol
- JP: Javier Pena
- LG: Lucy Gilchrist
- MG: Maarten van Ginkel
- MH: Monique Henry
- MK: Mujeeb Kazi
- ML: Morten Lillemo
- MMK: M. Mohan Kohli
- MR: Matthew Reynolds
- MW: Manilal William
- RG: Ramón Gil

- RPL: Roberto Pargas Lara (UABCS, La Paz, Baja California Sur, Mexico)
- RS: Ravi Singh
- RV: Rey Villareal
- URBINA: Ricardo Urbina (private breeder, Mexico)
- WP: Wolfgang Pfeiffer
- ZZ: Zhangyong Zhy (student, China)

Classifiers

The last few spaces in the coding system provide a "classifier" code, which more specifically identifies the breeding aim within a ME. Some classifiers describe the specific biotic or abiotic stress being addressed, highlight the objective of the breeding effort, or identify the specific methodology used. The major ones are listed below:

- BR: Breeder selected
- BS: *Bipolaris sorokiniana*
- BYD: Barley yellow dwarf virus (BYDV)
- CCN: Cereal cyst nematode
- DD: Double dwarf
- DH: Doubled haploid
- DN: Russian wheat aphid (*Diuraphis noxia*)
- DOR: Dormancy
- DW: BW x DW cross
- ERFL: Erect vs. floppy flagleaf
- FE: Iron
- FG: *Fusarium graminearum*
- FN: Falling number
- GLI: Gliadins
- GLU: Glutenins
- G/SCA: General and specific combining ability
- HLB: *Helminthosporium* leaf blight
- HS: *Helminthosporium sativum* (= *Bipolaris sorokiniana*)
- HW: Hybrid wheat
- I: Individual plant or spike selection
- INT: Internationally outstanding
- IQ: Industrial quality
- KB: Karnal bunt
- LDG: Lodging
- LMW: Low molecular weight glutenins
- LR: Leaf rust
- MN: Micro-nutrient
- MOVAR: Multiple ovaries
- NEM: Nematode
- NU: Nitrogen utilization

- P: Purified or "head-rowed"
- PH: Physiology
- PM: Powdery mildew
- PP: Participatory plant-breeding
- PR: Porometer selected
- PU: Phosphorus utilization
- PUB: Pubescent
- Q: Quality
- R: Reserve
- REF: Reference
- RES: Resistant
- RLN: Root lesion nematode
- RR: Root rots
- SC: Scab (*Fusarium* spp.)
- SL: Salinity
- SPR: Sprouting
- SQ: Soft industrial quality
- SS: Special study
- ST: *Septoria tritici*
- STD: Standard
- SW: Spring x winter wheat cross
- SY: Synthetic wheat
- SYDER: Synthetic wheat derivatives (crossed once or more to common bread wheat)
- TC: Tissue culture
- TCL: BW x triticale cross
- THLF: Thick leaf
- TI: *Thinopyrum intermedium*
- TOL: Tolerant
- TS: Tan spot
- TWT: Test weight
- V (VAR): Variety
- WC: Weed competition
- WF: Winter/facultative
- WG: White (amber) grain
- WL: Waterlogging
- WS: Winter x spring wheat cross
- WX: Wide cross
- X: Excellent
- YC: Yield components
- YD: BYDV
- YLD: Yield
- YP: Yield potential

- YR: Yellow (stripe) rust
- ZN: Zinc
- 00: 2000
- 01: 2001

Some segregating populations or nurseries may have been developed using a shuttle breeding approach with a specific location or relevant NARS, and have been assembled to represent traits for a special target area. These, therefore, have been assigned a unique classifier code identifying the specific country, region or collaborating organization:

- BRA: Brazil/CIMMYT
- CH: Chengdu (China)/CIMMYT
- CRC: Australia CRC/CIMMYT
- ECU: Ecuador/CIMMYT
- FONT: Fontagro (Argentina)
- NX: Ningxia (China)/CIMMYT
- OCW: Oklahoma (USA)/CIMMYT Winter Wheat
- PA: Paraguay/CIMMYT
- PR: Poza Rica, Mexico
- PZ: Patzcuaro, Mexico
- SJ: Sierra de Jalisco (El Tigre), Mexico
- XI: Xinjiang (China)/CIMMYT
- YZ: Yangtze Valley (China)/CIMMYT

When the germplasm group does not address a specific problem but targets the entire respective ME, the default classifiers for each ME are used: IR, HT, HR, AS, SA, TE, and HL. See Table 1.

Table 1. Mega-environment abbreviations, designations, default classifiers, and names of International Screening Nurseries and Yield Trials (abbreviated) that are distributed from the CIMMYT bread wheat breeding programs, including those collaborative CIMMYT bread wheat breeding programs based in Turkey, Nepal, and Uruguay.

Mega-environment	Default classifier	International Screening Nurseries/ Yield Trials[1]
Spring wheat:		
ME1: Irrigated	IR	ESWYT, IBWSN, LACOS
Heat	HT	HTWYT
ME2: High Rainfall	HR	HRWYT, HRWSN, LACOS
ME3: Acid Soil	AS	ASWSN, LACOS
ME4: Semi-Arid (A, B, C)	SA	SAWYT, SAWSN, LACOS
ME5: Tropical Environment	TE	EGPYT, EGPSN, LACOS
ME6: High Latitude	HL	HLWSN, LACOS
Facultative wheat:		
ME7: Irrigated	IR	EYT-IRR, WON-IRR, FEFWSN, TIFCOS
ME8: High Rainfall	HR	WWEERYT, FEFWSN, TIFCOS
ME9: Semi-Arid	SA	EYT-SA, WON-SA, TIFCOS
Winter wheat:		
ME10: Irrigated	IR	EYT-IRR, WON-IRR, FEFWSN, TIFCOS
ME11: High Rainfall	HR	WWEERYT, FEFWSN, TIFCOS
ME12: Semi-Arid	SA	EYT-SA, WON-SA, TIFCOS

[1] For detailed explanation of nursery abbreviations see section "International Screening Nurseries and Yield Trials".

Examples of full nursery names

Table 2 lists examples for all six spring wheat MEs and for most common breeding generations, illustrating the alphanumeric coding system.

Table 2. Examples of coded nursery names by generation and mega-environment.

Mega-environment	ME1	ME2	ME3	ME4	ME5	ME6
Crossing blocks	CBSME1IR	CBSME2HR	CBSME3AS	CBSME4SA	CBSME5TE	CBSME6HL
Segregating populations	F1ME1IR	F1ME2HR	F1ME3AS	F1ME4SA	F1ME5TE	F1ME6HL
	F1TME1HT	F1TME2ECU	F1TME3BRA	F1TME4DW	F1TME5HLB	F1TME6KAZ
	F2ME1CH	F2MMKHR	F2ME3PU	F2ME4CRC	F2MKTE	F2ME6NEM
	F3ME1KB	F3ME2ST	F3ME3SPR	F3ME4FONT	F3ME5DD	F3ME6RR
	F4ME1WG	F4ME2YD	F4ME3ZAM	F4ME4RLN	F4ME5LDG	
	F5ME1IQ	F5ME2URY	F5ME3PZ	F5ME4BS		
	F6ME1SL	F6ME2SC	F6ME3PM			
	F7ME1WX	F7LGHR				
	F8ME1DH					
Advanced lines	ALJPIR	ALME2FN	ALME3TS	ALME4MN	ALME5NPL	ALME6CCN
Preliminary yield trials	PYTME1SW	PYTME2YZ	PYTME3WL	PYTME4DN	PYTGOFTE	
	PCME1NU	PCME2WC	PCME3TI			
Elite advanced lines	EALME1SQ	EALME2SY				
Yield trials	YTME1YC					
	EPCME1PH					

Pedigree Format

A standardized pedigree recording system is used for crosses. The female (stigma/ovary) parent is designated by listing it first (starting from the left) followed by the male (anther/pollen) parent (following on the right) separated by a slash (/). Thus, A is the female parent and B the male parent in the cross A/B. If this F1 (A/B) is pollinated with parent C, then the F1 is used as the female and C as the male, resulting in a cross which would be designated as A/B//C. Subsequent crosses with parental materials D, E, F, and G used sequentially as males are indicated using a number recording the cross order in the following fashion:

A/B//C/3/D/4/E/5/F/6/G

If, however, subsequent parents (D, E, F, and G) are crossed alternately as female and then as male, rather than always as a male as in the first example, the cross would be denoted as follows:

F/5/D/3/A/B//C/4/E/6/G

If the final cross is a top-cross, this is indicated at the end of the breeders' cross ID, with a "T". For details see section below on "Selection History Codes" and also Table 3.

Backcrosses are designated with an asterisk (*) and a number indicating the dosage of the recurrent parent. The asterisk and the number are placed next to the crossing symbol that divides the recurrent and donor parents. The following are examples of pedigree formats involving backcrosses:

- A is the recurrent parent: A*2/B
- B is the recurrent parent: A/3*B
- A/B is the recurrent parent: A/B*4//C/D
- C/D is the recurrent parent: A/B//5*C/D

Whether the recurrent parent is used as a male or female is indicated at the end of the breeders' cross ID, with respectively an "M" or an "F". For details see section below on Selection History Codes and also Table 3.

Selection History Codes

Every F1, segregating line or advanced line in the program is assigned a so-called breeders' cross ID (BCID) and a selection history. These codes record the process of selection, which describes where and how the initial cross was made and where and how subsequent selection took place for each generation of selection.

