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Chapter 7
Achieving Genetic Gains in Practice

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Abstract Accelerating the rate of genetic gain for grain yield together with key traits is pivotal for delivering improved wheat varieties. The key strategies of CIMMYT's spring bread wheat improvement program to continuously increase genetic gains and deliver elite wheat lines to national partners in the target countries include: breeding for product profiles that prioritize selection traits; robust choice of diverse parents by leveraging all phenotypic and genotypic data; effective crossing schemes with an optimal proportion of different types of crosses; early-generation advancement using the selected-bulk breeding scheme that reduces operational costs; the two generations/year field based "shuttle-breeding" that reduces the breeding cycle time while selecting breeding populations in contrasting environ-

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ments with diverse biotic and abiotic stresses; making advancement decisions for elite lines using data from intensive multi-trait, multi-year and multi-environment phenotyping; integrating new methods like genomic selection; utilizing yield and phenotypic data from international yield trials and screening nurseries generated by worldwide partners for identifying and utilizing superior lines; and maintaining effective partnerships with the National Agricultural Research Systems who serve as key leaders in developing, releasing, and disseminating varieties to farmers. In addition to these strategies, new breeding schemes to reduce the cycle time and recycle parents in 2–3 years are being piloted and optimized to further accelerate genetic gain.

Keywords Product-profile · Crossing · Selection · Advancement · Phenotyping

7.1 Learning Objectives

- Product profile-based breeding.
- Parental selection and crossing strategies.
- Early-generation advancement and selection strategies.
- Advancement decisions for elite lines and phenotyping strategies.
- International screening nurseries and yield trials.
- Integration of genomic selection.
- Partnerships with national programs.

7.2 Introduction

Wheat, the world's second largest food crop and it's largest primary commodity is grown on over 215 million hectares annually and is consumed by over 2.5 billion people in 89 countries. With a global production of about 760 million metric tons, wheat provides 20% of the world's calories and protein [1]. However, with an increasing global population and changing diets, the current global average rate of wheat yield increase (0.9%) is insufficient to meet the projected rising demands by 2050 [2]. Moreover, other escalating challenges like the evolution and spread of new biotypes of diseases and pests, climate change including weather variabilities, temperature fluctuations, increased frequencies of drought and heat stresses etc. [3–6], necessitate continuous efforts to accelerate the rate at which biotic and abiotic stress resilience is built into new wheat varieties, along with higher grain yield (GY), market-preferred traits and nutritional quality. While this can be achieved through a combination of genetic gains, improved agronomy, and policy changes, increasing genetic gains is a highly effective and feasible intervention for delivering improved wheat varieties to farmers.

The International Maize and Wheat Improvement Centre's (CIMMYT's) spring bread wheat breeding program that is widely recognized as the main source of new varieties and elite lines, especially for the developing world, delivers over 1% annual genetic gain for GY, while ensuring diverse resistance to rusts and other important diseases and building climate resilience [7, 8]. The elite spring bread wheat lines developed by CIMMYT's Global Wheat Program (GWP) are released by national programs and private companies and grown on about 40 million ha in developing countries. In addition, another 20 million ha are sown to varieties that are derived from national breeding programs by using a CIMMYT bred line as parent. This makes CIMMYT's GWP by far the biggest provider of spring bread wheat germplasm globally and driver of genetic gain by deploying many successful breeding strategies to continuously deliver improved germplasm to the target countries in Asia, Africa and Latin America with impacts reaching beyond these targeted geographies. In addition, CIMMYT also breeds winter/facultative wheat (Box 7.1), adapted to West and Central Asia, from Ankara, Turkey and for China from Beijing. In this chapter, we discuss some of the main strategies deployed by the wheat breeding program to achieve genetic gains for GY together with other key biotic, abiotic, nutrition and quality traits while enhancing genetic diversity for relevant traits in elite breeding germplasm.

Box 7.1: Winter and Facultative Wheat

Winter and facultative wheat varieties cover around one third (80 million ha) of the global wheat area [9]. The biggest winter wheat producers are China, Russia, USA, France and Ukraine. Except in China, basically all winter wheat produced is rainfed. The terms winter, facultative and spring refer to sowing time and therefore define the adaptation of wheat to low temperatures. While this makes sense for countries that experience winter, it is misleading for the global south, where more than 90% of all wheat is of spring type and sown in fall/winter. For facultative wheat, there exists no clear definition and is compared to true winter wheats, in general less cold tolerant, has a shorter vernalization period, starts growth in spring earlier, flowers earlier and is grown in areas with milder winters, late fall rains or when late sowing is required due to tight crop rotations. Central and West Asian countries and South America grow facultative wheats on large areas. The Turkey-CIMMYT-ICARDA International Winter Wheat Improvement Program based in Turkey is developing winter and facultative wheats for these regions.

The main genetic difference between winter and spring wheat is the allelic combination for vernalization (*Vrn*) and Photoperiod (*Ppd*) and presence of alleles for frost tolerance (*Fr*). The combination of these alleles is a major determinant for the adaptation of a wheat cultivar [10]. Winter wheats are also considered to have a better tillering capacity. The knowledge of the genetics of adaptation in wheat has revealed that the distinction between what is a winter and a spring wheat is now very blurred and it really depends on the environment. For example, in the UK, some recently released spring wheats can be sown in autumn and some winter wheats are adapted to early spring sowing. By definition, winter wheats require vernalization, frost tolerance,

(continued)

Box 7.1: (continued) and are generally photoperiod sensitive while ‘true’ spring wheats are vernalization and photoperiod insensitive and susceptible to freezing temperatures. But, there are combinations of alleles that defy this broad characterization.

Winter wheat can survive freezing temperatures after they had gone through a hardening process. (see [11]) The biological limit to survive low temperature in wheat is −20 °C for 12 h without snowcover. Only rye and Triticale (up to −23 °C) are more tolerant. Vernalization is a widespread temperature control mechanism in the plant kingdom that assures that plants do not enter generative stages prior to winter. Vernalization is fastest when wheat is exposed to temperatures between 4 and 5 °C for 4–8 weeks. Wheat vernalizes between −2 and 16 °C, but lower or higher temperatures extend the time to vernalize significantly. The 4–8 weeks required to vernalize winter wheat defines the limit for rapid cycling and doubled haploids. Winter wheat breeding programs using single seed descent on a commercial scale are therefore limited to 3 cycles per year.

For other traits, the genes in winter and spring wheat are similar, though spring and winter wheat gene pools are distinctly different. To exploit these genetic differences, winter and spring wheats are often crossed. Spring type is dominant over winter type. Derivatives of Spring × Winter crosses developed in the 70s at CIMMYT represented a breakthrough in yield stability and yield potential and were released worldwide in the global south. Today, WxS crosses are made to exploit heterosis in hybrid programs and in particular to raise the yield potential. While WxS derivatives have excellent yield potential, many lines still need to be improved for grain plumpness i.e. less grain shrivelling. It is foreseen, that winter × spring crosses and their derivatives become increasingly important for global wheat improvement.

7.3 Product Profile-Based Breeding

To deliver client-oriented improved germplasm with high potential for adoption by farmers, the spring bread wheat program has recently adopted the approach of breeding for product profiles, which is similar to the mega-environment (ME) targeted breeding approach used for decades [12]. A product profile is defined as a set of targeted attributes that a new plant variety, or animal breed, is expected to meet in order to be successfully released onto a market segment [13]. It is essentially a combination of basic or must-have traits and value-added traits targeted in a new variety that can replace a current market-leading product in a target production zone. Hence, through consultations with national partners, considering the requirement of target countries for releasing varieties, knowledge accumulated over years of international collaboration, knowledge of the consumption of wheat-based products (end-use quality) by rural and urban populations, consideration of agro-ecological conditions, and market segmentation, the GWP has prioritized six market segments/product profiles (Table 7.1) along with the key selection traits (Table 7.2)