Each BCID begins with a letter designation of the cross origin (e.g. CM = cruza mexicana; Spanish for "Mexican cross"). This is followed by an indication of the kind of cross (e.g. SS = spring x spring wheat; SW = spring x winter wheat), the abbreviation of the year when the cross was made (e.g. 00 = 2000), and of the location (e.g. Y = Yaqui Valley) and finally a sequential number representing the order in which that cross was made within the crossing cycle (e.g. 01001).

After this BCID, there follows the selection history: the numbers identify the individual plant(s) selected and the letter indicates the location where selection took place and/or under what specific conditions selection was conducted.

The zero-letter combinations (e.g. 0Y, 0M, etc.) are reserved for populations harvested in bulk in that generation, meaning that the entire plot was cut and threshed as one unit. A zero followed by a number and then by a letter (e.g. 010M, 030Y) indicates a procedure during the so-called "modified pedigree/bulk" selection method or the "selected bulk" selection method, in which a certain number (in the examples: 10 or 30) selected spikes are bulk- (0) harvested.

The location where the selection was made and, in some cases, the special type of selection performed, is indicated by a letter code. The following letter codes indicate the Mexican locations where CIMMYT breeders carry out selection (maximum code length is five spaces):

- B: El Batan
- TSB: El Batan, tan spot
- YDB: El Batan, BYDV
- M: Toluca ("M" stands for the State of Mexico)
- SCM: Toluca, scab
- Y: Cd. Obregon, full irrigation ("Y" stands for Yaqui)
- LNY: Cd. Obregon, low nitrogen
- LPY: Cd. Obregon, low phosphorus
- HY: Cd. Obregon, heat (heat, late planting)
- KBY: Cd. Obregon, Karnal bunt
- SY: Cd. Obregon, semi-arid (reduced irrigation)
- PR: Poza Rica
- PZ: Patzcuaro
- SJ: Sierra de Jalisco (El Tigre)
- AL: Selection for tolerance to low pH and aluminum toxicity in laboratory test (El Batan)

Selection history location codes for other countries have been determined by the cooperators in those countries.

For more detailed information regarding crosses, selection histories, and pedigree abbreviations, see the following CIMMYT publications:

1. B. Skovmand, R. Villareal, M. van Ginkel, S. Rajaram, and G. Ortiz-Ferrara. 1997. *Semidwarf Bread Wheats: Names, Parentage, Pedigrees, and Origins.* Includes diskette.
2. M.M. Kohli and B. Skovmand. 1997. *Wheat Varieties of South America: Names, Parentage, Pedigrees, and Origins.* Includes diskette.

Examples of actual BCIDs and selection histories are presented below:

Table 3. Six fully detailed examples of BCIDs and selection histories for three simple crosses, a top-cross, and a back-cross, respectively, selected according to the "pedigree" method, the "modified pedigree/bulk" method, and the "selected bulk" method.

Type of cross	Breeder's cross ID (BCID)	Selection history (by generation)							
		F1 (Top)	F2	F3	F4	F5	F6	F7	F8
A/B[1]	CM112233	—	35Y	15M	7Y	5M	12Y	0M	
A/B[2]	CMBW91Y0999	—	81Y	010M	010Y	010M	10Y	0M	
A/B[3]	CMSS92Y1001	—	030Y	030M	030Y	030M	53Y	0M	
A/B[3]	CMSS92Y1001	—	030Y	030M	030Y	030M	45Y	3M	0Y
A/B//C[2]	CMSS00Y2222T	050M	25Y	010M	010Y	010M	8Y	0M	
A/*2B[3]	CMSW01Y4000M	050M	030Y	030M	030Y	030M	78Y	2M	0Y

[1] = Pedigree selection method.
[2] = Modified pedigree/bulk selection method (see section below on "Breeding Methods and Germplasm Flow").
[3] = Selected bulk selection method (see section below on "Breeding Methods and Germplasm Flow").

Description of Major Breeding and Screening Locations in Mexico

Spring Wheat Winter Cycle

Ciudad Obregon (letter code "Y")

Cd. Obregon is located in northwestern Mexico in the State of Sonora at 27.5°N, 40 masl. From CIMMYT Headquarters in El Batan it takes 2-3 hours by plane or about 18 hours by car to reach Cd. Obregon. This region is located in the Arizona-Sonora desert as characterized by the Saguaro cactus. The experimental land is loaned to CIMMYT under agreement, and is not CIMMYT property. Mean rainfall during the crop cycle is about 48 mm. It is a dry, irrigated, low-altitude site. Yields are high, in the order of 8-11 t/ha in experimental plots and 5-8 t/ha in farmers' fields.

This is one of the two most important breeding and screening sites for CIMMYT. It represents ME1 when optimally irrigated and managed. Providing less water creates testing conditions for performance under reduced irrigation. Drastically reducing irrigation simulates aspects of ME4. Planting late allows ME1 and ME5 materials to be tested for heat tolerance. The use of supplementary lighting in the evening allows extension of day length similar to that in such high latitude locations as northern Kazakhstan, thereby allowing simulation of aspects of ME6.

Approximately 50, 20 and 10 ha are planted annually to breeding materials targeted to the respective MEs for irrigated and high rainfall environments, moisture stressed environments, and for hybrid wheat. Breeding nurseries are sown during the latter half of November until early December, and harvested from mid April to early May. Late plantings to expose materials to heat conditions during grainfilling are sown in January and February, and harvested in May and June. Yield trials for ME1, ME4 and ME5 are planted here.

Artificial inoculation of LR and SR by spray application of liquid spore suspensions to susceptible border-mixtures (including 6-10 highly susceptible genotypes representing a range in defeated major genes for resistance, maturity and height) ensures adequate final infection of the entire targeted fields. The race composition of the inoculum is updated regularly to include newly detected races as well as most virulent ones, under the responsibility of Ravi Singh. Rust inoculation is carried out in the latter part of January.

Genotypes targeted for environments experiencing KB are inoculated with a liquid spore suspension in the boot stage and subjected to thrice daily overhead watering with a sprinkler system during flowering to optimize conditions for infection and disease spread, under the responsibility of Guillermo Fuentes. LS and bacterial blight may occur either naturally or be artificially inoculated.

Spring Wheat Summer Cycle

Toluca (letter code "MV", for Mexico verano (*verano* is "summer" in Spanish))
The experiment station near Toluca, Atizapan, is located at 19^{o}N, 2640 masl, west of Mexico City in the State of Mexico. From CIMMYT Headquarters in El Batan it takes 1.5-2.0 hours by car to reach the Toluca site. Some of the land used is CIMMYT property; the rest is given in loan by agricultural research authorities of the State of Mexico or rented from private farmers. Mean rainfall during the crop cycle is about 800 mm. It is a temperate, high rainfall, high altitude site characterized by extremely high disease pressure. Yield may approach 9-10 t/ha in experimental plots and 3-5 t/ha in commercial fields.

Toluca is the second most important breeding location for CIMMYT. Although little commercial wheat is grown in the immediate surroundings, the location represents ME2 conditions very well.

About 25 ha and 10 ha are planted annually to breeding materials targeted to the respective MEs for irrigated and high rainfall environments, and moisture stressed environments. Breeding nurseries are sown from the first part of May until early June, and harvested in late October to mid November. Yield trials for ME2 and ME3 are planted here.

Spray applications of susceptible border-mixtures provide YR and LR infection. YR almost always develops very well, but LR only increases during the latter part of the crop cycle and severity levels may remain low. Artificial dispersal of infected straw from the previous cycle at the tillering stage in between the rows with young tillering plants initiates epidemics of ST and *Fusarium nivale*, both of which generally reach medium to high levels of severity. In order to create FHB infection, the central florets of 5-7 individual spikes per selected entry are inoculated with a small piece of cotton soaked in a *Fusarium graminearum* solution (200,000 spores/L), allowing screening for so-called resistance Type II.

Although the above diseases are artificially inoculated, they also occur naturally. BYDV infection generally occurs naturally in the plots, and is not artificially inoculated in the breeding program. Occasionally some natural infection by bacterial diseases and tan spot are also observed.

Abiotic stresses include waterlogging, lodging and pre-harvest sprouting due to excess rain. To determine pre-harvest sprouting tolerance advanced lines considered for ME2 and ME3 are planted at Toluca in late January, when the coldest period of the winter has passed. They are allowed to ripen during the peak rainy summer season. Materials are then screened visually for sprouting tolerance. Selected lines are sent to CIMMYT's Quality Laboratory, headed by Javier Peña, and tested for alpha-amylase activity. This enzyme is activated at germination and is involved in the process of starch degradation. Tolerant lines will have low enzymatic activity under rainfall free conditions, as reflected in high falling numbers, with a slow rate of change under increasing rainfall.

El Batan (Letter code "BV", for Batan verano)
El Batan is located at 19°N, 2249 masl. It is the administrative center of CIMMYT and of the CIMMYT Wheat Program, situated to the northeast of Mexico City in the State of Mexico at about 30-45 minutes from the international airport. The land is CIMMYT property. Irrigation is available during periods of erratic rainfall. El Batan may represent ME2 and/or ME4, depending on rainfall, water availability and irrigation regime.

Due to land limitations, plantings (3 ha total) are usually restricted to fixed advanced lines (e.g. ALs, PCs, EALs, EPCs), multiplications of selected advanced materials, and special studies. Regular sowing commences in the second half of

May and finishes in mid June. The materials are harvested in late September/October. LR develops in epidemic proportions almost every year following artificial inoculation. YR occurs at irregular frequencies. RWA is endemic in the region. TS epidemics are generated using inoculation.