Table 7.1 Spring wheat market segments for CIMMYT wheat breeding pipelines

Market segment (broad) – bread wheat	Mega-environment	Representative wheat countries/regions	Area (million ha)	Average grain yield (t/ha)	Total wheat production (million tons)	Value of crop (billion USD)[a]	Farming family (million)	Food for people in market segment (million)
1. Hard White-Optimum Environment-Normal Maturity (HW-OE-NM)	1	Northwestern Plain Zone of India, Central and Northwestern Pakistan, irrigated mid hills of Nepal, Afghanistan, Iran, Iraq, Libya, Turkey, Egypt, Uzbekistan, Mexico, Chile, Zambia, Zimbabwe.	26.25	4.3	112.9	25.96	19.69	940
2. Hard White – Heat Tolerant-Early Maturity (HW-HT-EM)	5a	Northeastern Plain Zone of India, Bangladesh, Terai of Nepal, in addition to some wheat growing areas in Myanmar, Egypt, Sudan, recently opened irrigated areas of Ethiopia, Bolivia and Mexico.	10.46	2.46	25.7	5.92	9.92	322
3. Hard White – Drought Tolerant Normal Maturity (HW-DT-NM)	4a	Afghanistan, Iran, Iraq, Lebanon, Turkey, Syria, Morocco, Algeria, Tunisia, Libya, Mexico and Central American countries.	8.9	2.16	19.2	4.42	2.94	107
4. Hard White-Drought Tolerant Early Maturity (HW-DT-EM)	4c	Central and Peninsular zones of India, and Southern Punjab of Pakistan.	7	2.84	19.9	4.57	4.6	248
5. Hard White – High Rainfall – Normal Maturity (HW-HiR-NM)	2	Highlands of Ethiopia, Nepal, India, Mexico and other countries.	2.08	3.3	6.9	1.58	2.3	113

(continued)

Table 7.1 (continued)

Market segment (broad) – bread wheat	Mega-environment	Representative wheat countries/regions	Area (million ha)	Average grain yield (t/ha)	Total wheat production (million tons)	Value of crop (billion USD)[a]	Farming family (million)	Food for people in market segment (million)
6. Hard Red-High Rainfall – Normal Maturity (HR-HiR-NM)	2/4b	Highlands of Kenya, Uganda, Tanzania, Rwanda, Bolivia, Turkey, Iran and Mexico (spillover benefitting countries in southern Africa and South America with 9.8 million ha).	0.31	1.9	0.6	0.14	0.15	3
Total			55.0	3.37	185.2	42.59	39.59	1732

[a] Additional USD 10 billion estimated value of wheat straw, essential for livestock in the targeted market segments

Table 7.2 Selection traits and their priorities in the product profiles

	Product profile/market segment				
Key traits	1. Hard White-Optimum Environment-Normal Maturity (HW-OE-NM)	2. Hard White – Heat Tolerant – Early Maturity (HW-HT-EM)	3. Hard White-Drought Tolerant – Normal Maturity (HW-DT-NM)	4. Hard White-Drought Tolerant – Early Maturity (HW-DT-EM)	5. Hard White – High Rainfall-Normal Maturity (HW-HiR-NM) & 6. Hard Red-High Rainfall-Normal Maturity (HR-HiR-NM)
High and stable yield potential	XXX	XXX	XXX	XXX	XXX
Water use efficiency/ Drought tolerance	X	X	XXX	XXX	XX
Heat tolerance	XX	XXX	XX	XXX	X
End-use quality	XXX	XXX	XXX	XXX	XXX
Enhanced grain Zn (and Fe) content	XXX	XXX	XXX	XXX	XXX
Stem rust (Ug99 & other)	XX	XX	XX	XXX	XXX
Stripe rust	XXX	XX	XXX	XX	XXX
Leaf rust	XXX	XXX	XXX	XXX	XX
Septoria tritici blotch	–	–	XXX	–	XXX
Spot blotch	X	XXX	–	X	–
Fusarium – head scab and myco-toxins	–	–	–	–	XX
Wheat blast	X	XXX	X	X	X
Maturity	Normal-late	Early	Normal	Early	Normal
	Importance: *X= low*, *XX= moderate*, *XXX= high*				

Common agronomic traits: Plant height, stem strength, leaf health, spike fertility, grain size, grain plumpness, etc for targeting wheat area of approximately 55 million ha (spillover benefit reaching to another 9.8 million ha) in Asia, Africa and Latin America. Chapters 8, 9, 10, 11 and 12 highlight the importance of biotic and abiotic stresses, end-use and nutrition quality for wheat breeding. Moreover Chap. 3 describes the targeted breeding environments.

7.4 Parental Selection and Crossing Strategies

Chapters 5 and 6 describe the breeding methods. The selection of parents for crossing is one of the most important steps for improvement of GY and other traits [14]. Hence, all the available phenotypic data for GY, agronomic traits, disease resistance, end-use quality, and molecular marker data are leveraged to select the best parents. Since diversity is also a key criterion, parental selection each year is done simultaneously from four different cohorts of elite breeding lines that are at different stages of GY testing. This includes about 1% (~100) of lines in the stage 1 or first-year GY trials, 15% (~150) of lines in the stage 2 or second-year yield trials, 30% (~80) of lines in the stage 3 or third-year yield trials, and 10% (~20 most outstanding) of lines in the international trials are recycled as parents. In addition, elite lines from pre-breeding programs, national partners (including private sector), newly released varieties, targeted synthetics, donors for new genes/traits are also used and about 10% of the crosses made are with these parents.

An optimal proportion of simple crosses, top crosses (three-way) and single-backcrosses (BC_1) is made each year [15] to obtain superior progenies and increase the genetic gain for multiple traits simultaneously. A simple cross is made among elite parents or between an elite parent and another parent that is a donor for a trait that the elite parent lacks. Currently, about 1500 simple crosses are made annually in the summer season (May-October) in the field at CIMMYT's headquarters at El Batan to include parents immediately from the main crop season in Ciudad Obregon (Cd. Obregon or Obregon) and other field sites worldwide (November-May). In cases where both the parents are not elite, a top cross is made using a third elite parent. Similarly, when one parent lags in GY, or when non-CIMMYT parents are crossed, a BC_1 is made using the elite parent as the recurrent parent. The BC_1 approach was initiated in the early 1990s, to transfer 3–4 quantitative trait loci (QTL) based adult plant resistance to leaf rust (LR), and to introduce some major rust resistance genes from winter wheat [16]. However, it was observed that the frequency of BC_1-derived advanced lines with the same or higher GY than the checks was 6–7 times higher than the lines derived from simple and top crosses. Hence the BC_1 approach was very advantageous, because in addiction to shifting the mean GY of the progeny towards the higher yielding parent, it was also possible to simultaneously utilize the useful GY QTL from the donor parent. But we observed that making a second backcross to obtain BC_2 was not very useful, as the GY shifted towards the recurrent parent's GY. Nonetheless, BC_2 is required for transferring traits from distant sources, e.g. high zinc content, where land races and synthetics are used, for the incorporation of resistance genes through marker-assisted backcrossing etc. Each year, about 1200 top crosses and BC_1s (about half each) are made in the field in Obregon. Double crosses (4 way, between two F_1s) were used in the 1970s [12], but were discontinued in the early 1980s, because of too much variation in the F_2s and until today, no CIMMYT line derived from a double cross has been released.

7.5 Early-Generation Advancement and Selection Strategies

A combination of two effective breeding strategies is used to achieve genetic gains for key traits in early generations. One of them is the selected-bulk breeding scheme, where all segregating early generations until the F_4 or the F_5 stages are selected visually for agronomic features, phenology, LR, stem rust (SR), stripe rust (YR), spike fertility and tillering capacity; spikes from the selected plants are harvested and threshed in bulk; grains sieved to retain only larger, plump and healthy grains [16]. This scheme proved to be highly effective considering the operational costs, as it permitted retaining large numbers of selected plants in each population at a low cost.

The other successful strategy involving the growing of two generations per year, thereby reducing the breeding cycle time by half (five years for obtaining the stage 1 GY trial results) is the Obregon-Toluca field-based shuttle breeding program, where germplasm is shuttled between these two contrasting environments in Mexico. Obregon, which is located at 39 m.a.s.l in the Sonora desert of Northwestern Mexico has CIMMYT's main wheat breeding and GY phenotyping research station, the Centro Experimental Norman E. Borlaug (CENEB), where wheat is sown in November and harvested in late April/May. The desert conditions in Obregon along with insignificant to no rainfall during the crop season facilitate screening for extreme drought stress under drip irrigation, as well as for GY potential under full irrigation. In addition, screening for tolerance to early and terminal heat stresses is feasible by altering the planting time. Besides, Obregon also favors screening and selecting segregating populations, head-rows and advanced lines for biotic stresses like SR and LR. On the other hand, Toluca located at 2640 m.a.s.l in the highlands of the State of Mexico has CIMMYT's research station, where wheat is sown in May and harvested in September/October. It serves as an ideal site for screening diseases like YR, STB (Septoria tritici Blight) and FHB (Fusarium Head Blight), because of cooler temperatures and high rainfall (>1000 mm) favoring epidemics of these diseases. The adaptation and GY stability of CIMMYT's elite lines in a range of targeted environments has been attributed to the response from selection under these highly contrasting shuttle-breeding environments, with diverse day-length, temperature regimes, rainfall patterns and biotic stresses during the breeding cycles [17].