Candidate lines for the International Screening Nurseries and Yield Trials, intended for final large-scale multiplication in the disease-free location of Mexicali in far northwestern Mexico, are first increased in small plots in El Batan. These increases are planted in an isolated "Mexicali block", under the strictest protection against diseases using fungicides. Spring wheat material selected in Cd. Obregon or Toluca by visiting scientists and trainees must also be grown in this block for one cycle before being sent to them.

Screen- and greenhouse facilities for plantings are also available. All introductions from outside Mexico are first planted in a screenhouse, to allow careful scrutiny, before distribution to CIMMYT breeders for use in their programs.

The grounds at CIMMYT headquarters also house major laboratory complexes, plus the germplasm bank.

Patzcuaro (Letter code "PZ")
This field site is located at 19°N, 2400 masl, to the west of Toluca in the State of Michoacán, about five hours' drive from CIMMYT headquarters at El Batan. This high rainfall ME2/ME3-type site, operated by researcher Rebeca González of Mexico's National Institute of Forestry, Agriculture, and Fisheries Research (INIFAP). It is used to screen and select for resistance to ST, *S. nodorum*, FHB, and tolerance to low pH. About 1-2 ha of materials are planted.

El Tigre (Letter code "SJ")
This field site is a local farmer's property located to the west of Mexico City and south of Guadalajara in the State of Jalisco, at 21°N, 2300 masl in mountain range called the Sierra de Jalisco (hence "SJ"). In this very high rainfall location, ME2 and ME3 materials are evaluated in some years for response to such diseases as *Septoria* spp. and *Fusarium* spp. About 0.5-1.0 ha is planted.

Winter/Facultative Wheat Winter Cycle

Toluca (letter code "MI", for Mexico invierno) (*invierno* is "winter" in Spanish)
Winter wheat materials are sown at the start of the dry winter season in November and early December using irrigation on about 7 ha at CIMMYT's Atizapan station near Toluca. In May/July the rainy season begins. Harvest is in July.

This site represents ME7 and ME8 for facultative wheats and to a certain extent ME10 and ME11, when planted in November. If irrigation is withheld, it represents semi-arid ME9, and to an extent ME12. Several weeks of night temperatures below –5^{0}C are common. There is no snow cover. Vernalization is usually sufficient for most winter wheats to initiate flowering. However, relatively short days compared to those at greater latitudes, result in some winter/facultative germplasm maturing very late due to their unsatisfied photoperiod requirement. BYDV is a regular and severe stress. YR develops well in most years if properly inoculated, but LR usually remains at low levels.

The winter/facultative breeding efforts centers on developing materials to support the spring bread wheat breeding effort. Spring x winter wheat crosses are made here. Spring wheat can be planted in mid January, and due to the late planting generally survives the cold without much damage. By May both winter and spring materials will flower at more or less the same time allowing hybridization. These crosses contribute specific characters to the spring wheat gene pool, such as novel resistance or yield genes, and provide extended genetic diversity.

Some facultative and winter germplasm is developed in this breeding program targeted towards the irrigated winter/facultative regions (e.g. China), and special trait populations are developed. These are tested in yield trials during the winter cycle.

CIMMYT has a joint Winter/Facultative Program with the Turkish National Program, based in Ankara, Turkey. The latter program carries the main responsibility within the CIMMYT Wheat Program structure for developing improved germplasm for most winter/facultative areas in the developing world.

Disease Resistance Screening

The most important diseases for each ME are listed in the Table 4. The selection process in Mexico, which is structured according to ME, in conjunction with multilocation screening aims to select germplasm that carries durable resistance to the diseases that are prevalent in each respective ME.

Table 4. Major diseases present in each mega-environment.

Mega-environment	Major pathogens/pests (in order of importance)
ME1	*Puccinia recondita* (leaf rust (LR)), *P. striiformis* (stripe or yellow rust (YR)), *P. graminis* (stem rust (SR)), *Blumeria* (previously *Erysiphe*) *graminis* (powdery mildew (PM)), *Tilletia indica* (Karnal bunt (KB)), root rots (RR), *Fusarium graminearum* (fusarium head blight (FHB))
ME2	*P. striiformis*, *Septoria tritici* (septoria leaf blotch (ST)), *P. recondita*, *P. graminis*, *F. graminearum*, BYDV, *Xanthomonas campestris* pv. *translucens* (black chaff), *B. graminis*, root rots, *Pyrenophora tritici-repentis* (tan spot (TS))
ME3	*P. striiformis*, *S. tritici*, *P. recondita*, *P. graminis*, *F. graminearum*, BYDV, *X. campestris* pv. *translucens* (black chaff), *B. graminis*, root rots, *P. tritici-repentis* (tan spot (TS))
ME4	*P. recondita, P. striiformis, P. graminis, Septoria* spp., common bunts (*Tilletia foetida* and *T. caries*), various nematodes, root rots, *Fusarium* spp., *P. tritici-repentis*
ME5	*P. recondita, Bipolaris sorokiniana* (helminthosporium leaf blight (HLB)), *F. graminearum, Sclerotium rolfsii, B. graminis*
ME6	*P. recondita*, *Fusarium* spp., *P. graminis*, *P. striiformis*, *P. tritici-repentis*, root rots
ME7	*P. striiformis*, *P. recondita*, *B. graminis*, common bunts, *Ustilago tritici* (loose smut (LS)), BYDV
ME8	*P. striiformis*, *P. recondita*, *S. tritici*, *B. graminis*, *Fusarium* spp., root rots, common bunts, eyespot, BYDV
ME9	*P. striiformis*, common bunts, *P. recondita*, Russian wheat aphid (*Diuraphis noxia* (RWA or DN))
ME10	*P. striiformis*, *P. recondita*, *B. graminis*, BYDV, common bunts, root rots, nematodes, *Ustilago tritici*
ME11	*P. striiformis*, *P. recondita*, *B. graminis*, *Septoria* spp., *Fusarium* spp., BYDV, root rots
ME12	*P. striiformis*, common bunts, root rots, nematodes, *P. recondita*, *B. graminis*, BYDV, eye spot

The most important diseases in the major breeding/screening environments in Mexico are described in the Table 5. For most of the globally important diseases the breeders have sites at their disposal within Mexico where relevant disease screening and selection of resistance can be practiced. One major exception is PM. However, virulence spectra in Mexico may of course vary greatly from those in the target MEs elsewhere in the world.

Table 5. Major diseases present in key CIMMYT breeding/selection/screening sites. Less frequent diseases are listed in parentheses.

Location	Major diseases/insects for selection
Cd. Obregon	*Puccinia recondita, P. graminis, Tilletia indica, (Ustilago tritici)*
Toluca	*P. striiformis, P. recondita, Septoria tritici,* F*usarium graminearum, F. nivale, Xanthomonas. campestris* pv. *translucens*, BYDV
El Batan	*P. recondita, P. graminis,* X. *campestris* pv. *translucens, BYDV, Diuraphis noxia* (Russian wheat aphid, RWA), *Pyrenophora tritici-repentis, (U. tritici, P. striiformis)*
Patzcuaro	*F. graminearum, S. tritici* and *S. nodorum*
El Tigre	*S. tritici, S. nodorum, F. graminearum*, and *P. recondita*

Breeding Methods and Germplasm Flow

The Crossing Blocks

The Crossing Blocks (CB) are collections of elite breeding parental stock and source materials arranged by mega-environment (ME). In order to facilitate crossing operations, the CBs are sown on four or five different dates, about 10 days apart. The largest CBs are the spring wheat CBs. In the Toluca winter cycle, a winter wheat CB is assembled and planted.

Spring Wheat Crossing Blocks

The production of high yielding, widely adapted, stable and durably resistant bread wheat germplasm with acceptable quality is the primary consideration of the breeding process. Separate CBs are used for each ME. The specific breeding objectives for each ME are outlined above in the "Objectives within Each Mega-Environment" section.

Within each CB germplasm is grouped according to geographic zone of adaptation or specific character expression, such as disease resistance, abiotic stress tolerance or end-use quality. CB entries include the major commercial varieties released in different target countries, and elite CIMMYT and other germplasm identified from international and national testing. The CIMMYT Pathology Program also provides lines to the CBs with novel genes and/or high levels of resistance to key diseases. The CIMMYT Wide Cross Program likewise may contribute lines containing alien introgressions, including synthetic hexaploid wheat, providing resistance/tolerance to biotic/abiotic constraints.

Genotypes from each section of the CB carry genes specific to their defined ME. For example, ME1 genotypes carry genes or combinations of genes coding for one or more of the following: high yield potential, dwarfing genes (*Rht1*, *Rht2*, and/or *Rht8*), lodging tolerance, durable resistance to the rusts, KB, FHB, PM or RR, tolerance to heat and saline soils, improved industrial quality, etc.

On average 25% of the CB entries are replaced every crop cycle by new entries expressing superior or new useful genetic diversity.

There are five spring wheat CBs arranged by ME. These are:

- CBME1IR: for irrigated environments,
- CBME2HR: for the high rainfall areas (includes a ME3AS section),
- CBME4SA: for semi-arid areas,
- CBME5TE: for the warm, humid tropical environments,
- CBME6HL: for the high latitude areas.

Considerable genetic diversity enters the breeding system in the form of introductions from most collaborating countries. Between 1000-4000 entries are received annually from our global collaborators. Once introduced, these materials are classified according to their ME with regard to agronomic type, disease resistance and adaptability. Following this initial round of screening they may enter into Observation Nurseries (ON) where a limited number of crosses can be made, with later the best introductions being promoted to CB level allowing more extensive use as parents.