A description of the 'Obregon-Toluca shuttle' (Fig. 7.1) for early-generation advancement and selection strategies for simple crosses, top crosses and BC_1s is described in Table 7.3. In addition to the Obregon-Toluca shuttle, the Mexico-Kenya shuttle breeding program (Fig. 7.1) was initiated in 2008 to increase the frequency

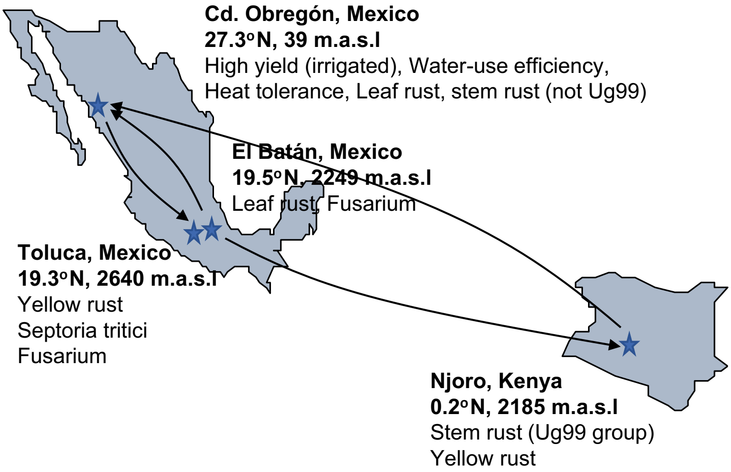

Fig. 7.1 The two-generations/year Ciudad Obregon-Toluca shuttle breeding implemented by Norman E. Borlaug in Mexico in 1945 to reduce breeding cycle time, and the Mexico-Kenya shuttle-breeding initiated in 2008 to rebuild resistance to stem rust in CIMMYT wheat germplasm

of resistance to the Ug99 race group of SR fungus [18]. This shuttle has permitted to drastically increase the frequencies of alleles involved in quantitative resistance to SR in combination with high GY potential, as well as the enrichment of breeding lines with some race-specific resistance genes. In this shuttle, the F_3 and F_4 selected-bulk populations (about 1000 plants/population) that are harvested in Toluca in September are shipped to Njoro, Kenya, selected for two consecutive seasons and the resulting F_5 and F_6 selected-bulk populations are brought back to Obregon for individual plant selection. To reduce a year in breeding cycle time, the procedure was modified in 2020 by shipping F_2s (from F_1-top and BC_1) to Kenya for shuttle breeding.

About 70,000 individual plant-derived plots (2-rows, 0.2 m^2), which comprise the F_5 to F_7s (from the Obregon-Toluca shuttle and the Mexico-Kenya shuttle) are grown in Toluca during the months of May to October (Table 7.3). The best lines are selected for agronomic traits, YR and STB resistance. This is followed by planting of about 25,000 selected plots (2-rows, 0.56 m^2) in Obregon during the months of November to April, which are further selected for agronomic traits and LR resistance. The selected plots are then cut to obtain enough seed, selection for grain characteristics is done, and seeds from the selected lines are retained for the first year of GY trials. About 13,000 selected plots (2 rows, 0.3 m^2) of advanced lines are then grown in Toluca (and El Batan for seed multiplication for international shipment) during May to October, selected for agronomic traits, YR and STB resistance. Finally, about 9000 elite lines are selected for evaluation in the first year of GY trials, using the seed retained previously in Obregon. Simultaneously, a parallel set of these plots are also grown for SR and YR phenotyping in Kenya.