Winter/Facultative Wheat Crossing Block

Similar principles hold for the facultative/winter wheat crossing activities. However, only one cycle per year is possible. Four to five dates of the winter/facultative crossing block (CBME7-12) are sown at Toluca in November and December at two-week intervals. This CB is a collection of the best advanced lines and commercially released varieties from winter and facultative wheat breeding programs around the world, plus elite lines from the CIMMYT/Turkey winter/facultative breeding program and from the base program itself. Institutions like the Oregon State University (OSU), Oklahoma State University (OKSU), and other US university programs, breeding programs in central and Eastern Europe, and various Chinese Academies of Agricultural Sciences have also contributed significantly to the infusion of winter/facultative germplasm. About 500-3000 entries are introduced annually from abroad. As stated above the CBME7-12 is primarily used as a means of introducing variability into the spring bread wheat gene pool.

Within the Wheat Program framework the CIMMYT/Turkey program is primarily responsible for the production of winter/facultative types, and does so in collaboration with the Turkish NARS. The resulting germplasm is distributed to NARSs in the form of various screening nurseries and yield trials listed in the "International Screening Nurseries and Yield Trials" section and Table 1.

Advanced facultative/winter lines emanating from the breeding program described above are submitted to the CIMMYT/Turkey program to be included in their outgoing nurseries and yield trials. In addition, a small number of facultative/winter lines from the base program are distributed to NARSs upon request on a limited scale under the name Favorable Environments Facultative and Winter Wheat Screening Nursery (FEFWSN).

Simple, Back-, and Top-crosses

Simple crosses

Crosses are always directed toward a specific ME, taking into account the relevant requirements for the respective ME. Resulting segregating populations are also labeled according to the intended ME (see "Nomenclature of Breeding Materials" section).

For irrigated (ME1, ME5) and high rainfall (ME2, ME3) conditions a total of about 1500-2000 simple crosses are made per crop cycle, totaling 3000-4000 per year. Crosses for ME4 and ME6 total about 1500 per annum. Between 250 and 400 new hybrid combinations are created every year in the Hybrid Wheat Program.

An elite sub-set of parents from within each CB, representing unique combinations of outstanding characteristics for all high priority traits are selected to be used as common parents in simple crosses, and in back- and top-crosses. Demands on entries for this elite list are very strict, and require a minimum of very high yield, excellent durable disease resistance (combination of several minor genes), and outstanding industrial quality (strong gluten, high protein %). Since these lines come from the CBs that are planted on various planting dates thus providing some flexibility, they are most often used in crosses as pollen donors, particularly when crossing to entries that may have only one planting date (e.g. ONs, F1s, introductions). Hence this elite set of male parents is called the "Male Master List". As a result most newly introduced lines are used as females in crossing, which also indirectly expands the genetic base of CIMMYT bread wheat cytoplasm.

F1. The F1s are planted in the following cycle as a double row of 1-2 m. They are exposed to artificial disease epidemics, either in Cd. Obregon (LR, SR) or Toluca (YR, ST, LR, SR). The best entries are back- or top-crossed. The best entries towards at the end of the cycle are harvested in bulk at maturity, and their seed planted as an F2 population in the following crop cycle.

Back- and top-crosses

Outstanding F1 populations (or plants grown from their reserve seed: F1R) are backcrossed to one of the original parents or sometimes both, if the proposed recurrent parent has been selected as an elite member of the Male Master List during the crossing cycle at hand. If only one backcross is made, these are called "limited" backcrosses. They allow the unique opportunity of conserving the proven desirable gene-blocks in the elite recurrent parent from the Male Master List through its 75% theoretical gene contribution to the limited backcross, with the possibility to expand genetic variability in the choice of the donor parent through its reduced but crucial 25% contribution. With this approach, quite distant genetic stocks can be introgressed into stable unions with more proven materials. For the past 15 years limited backcrosses have proven very effective in expanding adaptation and performance.

If an F1 seems visually outstanding but neither of the two original parents are in the present Male Master List, then a top-cross with another, preferably related, entry from the Male Master List may be considered. In rare cases very outstanding F1s may be both backcrossed and top-crossed to distinct elite Male Master List entries.

In practice about one third of the most outstanding F1s are backcrossed or top-crossed. Per cycle about 700-1000 top- and limited backcrosses are made.

As a rule, 4-5 spikes are crossed for simple crosses and 7-10 for top- or limited backcrosses. The latter is a larger number since the resulting F1-top generation is expected to immediately segregate, unlike the homogeneous F1, and planting a larger population allows some initial (negative) selection.

Segregating Populations

Once a cross has been made and classified by target ME, its segregating progenies are selected in a "shuttle" process in which subsequent generations are alternately grown in Toluca and Cd. Obregon. Certain generations may be planted under the real or simulated stresses specific to its targeted ME (e.g. drought). However, as all elite CIMMYT advanced material is tested over a wide range of environments both in Mexico and internationally, some materials may also in the process enter different ME selection streams as additional adaptation becomes apparent.

The breeding and selection strategies described here are by no means rigid procedures that are adhered to under all circumstances. Considerable flexibility exists within the system, allowing material to be channeled in different directions as the need and opportunity arises.

Selection methods

In the early days of spring wheat breeding at CIMMYT, the pedigree selection method was used almost exclusively. In this method individual plants are selected at each segregating generation and promoted as individual entries. This has been the most widely used method for wheat breeding worldwide, and has some advantages such as the possibility of using previous years' plant-based data in selection. However, because of the enormous number of entries to handle, record keeping and nursery preparation becomes very laborious.

In the early 1980s, the pedigree selection method was replaced with a combination of pedigree and bulk breeding, named the "modified pedigree/bulk" selection method (see later section). Individual plants were selected in the F2 and individually promoted to the F3 in a pedigree fashion. In the subsequent generations desirable spikes from each selected plot were bulked. In the F6 individual spikes were selected and individually promoted to the F7 (see later section for details).

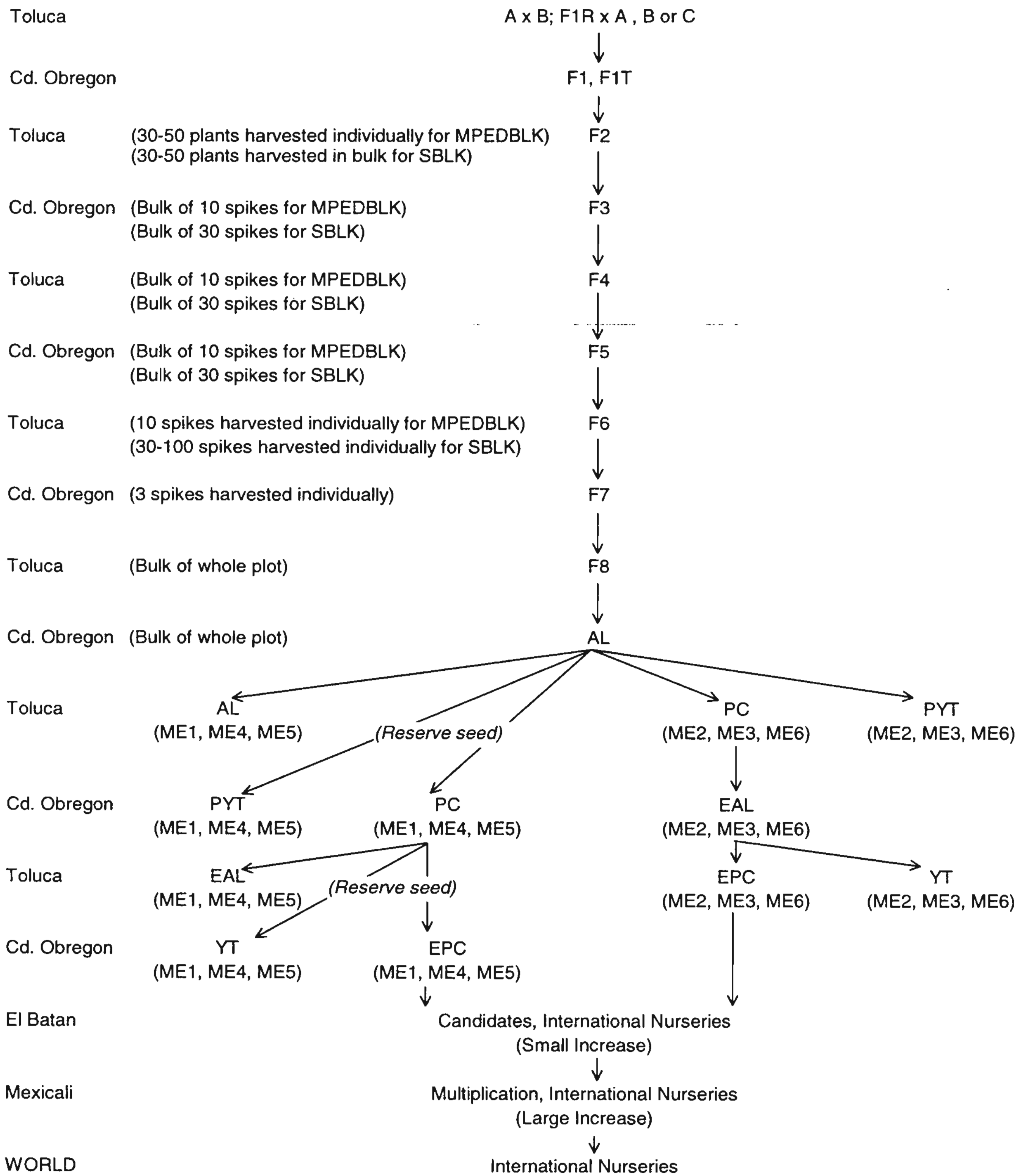
In the late 1980s, the first preliminary attempts were made to apply what would later be called the "selected bulk" selection method, in which in all generations starting from the F2 plants were bulked, until in the F6 individual spikes were selected and individually promoted to the F7. By the second half of the 1990s, the selected bulk approach began to be quite extensively applied in bread wheat breeding, and it is now the main selection method used in our breeding program. This latter selection method is described in detail below. Finally a few words are devoted to the modified pedigree/bulk method.