Table 7.3 Description of the early-generation advancement and selection strategies for simple crosses, top crosses and single-backcrosses (BC_1) in the shuttle breeding scheme

Year	Activities	Field	Duration	Details
1	Crossing	El Batan	May–October	Parents sown as crossing block on 3 sowing dates. About 1500 simple crosses are made.
	F_1s (simple crosses) grown	Obregon	November–April	The 1500 F_1 (simple crosses) are sown (2 rows/1 m long) and about 1200 top/BC_1 are made. About 750 selected F_1 plots are harvested to obtain the F_2 populations.
2	F_2s (simple crosses) & F_1s (top/BC_1) grown	Toluca	August–October	About 1200 F_2 plants per simple cross (~700 crosses) and 400 per top/BC_1 cross (~600 crosses each) are grown with 8–10 cm spacing; and selected for agronomic and disease resistance traits. The spikes from the selected plants are harvested in bulk.
	F_3s (simple crosses) & F_2s (top/BC_1) grown	Obregon	November–April	About 400 F_3 plants per simple cross (~700 crosses) and 1200 F_2 plants per cross from F_1 top/BC_1 (~600 crosses each) grown with 8–10 cm spacing; and selected for agronomic and disease resistance traits. The spikes from the selected plants are harvested in bulk.
3	F_4s (simple crosses) & F_3s (top/BC_1) grown	Toluca	May–October	About 400 F_4 plants per simple cross (~700 crosses) and 400 F_3 plants per cross from F_1 top/BC_1 (~600 crosses each) grown with 8–10 cm spacing; and selected for agronomic and disease resistance traits. The spikes from the selected plants are harvested in bulk.
	F_5s (simple crosses) & F_4s (top/BC_1) grown	Obregon	November–April	About 300 F_5 plants per simple cross (~700 crosses) and 300 F_4 plants per top/BC_1 (~600 crosses each) grown with 8–10 cm spacing; and selected for agronomic traits and leaf rust resistance. Selected plants are harvested individually and selection for grain characteristics is done after threshing.
4	F_6s (simple crosses) and F_5s top/BC_1 grown	Toluca	May–October	About 70,000 individual-plant derived plots (2-rows, 0.2 m^2) are selected for agronomic traits, uniformity, yellow rust and Septoria tritici blight resistance. Bulk harvesting several thousands of lines is not possible in Toluca due to rainy conditions hence the left-over seed kept in Obregon is used after culling the discarded lines.
	F_6s (simple crosses) and F_5s top/BC_1 grown	Obregon	November–April	About 25,000 plots (2-rows, 0.56 m^2) are selected for agronomic traits, uniformity and leaf rust resistance. The selected plots are cut to obtain sufficient seed, grain selection is done, and seeds from the selected lines are retained for the first year of yield trials and for phenotyping/multiplication.

(continued)

Table 7.3 (continued)

Year	Activities	Field	Duration	Details
5	Advanced lines grown	Toluca	May–October	About 13,000 plots (2 rows, 0.3 m^2) are selected for agronomic traits, yellow rust and Septoria tritici blight resistance. About 9000 lines are selected for evaluation in the stage 1 (first year) yield trials using the seed retained in Obregon.
		El Batan	May–October	Seed multiplication under chemical control for stem rust and yellow rust phenotyping in Kenya is done.

7.6 Advancement Decisions for Elite Lines and Phenotyping Strategies

Advancement decisions for elite lines that are to be included in the international nurseries are made using phenotyping data for several traits evaluated in multiple locations/environments, as described in Table 7.4. About 9000 elite lines that enter the stage 1 of GY testing in Obregon in year 5 from crossing are phenotyped for GY at the research station in Obregon during the months of November-April. Traits like days to heading, days to maturity, plant height, lodging and agronomic scores are also recorded. Simultaneous screening for SR and YR is done in Njoro and about 1400 lines are selected, using the stage 1 GY, SR and YR data, in addition to an acceptable range for agronomic traits like plant height, heading and maturity. These selected lines are then phenotyped for resistance to several diseases and end-use quality in Toluca, El Batan and Njoro. Simultaneously, seed multiplication is done in El Batan, as required by the Mexican quarantine system, before large-scale seed multiplication in Mexicali (Karnal bunt free site in Mexico) can be done for international nurseries.