Diagram

The following diagram is a hypothetical representation of germplasm flow in the "modified pedigree/bulk" (MPEDBLK) and "selected bulk" (SBLK) selection methods, starting out from parental crossing in Toluca, and resulting in replicated yield testing and final international nursery distribution, according to the standardized abbreviations described in the "Nomenclature of Breeding Materials" section:

Diagram of Germplasm Flow

(For full description see text)



When the original crosses are made in Cd. Obregon, the selection and yield testing process is very similar, except that the test locations are alternated in different order.

F1Top. Within the F1Top populations an artificial epidemic is created of the prevalent diseases. Because the seed originates from hand-made crosses, and hence seed quantity is small, superior recombinants combining all desired traits are rare. Only some negative selection is practiced in the first segregating generation of the F1Top. Seed samples from all remaining acceptable plants are promoted to the F2, where larger populations are possible.

F2. The F2 populations consist of about 1500-2000 plants per cross, which are space-planted in 4-6 double rows of 10 m each. Simple, top- and (limited) backcrosses are represented in the F2. Again a disease epidemic is created. The poorest F2 populations (10-15%) are discarded prior to any within-population selection.

Within the remaining F2 populations, the best space-planted plants are selected by the breeders and experienced research assistants during 3-5 rounds of selection based on good agronomic type (considering the targeted ME), phenology, and disease resistance. Important traits are:

- Synchronous tillering,
- Appropriate height,
- Healthy leaves,
- Durable disease resistance,
- Preferred spike type,
- Large spike,
- Good fertility,
- No shattering,
- No lodging,
- Stay-green character,
- Desired maturity.

Selected plants are identified by attaching a recognizable weather-resistant label around several of its tillers immediately below the flagleaves, or two spikes of the plant are spray-painted with a hand-held spray-paint can. Plants selected in the initial rounds but later found to be inferior are discarded by bending them over.

Several spikes (2-5) of the remaining selected plants are harvested, totaling 30-60 spikes per cross, and threshed in bulk. The seed is visually observed for grainfilling characteristics, plumpness or boldness, lack of diseases and yellow berry, and other markings. Populations with a high proportion of poor seed are discarded. If the number of populations is small, harvest and subsequent discard on a seed-basis can be carried out on individual F2-plants, with seed bulked only from those plants within an F2-population that showed general desirable characteristics. For ME5 and most ME1 populations, only white kernels are promoted.

F2s targeted to ME4 are sown at a depth of 10 cm with a reinforced seed-drill using a sowing rate twice that used for other MEs. From the plants that emerge (we aim for 40% emergence), those of semidwarf height or slightly taller, with good rust resistance, are selected.

F3. One of the advantages of the selected bulk selection method is that a selected F2 population will only generate one F3 seed lot and hence only one F3 plot. The result is a reduction in the number of F3 plots compared to the modified pedigree/bulk method, where each selected F2 plant becomes an individual F3 plot. Since empirical observations at CIMMYT have shown that the mean number of plants promoted per cross in the F2 is on average about ten, the number of F3 plots drops to about 10% of what would have been the case in the modified pedigree/bulk method. However, since the bulked F3 contains seed of a number of selected plants from the F2 (from around ten, up to sometimes 100), F3 plot size needs to be considerably larger than that used in the modified pedigree/bulk method (1-2 m double or triple row). The larger plot is required to allow the bulked genetic variability to be properly sampled. Usually individual F3 plots are space-planted as two double rows of 10 m each.

With this method fewer individual seed lots need to be handled at harvest, threshed, seed selected, prepared for planting, and labeled. Also the number of entries in the field books decrease. This constitutes significant savings in time, labor, and costs, and reduces potential sources of error in the program. Generally this method requires less land.

All F3 materials are planted under well-watered conditions. Again an epidemic is created of the prevalent diseases. The poorest F3 populations (10-15%) are discarded prior to any within-population selection. The best individual plants within the segregating space-planted F3 populations are selected by the breeders based on agronomic type as detailed above for the F2. As in the F2, several spikes (2-5) of the remaining selected plants, totaling 30-60 per cross, are harvested and threshed in bulk. The seed is visually observed, and poor populations discarded. This generates the bulked F4 seed for the next generation.

F4 and F5. The methodology detailed in the F3 is largely repeated. However, seeding rate per plot may be somewhat increased (by about 50% relative to the F2 and F3). Under farmers' conditions seed is usually densely planted at seeding rates of 100 kg/ha and up, allowing little tillering though a dense crop stand. During these F4 and F5 generations the plants should develop more or less as they would in commercial conditions, although individual plants should still be visible, so individual plant selection can be practiced. Epidemics of the prevalent diseases are created. The number of populations retained further decreases from the F4 to the F6.

Those F4 and F5 populations targeted to ME4 are always sown under drought stress in Cd. Obregon (one pre-seeding irrigation) and the prevailing rainfall conditions when in Toluca. This method ensures that all materials are selected in the segregating phase for LR and YR resistance, responsiveness to non-limiting water availability, and drought tolerance. The ME4 F6 is managed as per the other MEs.

F6. Planting methodology for the F6 is as for the F3-F5, but harvest differs. Again, individual plants are selected based on good agronomic type and response to the created disease epidemic. But now individual spikes from the best plants are harvested and kept separate for threshing and planting. The total number of spikes selected per cross is quite large (20-100), since significant genetic variability may still be contained in the F6. This is due to the fact that the initially selected and presumably diverse F2 plants were bulked to form the F3, rather than separately planted as in the pedigree or modified pedigree/bulk method.

No seed selection is practiced because seed quantity obtained from individual spikes is low. The F7 are to be planted as head-rows during the next cycle.

F7. Head-to-row planting in one 1-m triple or double row allows thousands of entries to be planted in a small area. Again, an epidemic is created of the prevalent diseases. The best, uniform lines are selected and harvested in bulk. Seed selection follows. These entries are promoted to advanced lines (AL).

Empirical observations have shown that certain F7 plots contain very attractive plants but are not uniform enough to be bulk harvested to enter ALs and subsequent yield testing. The reason for this is partly that modified pedigree/bulk selection practiced on the later generations (F4-F6) allowed discard of unstable plots. Given the usually large number of plots planted per cross in the modified pedigree/bulk method, this was very feasible. In the selected bulk method, one plot represents the cross in any generation; therefore, discarding it on the basis of lack of uniformity would result in loss of the entire cross. For this reason F7 progeny of the selected bulk method, which appear promising but lack uniformity, are reselected by harvesting three individual spikes, which subsequently become F8 head-rows.

F8. The F8 head-rows are planted in one1-m triple or double row. As in the F7 an epidemic is created of the prevalent diseases, and uniform lines with outstanding agronomic type are selected and harvested in bulk. Seed selection follows. The remaining entries are promoted to advanced lines (AL).

In Mexico, segregating generations targeted for specific MEs may occasionally be sown outside the regular Cd. Obregon/Toluca shuttle in other locations such as El Batan or Patzcuaro. In some instances, yield trials may also be conducted in the early segregating generations, depending on the nature of the material.

Advanced Lines and Yield Trials

AL. The newly bulked F7s or F8s forming the advanced lines are exposed to observation for agronomic type and disease resistance in solid stands of 1-2 m. The best AL entries are promoted to first-year Preliminary Yield Trials (PYT).

PYT and PC. The PYTs, including checks, are planted and analyzed according to specific unreplicated statistical designs to eliminate the lowest yielding 50-60% of the yield distribution.

PYTs targeted for ME1, ME4, and ME5 are carried out in Cd. Obregon. This is how the following targeted conditions can be simulated:

- ME1, by applying 4-5 irrigations as moisture is required.
- ME4, by applying one pre-seeding irrigation and one auxiliary irrigation 70 days post emergence thereby creating semi-stressed conditions. This allows screening for input (water) responsiveness.
- ME5, by planting late (in January or February) resulting in considerable heat stress at the time of flowering and grain filling.

Lines targeted for ME2 and ME3 are grown in PYTs in the high rainfall environment of Toluca. Thus the target environment (e.g. irrigated, heat, high rainfall, drought) is represented or simulated during the yield trial phase.

In Cd. Obregon the trials are either planted on beds (per entry: 2 beds, 80 cm wide/3-5 m long, with 2-3 rows/bed,) or in flat irrigation basins called melgas (*melga* is "irrigation basin" in Spanish) with 30 plots/melga. In melgas every entry is sown as an eight-row plot, 3.8 m long, with 20 cm between rows. In Toluca all yield trials are bed-planted.

In bed plantings all rows are harvested across their entire length. In melga plantings the outer rows on each side (1st and 8th row) are left unharvested, as is the front and back 50 cm of each plot; only the center of the plot is harvested.

Prior to harvest the entries are keenly scrutinized for lodging tolerance.

PCs (for *parcela chica,* "small plot" in Spanish) contain exactly the same entries as the PYTs, and are planted during the same crop cycle as the yield trials, but separately in an area where relevant diseases are artificially inoculated. The PCs provide disease resistance data to allow proper identification of the most outstanding entries in the PYTs. In addition the PCs form small seed multiplication plots, where rogue plants are removed to provide clean pure seed for the subsequent cycle.

During the summer cycle in Central Mexico, PCs associated with the PYTs in Toluca may be sown in several different sites in addition to Toluca and El Batan, such as in Patzcuaro and El Tigre, for wider disease exposure and evaluation of their adaptation.

Joint data from the PYTs and PCs on absolute and relative yield, agronomic type, uniformity, lodging, and disease resistance are used to make the final selection decisions. The best lines are promoted to elite advanced lines (EAL).

PYT seed from these selected entries is submitted to CIMMYT's Quality Laboratory for evaluation of the industrial quality, including the following traits based on whole meal and mixograph analysis:

- Hardness (by NIR) and hardness class (H = hard; SH = semi-hard; SS = semi-soft; S = soft)
- Grain protein % (by NIR; 12.5% moisture basis)
- SDS sedimentation volume (ml)
- Sedimentation index (SDS sedimentation volume/protein %)
- Mixing properties (mixograph) of sifted ground-meal (mixing time (min.) and mixographic type (1-6))

EAL. The top-yielding lines from the PYTs are grown as EALs and exposed to disease epidemics. If the EALs are grown in Cd. Obregon, as is the case for the top-yielding lines identified in the ME2 and ME3 PYTs grown the previous cycle in Toluca, then "Cd. Obregon" seed from the best EALs is sent for quality evaluation. This is done to provide a seed sample that is less weathered than the PYT seed sample from the previous Toluca cycle, which is also submitted for quality analysis. Quality data on both samples provides a truer picture of the genotypic and phenotypic quality profile.

The best EAL entries for agronomic type and resistance are promoted to replicated second-year yield trials (YT). Also taken into consideration are industrial quality data, based on seed from the previous PYTs; this data is generated concurrently by the CIMMYT Quality Laboratory.

YT and EPC. The best EAL entries enter second-year yield trials (YT). As with the PYTs, the materials are grown under relevant represented or simulated environmental conditions. Latinized alpha-lattice designs with two replications are used. The trials are spatially analyzed.

In the case of ME4, one pre-seeding irrigation is applied at the YT stage to create very severe drought stress conditions. This procedure ensures that input (water) efficiency plus drought tolerance are combined with input (water) responsiveness (as determined under mild stress in the PYT phase).

EPCs (for elite "parcela chica") containing the same entries as the YTs are planted separately in an area where diseases are artificially inoculated. In the case of Cd. Obregon plantings, the group headed by Guillermo Fuentes also tests the lines included in the EPCs for response to KB, in separate special nurseries. As with the PCs, disease response data and clean seed are obtained.

Following data taking on the YTs and the EPCs, the best entries are selected as candidates for international screening nurseries and international yield trials for global distribution. Seed of these selected entries is submitted to the CIMMYT Quality Laboratory to be fully evaluated for quality, including the following traits:

Grain characteristics:

- Color (red/white)
- Test weight (kg/hl)
- Thousand kernel weight (g)
- Hardness (by NIR) and hardness class (H= hard; SH = semi-hard; SS = semi-soft; S = soft)
- Protein content (% by NIR; 12.5% moisture basis)
- SDS-sedimentation volume (ml)
- Falling number (sec.; 14% moisture basis)

Storage protein composition:

- High molecular weight glutenin subunits at the Glu-A1, Glu-B1, and Glu-D1 loci
- Low molecular weight glutenin patterns (G = good; G? =medium good; P? = medium poor; P = Poor)
- Presence or absence of Secalins due to the 1B/1R translocation

Flour characteristics:

- Flour yield (%)
- Flour protein (%; by NIR)
- Flour SDS-sedimentation volume (ml)
- Flour sedimentation index (sedimentation volume/protein %)
- Flour yellowness (yellow, light-yellow, white)
- Mixing properties (mixograph mixing time (min.) and mixographic type (1-6))

Dough characteristics and baking performance:

- Dough tenacity (alveograph P value (mm))
- Dough extensibility (alveograph L value (mm) and P/L value)
- Dough strength (alveograph W (10^{-4} J)
- Gluten type (based on test results, S = strong; MS = medium strong; W = weak; T = tenacious; WT = weak tenacious)
- Pan-bread loaf volume (ml)
- Crumb structure (VG = very good; G = good; F = fair; P = poor; VP = very poor)

An overall quality score or "USE TYPE" is given based on gluten strength characteristics and grain protein content (1 = strong; 2 = medium strong; 3 = hearth type; 4 = soft; 5 = tenacious; a > 12.5% flour protein; b > 10% flour protein). This score is a summary of all the above measured traits.

Grain protein is generally negatively correlated with grain yield. An "a" value for flour protein, indicating a phenotypically high protein level, may be associated with lower yield. On the other hand a line with high yield and an "a" protein level represents germplasm with the genetic ability to produce high protein levels, and could serve as an excellent parent in crossing. Protein levels and quality in general are always evaluated in conjunction with yield performance.

Space permitting, yield trials may be sown in other (simulated) mega-environments to gauge the performance of materials outside their initially targeted ME. Although genotypes are developed for a designated/targeted ME based on their parentage, which is enforced through the stresses applied during selection, their performance may justify them crossing over into other MEs.

Breeding for ME6: A Variation on the Basic CIMMYT Breeding Scheme

Materials destined for the high-latitude areas of Central Asia and Northeastern China are grown under supplementary lighting in Toluca and Cd. Obregon. Crosses are made combining key materials from Central Asia and China with disease resistant, high yielding CIMMYT germplasm. High quality lines from Canada and North Dakota are also used in the crossing strategy.

In the F2, individual plants are selected and grown as F3 plots with and without lights. Differences in flowering date between the two light treatments are noted. Those exhibiting a photoperiod response are kept and the process is repeated in the F4. Plots are inoculated with rust from F1 onwards.

Rust resistant lines of standard height (non-semidwarf) exhibiting a photoperiod response are selected and sent in the F5 to Kazakhstan and Siberia for selection under local conditions. The best lines are kept by local cooperators and included in regional yield trials. These lines are returned to CIMMYT Mexico and included in the crossing program.

The Modified Pedigree/Bulk Method

From the early 1980s till the second half of the 1990s, the main selection method used at CIMMYT was the modified pedigree/bulk selection method. It has been very successful and produced many of the new widely adapted wheats now being grown in developing countries. As the selected bulk scheme is equally effective genetically and provides improved resource-use efficiency, the modified pedigree/bulk method was largely discontinued at CIMMYT.

The key differences of the modified pedigree/bulk selection method with the selected bulk selection method are indicated below. The modified pedigree/bulk selection method starts of with a "pedigree" selection in the F2 followed by three "bulk" selections in the F3 till the F5, and rounded of by another pedigree selection from the F6 to the F7, hence the name modified pedigree/bulk selection method.

F2. The first main difference in the modified pedigree/bulk selection method compared with the selected bulk method, is that in the former method the selected F2 plants are individually harvested and threshed. Following visual selection for seed traits, seed from these best F2 plants generate separate F3 plots.

F3-F5. The F3 is planted in plots of 1-2m in length with 2-3 rows/bed, at a commercial seeding density (100 kg/ha). The total number of F3 plots for all MEs easily reaches 20,000-30,000.

In the F3-F5 generations between-plot selection identifies those with the best agronomic type, most durable resistance, least lodging and best uniformity. From within these selected plots 10-15 large and highly fertile spikes are harvested and threshed in bulk. This bulk seed lot is visually evaluated for seed traits. The best seed lots are promoted to the next generation and planted as described for the F3.

F6. The F6 is planted as the F3-F5. However, at maturity 10 spikes are harvested separately from the agronomically most desirable plots, and planted as head-rows in the F7. The total number of F3-F6 plots often exceeds 40,000.

F7. The visually most attractive F7 head-row plots are harvested in bulk and promoted to ALs. From then on the process involving yield trial testing is equivalent to that described above for the selected bulk selection method.

Hybrid Bread-Wheat

Introduction and objectives

Raising the yield potential of wheat to meet the ever-increasing worldwide demand for wheat-derived food products has always been, and remains, the major concern of CIMMYT. Exploiting whatever heterosis may be found in wheat through the development of hybrid varieties is one way of achieving greater yield potentials.

Putting together the components for hybrid wheat production is not new to CIMMYT. When the first hybridization system with potential for commercial application was reported in the early 1960s, that is, the discovery of cytoplasmic male sterility (CMS) and fertility restoration (RF) genes, CIMMYT started a significant effort to breed male-sterile female and good restorer male lines within the successful genetic backgrounds of that time. This effort started in 1962 and was then headed by Ingeniero Ricardo Rodriguez.

In 1996, CIMMYT entered in agreement with the Monsanto Co. to explore the development of hybrid wheat varieties and seed production systems for Mexico, based on the Genesis®

technology, a chemical hybridization agent (CHA) developed by Monsanto. This program was phased out in 2002 in favor of the CMS/RF system, as Genesis® was no longer available for commercial-scale production of hybrid wheat.

Regardless of the method of hybrid production, the ultimate goal of CIMMYT is to develop a hybrid wheat technology that can be adopted by NARSs to raise their yield potentials in wheat. Previous research on combining ability of CIMMYT highest yielding and most widely adapted material allowed us to identify groups of lines that were suitable either as female or male parents in hybrid crosses. Although the Yaqui Valley of Mexico (high yielding, irrigated environment) was initially considered as the target environment, it is historically known that lines bred and tested under these conditions by CIMMYT have shown wide adaptation and are successfully grown in many other irrigated areas around the world. Therefore, we aim to convert our best combining female lines into male-sterile lines (using CMS) and introduce both adequate fertility restoration and good "male traits" (see below) into our best combining male lines. This will result in the development of two groups of relevant parental germplasm for those NARSs wishing to explore the hybrid wheat option.

The following section summarizes the general procedures used by CIMMYT Hybrid Wheat sub-program to achieve this goal.

Putting together the components of a CMS/RF-based hybrid production program

Female line development. Female line development is conducted during both the winter cycle in Cd. Obregon and the summer cycle in El Batan.

This is done by transferring the nucleus of our best combining female lines into the cytoplasm of *Triticum timopheevii* through repeated backcrossing. Several male sterile lines are used as sources of the *T. timopheevii* cytoplasm (A-lines) with their corresponding maintainer lines (B-lines) used to produce A-line seed every year.

Currently available CMS sources are increased for further use in small seed production blocks, designated as CBHWAINC (Crossing Block Hybrid Wheat A-line Increase), in which each A-line is sown surrounded by the corresponding B-line. Each of these sub-blocks is planted under moderate isolation and controlled handcrossing is used to maintain the genetic identity of the A-lines.

To make the initial crosses, the CMS sources are space-planted in 2 double-rows of 2 m, along with the lines to "convert" in a crossing-block designated as CBHWNEWA (Crossing Block Hybrid Wheat New A-line). The initial cross is made on a "paired single-plant" basis, by pollinating three single plants from the CMS source with pollen from three single plants from the lines to convert. Tags in the field identify plants from each pair. Also, one spike from the line to convert is covered with a glassine bag to produce pure seed for use as the recurrent parent in the following backcross.

In the following cycle, the F1 seed from each cross and remnant seed from the recurrent parent plant used in the initial cross are space-planted in paired rows of 2 m, on the same bed. From each cross, one of the three rows of F1s is selected based on sterility (it should exhibit 100%

male sterility) and uniformity and, within this row, three sterile plants are selected to be pollinated by pollen from three different recurrent parent plants sown on the same bed, thereby producing BC1F1 seed. Again, one spike from each pollen donor plant is bagged to produce pure seed that will be used as the recurrent parent in the corresponding pair, in the next backcross.

In the following cycle, the BC1F1 seed from each cross and remnant seed from the corresponding recurrent parent plant are space-planted in paired rows of 2 m, on the same bed. From each cross, one of the three rows of BC1F1 is selected based on sterility and phenotypic similarity with the recurrent parent and, within this row, three sterile plants are selected using the same criteria. These plants are pollinated by three different recurrent parent plants sown on the same bed, thereby producing BC2F1 seed.

This backcrossing on a paired-plant basis is repeated until BC7F1 or BC8F1 plants are produced, depending on the similarity between the BCnF1 plants and their corresponding recurrent parents. Each cycle very strict selection for sterility and phenotypic similarity to the recurrent parent is performed. This conversion is carried out in nurseries designated as CBHWBCnF1 (Crossing-Block Hybrid Wheat Backcross n F1, n being the number of backcrosses).

At the end of the process, sterile female lines (now called A-lines) are planted in small blocks (CBHWAINC), in isolation, surrounded by the recurrent female line (now called B-line or maintainer line) to produce larger quantities of A-line seed for hybrid production and/or eventual distribution.

To date, A/B-line combinations have been developed using 50 of CIMMYT's elite genetic backgrounds (in terms of yield potential, rust resistance and wide adaptation) and A-line seed increase will be conducted for the first time during the El Batan 2002 summer cycle. At least one of these backgrounds has previously been identified as a good female combiner and will therefore be increased in larger quantities to be used as a "female tester" for fertility restoration and combining ability of new advanced male lines.

Our current goal is to sustain a conversion program involving 10-15 of the best new lines developed by CIMMYT's bread wheat program every year and that can be considered as female lines according to their parentage.

Male line development. This effort is conducted during both the winter cycle in Cd. Obregon and the summer cycle in El Batan.

Regardless of the system used (CHA or CMS), hybrid seed production can only be successful if pollinators have adequate "male traits." These are good anther extrusion (ability of the anthers to get out of the glumes before they shed all their pollen), large anther size, and good pollen production and viability. All these traits are not needed for conventional varietydevelopment in wheat, a complete self-pollinating crop, and therefore have not been bred into CIMMYT's germplasm in the past. The adequate expression of male traits is very rare in wheat and, so far, it has been identified only in some Chinese spring wheats and the winter wheat cv. Piko. Improving the male traits of our best-combining male lines is therefore a major component of our breeding effort, and is conducted simultaneously with the transfer of Rf genes.

Many sources of fertility restoration genes have been used, including material developed at CIMMYT during the 1960sand early 1970s. Recently, advanced (fixed) lines with good restoration ability have been developed in some modern CIMMYT backgrounds. All these stocks, along with any new Rf sources we might introduce, are planted in special nurseries called ONHWRF (Observation Nursery Hybrid Wheat Fertility Restoration) where they are evaluated for agronomic type, reaction to LR or YR (depending on the location), industrial quality, and fertility restoration ability. The latter attribute is evaluated by using each of the Rf lines as pollinator on one or several CMS tester lines (3-5 spikes per cross) and evaluating the extent of fertility restoration on the resulting F1 hybrids planted the following cycle as double-rows of 0.5 m (visually and by comparing % seed-set of F1 and B-line of CMS tester). The purpose of this evaluation is to limit the number of Rf sources to only the best restoring ones, which are also resistant to rusts, agronomically attractive with acceptable industrial quality.

When transferring Rf genes into a non-Rf background, it is important to use a source with the *T. timopheevii* cytoplasm so the fertility restoration ability of segregating progenies can be expressed directly through their apparent fertility. If a normal cytoplasm-bearing source of Rf genes is used, then testcrosses of selected progeny to male sterile lines are made to evaluate their restoration ability, which considerably lengthens the process.

The current strategy for the simultaneous introduction of both fertility restoration and male traits into elite male backgrounds relies extensively on limited backcrosses (Rf source with *timopheevii* cytoplasm crossed as female to one elite male and backcrossed to the latter) and top-crosses (Rf source with *timopheevii* cytoplasm crossed as female to a source of good male traits, top-crossed to good-combining male). The subsequent selection procedure follows a pedigree selection scheme until the F7 generation.

The material used in the initial crosses is grouped in nurseries designated as CBHWMALE (Crossing-Block Hybrid Wheat MALE) and planted (somewhat spaced) in 2 double-rows of 2 m, at 4 planting dates. Checks expressing varying levels of male traits are also included in this nursery. Resulting F1s are space-planted in double-rows of 1 m in nurseries called F1HWMALE (F1 Hybrid Wheat MALE), along side the CBHWMALE for backcrossing and topcrossing.

All but 5 seeds (reserve) from each resulting backcross/top cross population are space-planted in nurseries designated as F1THWTCM (F1-Top Crosses Hybrid Wheat *Timopheevii* Cytoplasm Male). Starting in the Cd. Obregon 2001-2002 cycle, top and backcrosses will be made to generate as large a progeny as logistically feasible (the objective is to generate 300-500 plants). Selection in the F1T populations is performed on a single plant basis for complete fertility, good male traits, LR or YR (depending on location) good agronomic type and similarity to the elite male line used in the cross. Selected plants are bulked together to form F2 populations, which are space-planted, along with selected F2 populations derived from single crosses in 6 double-rows of 8 m (about 1000 seeds sown).

Selection in the F2-F6 populations (designated as F2-6HWTCM for F2-F6 Hybrid Wheat *Timopheevii* Cytoplasm Male) is also performed on a single plant basis as described for the F1T populations, with most stringent selection for fertility and phenotypic similarity to the elite male parent. Single plant progenies from F2 to F5 generations are space-planted the following cycle in 2 double rows of 2 m.

At the F7 generation (F7HWTCM, sown in 1 double-row of 2 m), families selected based on the previously listed criteria (plus phenotypic uniformity) are formally tested for restoration ability by pollination with a CMS tester line; fertility restoration is scored the following cycle on the resulting hybrids. In addition, visual observations of the level of hybrid vigor in these test-hybrids (by comparison to the female CMS tester and the F7 line used as male, planted in adjacent plots) are used to discard F7 candidate male lines that do not produce test hybrids with visible advantage over their parents.

Finally, the lines that make it through this selection process are evaluated in replicated yield trials as described for the other bread wheat breeding programs, to select the highest yielding materials. The opportunity exists to conduct an in-depth characterization of selected candidate males (agronomic traits including flowering date, male traits, quality attributes). The last phase of male line development includes seed purification and production.

Shuttle Breeding Efforts outside Mexico

Some segregating and advanced materials are selected outside the regular Cd. Obregon-Toluca shuttle process and/or in other countries by CIMMYT staff and/or NARS cooperators and returned to Mexico for incorporation into the breeding program. The most important of these international shuttles are:

- CIMMYT/China — *Fusarium* spp., PM
- CIMMYT/Ecuador — YR
- CIMMYT/Kazakhstan, Almaty — Photoperiod sensitivity, drought tolerance
- CIMMYT/Mexico, La Paz — Salinity
- CIMMYT/Nepal — ME5 adaptation
- CIMMYT/Turkey — Winter and facultative wheat
- CIMMYT/Uruguay — Spring and facultative wheat; LR, *Fusarium* spp., PM

Seed Multiplication for International Screening Nurseries and Yield Trials

During the first multiplication phase the selected lines are increased in relatively small plots in El Batan as Candidate International Yield Trials (e.g. C24thESWYT) and Candidate International Screening Nurseries (e.g. C14thHRWSN), where special care is taken to produce clean seed. The entries are treated with fungicides during their development.

During the second multiplication phase the lines are grown in larger plots in Mexicali, located in far northwestern Mexico, an irrigated high yielding and KB free location. At

this stage they are coded as Multiplication International Yield Trials (e.g. M24thESWYT) and Multiplication International Screening Nurseries (e.g. M14thHRWSN).
At the same time the entries are again yield-tested in Cd. Obregon (e.g. YTM24thESWYT), or Toluca (e.g. YTM14thHRWSN), depending on their target environment. The latter is done to identify more precisely key outstanding lines for direct introduction into the crossing blocks and special promotion with NARSs.

Finally the multiplied materials are distributed internationally as International Yield Trials (e.g. 24th ESWYT), and Nurseries (e.g. 14th HRWSN), plus some segregating populations by the International Wheat Improvement Network section within the CIMMYT Wheat Program.

International Screening Nurseries and Yield Trials

The bread wheat germplasm that emanates from the CIMMYT bread wheat breeding programs is internationally distributed in two main forms, international screening nurseries and international yield trials.

The international screening nurseries (e.g. IBWSN, SAWSN) serve as a vehicle for the dissemination of improved and genetically diverse bread wheat germplasm. The materials can be used in national wheat crossing programs, or tested for direct release to farmers. Aside from a list of lines that have been selected by cooperators in their own environments, the return of performance data to CIMMYT is of secondary, yet vital importance.

The international yield trials (e.g. ESWYT, SAWYT) serve both a germplasm distribution function and that of a research tool. CIMMYT breeders very much encourage collaborators to collect data on these yield trials and return them to CIMMYT. These data may include a range of traits depending on local production conditions; yield, yield components, heading, maturity, response to prevalent diseases, tolerance to such abiotic stresses as drought, heat, cold, soil acidity, plus miscellaneous data such as for example nematode resistance, chapatti-making quality or photoperiod sensitivity genes.

No data is requested or expected from the internationally distributed segregating populations (e.g. F4BME1INT), which are assembled with the sole purpose of allowing our NARS colleagues to carry out early generation selection.

The data collected from international yield trials are used extensively within the CIMMYT breeding programs to help define and fine-tune objectives, and direct subsequent crossing cycles for particular MEs.

Table 1 lists the various international screening nurseries and yield trials that the bread wheat breeders both at base and in Outreach assemble for distribution. Below their full names, ME designation and a brief description of the kind of lines included, are provided.

Spring wheat

- ESWYT: Elite Selection Wheat Yield Trial (ME1; very top-yielding advanced lines)
- IBWSN: International Bread Wheat Screening Nursery (ME1; top advanced lines)
- HTWYT: High Temperature Wheat Yield Trial (ME1HT; very top-yielding advanced lines)
- HRWYT: High Rainfall Wheat Yield Trial (ME2; very top-yielding advanced lines)
- HRWSN: High Rainfall Wheat Screening Nursery (ME2; top advanced lines)
- ASWSN: Acid Soil Wheat Screening Nursery (ME3; top advanced lines)
- SAWYT: Semi-Arid Wheat Yield Trial (ME4A, ME4B and ME4C; very top-yielding advanced lines)
- SAWSN: Semi-Arid Wheat Screening Nursery (ME4A, ME4B and ME4C; top advanced lines)
- HLWSN: High Latitude Wheat Screening Nursery (ME6; top advanced lines)
- LACOS: Lineas Avanzadas del Cono Sur (ME1, ME2, ME3, ME5, ME6; large genetic diversity, with lines from many collaborators; distributed by CIMMYT-Uruguay)
- EGPYT: Eastern Gangetic Plains Yield Trial (ME5; very top-yielding advanced lines; distributed by CIMMYT-Nepal)
- EGPSN: Eastern Gangetic Plains Screening Nursery (ME5; top advanced lines; distributed by CIMMYT-Nepal)

Winter/Facultative wheat

- FEFWSN: Favorable Environments (irrigated and high rainfall) Facultative and Winter Wheat Screening Nursery (ME7A, ME7B, ME8A, ME8B, ME10A, ME10B, ME11A and ME11B)
- FAWWON: Facultative and Winter Wheat Observation Nursery (ME7B, ME8A, ME8B, ME9A, ME9C, ME10B, ME11A, ME12A and ME12B; large genetic diversity, with lines from many collaborators; distributed by the Turkey-CIMMYT-ICARDA International Winter Wheat Improvement Program (TCI IWWIP) based in Turkey)
- WON-IRR: Winter Wheat Observation Nursery for Irrigated Areas (ME7B, ME8B and ME10B; top advanced lines; distributed by TCI IWWIP)
- EYT-IRR: Elite Yield Trial for Irrigated Areas (ME7B, ME8 and ME10B; very top-yielding lines from WON-IRR; distributed by TCI IWWIP)
- WON-SA: Winter Wheat Observation Nursery Semi-Arid (ME9A, ME12A and ME12B; top advanced lines; distributed by TCI IWWIP)

- EYT-SA: Elite Yield Trial Semi-Arid (ME9A, ME12A and ME12B; very top-yielding lines from WON-SA; distributed by TCI IWWIP)
- WWEERYT: Winter Wheat East European Yield Trial (ME7, ME8, ME9, ME10, ME11, ME12; distributed by TCI IWWIP)
- TIFCOS: Trigos Inviernos y Facultativos del Cono Sur (ME7, ME8; large genetic diversity, with lines from many collaborators; distributed by CIMMYT-Uruguay)

Trainees, Visiting Scientists and Mid-Career Fellows

Trainees

The In-service Training Program led by Reynaldo Villareal, which offers the annual Wheat Improvement Training Course and the Advanced Wheat Improvement Training Course, coordinates its training activities closely with the breeders. Trainees with a primary focus on bread wheat spend most of their practical time (about 40% of the total training period) with the breeders. Mostly they work in the field learning-by-doing between-plot selection and selection of individual desired plants within segregating plots. They also are also engaged in seed selection. The breeders also contribute related classroom lectures.

Visiting Scientists

Annually a large number of visiting scientists from various national wheat programs or other wheat research groups visit our breeding programs with the aim of collecting germplasm for use in their own programs. We recommend they spend 2-3 weeks at CIMMYT to allow them to achieve their selection objectives and visit some of the other programs at CIMMYT.

The germplasm collection program is as follows:

- Introduction to and familiarization with the bread wheat breeding philosophy and breeding strategies by reading this "Guide to Bread Wheat Breeding at CIMMYT" and consultation with the breeders,
- Tour of the breeding fields and visits to specific nurseries of special interest with the breeders, and acquiring an understanding of the field layout through the reading of the "Field Plan,"
- Determining which nurseries and yield trials should be visited in detail to select germplasm of interest, in order of priority, indicating these nurseries and yield trials in the "Field Plan" with the breeders,
- Visiting the fields to select 1-2 spikes of those nurseries and yield trials that have been prioritized, and harvesting these spikes in specially provided envelopes, writing the name of the nursery or yield trial and the entry number on the envelope,
- Threshing the harvested spikes after they have sufficiently dried,
- Organizing the envelopes by nurseries and yield trial, and the lines within an ascending entry order,
- Naming the new nursery as follows: V (for visitor)/Country/Name of visiting scientist (e.g. V/Mexico/Lopez), and numbering the entries starting from one till the last entry is numbered,

- Preparing a list of the new "V/Country/Name" nursery, in which behind the new nursery number the name of the original source nursery or yield trial is written followed by the number of the entry from which 1-2 spikes were harvested,
- Packaging of the envelopes with seed (closed with a paperclip) into specially provided boxes,
- Turning over the boxes with seed-containing envelopes plus the original list of the new V/Country/Name nursery and two photocopies personally to the respective breeder.

The seed of the new V/Country/Name nursery will be multiplied in hill-plots in El Batan in a special field block. During the crop cycle the plots are treated with fungicide on several occasions to ensure high quality seed for subsequent shipment to the visiting scientist. The person in charge of the CIMMYT Seed Health Unit, Monica Mezzalama, regularly monitors these multiplications.

It is expressly prohibited, according to rules set by the CIMMYT Wheat Program Director, to carry seed on one's person or in one's luggage straight from CIMMYT's breeding fields abroad. All seed must first go through the described multiplication phase in El Batan. These rules were put in place to protect the seed-receiving countries from potential exposure to novel pathogens, such as KB, that may threaten their commercial production.

Mid-Career Fellows

In addition to the regular training and visiting scientist program the CIMMYT Wheat Program sometimes provides the opportunity, depending on space and funding, to a select number of experienced persons from a NARS, who are in the middle of their career and show great professional promise, to spend 6-12 months in one of the bread wheat breeding programs, as a mid-career fellow.

In that position emphasis is not just on learning new germplasm or germplasm collection, but also on how to manage a large breeding program. This includes determination of objectives, effective leadership, and effective and efficient resource utilization.

For additional information, please contact one of the individual bread wheat breeders.

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