All the agronomic, GY, disease resistance and quality data generated during the summer season is used to select about 1000 lines from the 1400 lines, for inclusion in the stage 2 GY trials. These lines are evaluated for: GY under six simulated selection environments (SEs) in Obregon, LR and Karnal bunt resistance in Obregon, SR and YR resistance in Njoro, YR resistance in Ludhiana, SB (Spot Blotch) resistance in Agua Fria. Simultaneously, larger-scale seed multiplication of these lines also takes place in Mexicali. Finally, considering the multi-trait data generated for the lines comprising stages 1 and 2 GY trials, a strong selection criteria is applied to select about 280 white grained lines, which comprise the stage 3 GY trials, that are then evaluated for GY in three simulated environments in Obregon while a much larger scale seed multiplication is being done for international trials.

The phenotyping strategies for different traits evaluated in the elite lines are described for grain yield and other traits in Boxes 7.2 and 7.3, respectively.

Table 7.4 Traits phenotyped in the elite lines from different grain yield testing stages, the location or the environment where they are phenotyped, the time of phenotyping, the number of lines phenotyped and the number of replications (reps.) for phenotyping

Trait evaluated	Location/environment	Season/months	Number of lines	Reps.
Stage 1 of yield testing				
Stem and stripe rusts	Njoro-field	January–May (Off-season)	~9000	1
Grain yield	Obregon-field – Raised bed-5 irrigations	November–April		2
Days to heading	Obregon-field – Raised bed-5 irrigations			1
Days to maturity	Obregon-field – Raised bed-5 irrigations			1
Plant height	Obregon-field – Raised bed-5 irrigations			1
Quality traits	El Batan – quality laboratory	June–September	Selected (~1400)	1
Stem & stripe rusts	Njoro-field	June–October (Main-season)		1
Stripe rust and Septoria tritici blight	Toluca-field	May–October		1
Fusarium head blight	El Batan-field	May–October		1
Leaf rust				1
Stage 2 of yield testing				
Grain yield	Obregon-field – Raised bed-5 irrigations	November–April	~1000	2
	Obregon – Flat-5 irrigations		~1000	2
	Obregon-field – Raised bed-2 irrigations – moderate drought stress		~1000	2
	Obregon-field – Flat-drip managed – high drought stress		~1000	2
	Obregon-field – Early-sown heat stress-5 irrigations		~1000	2
	Obregon-field – Late-sown heat stress-5 irrigations		~1000	2
Days to heading	All the above six environments		~1000	1
Days to maturity	All the above six environments		~1000	1
Plant height	All the above six environments		~1000	1
Leaf rust	Obregon-field		~1000	1
Karnal bunt	Obregon-field		~1000	2
Stem & stripe rusts	Njoro-field	Off – and main-seasons	~1000	1
Stripe rust	Ludhiana and Karnal-field		~1000	1
Spot blotch	Agua Fria-field	November–March	~1000	1
Fusarium head blight	El Batan-field	May–October	~300	1

(continued)

Table 7.4 (continued)

Trait evaluated	Location/environment	Season/months	Number of lines	Reps.
Leaf rust and yellow rust	Seedling tests: Greenhouse, El Batan		~1000	1
Stagonospora nodorum blotch and tan spot	Seedling tests: Greenhouse, El Batan		~700	2
All quality traits			~500	1
Stage 3 of yield testing				
Grain yield	Obregon – Raised bed-5 irrigations	November–April	280	2
	Obregon – Flat-drip managed – high drought stress		280	2
	Obregon – Late-sown heat stress-5 irrigations		280	2

Box 7.2: Phenotyping for Grain Yield in Simulated Managed Environments at Ciudad Obregon, Mexico to Identify High and Stable Yielding, Drought Stress and Heat Stress Tolerant Elite Wheat Lines

Stage 1 GY trials. Lines are grown on raised beds at the optimal planting time (late November to first week of December) and irrigated optimally with five irrigations in total and with about 500 mm water. The GY evaluation plot size is 4.8 m^2 and the lines are sown as three rows over each of the two beds that are of 80 cm width.

Stage 2 GY Trials. About 1000 lines are evaluated for GY in six simulated environments, as follows: (a) **Raised bed-5 irrigations** – The lines are sown on raised beds at the optimal time and receive 500 mm water in five irrigations similar to stage 1 trials. (b) **Flat-5 irrigations** – The lines are sown in the flat planting system, as most of the irrigated wheat in developing countries is grown. Sowing is during the optimal planting time and the lines receive 500 mm of water in five irrigations. The plot size is 5.46 m^2, and the lines are sown in six rows that are 18 cm apart and 4.2 m in length. (c) **Raised bed-2 irrigations-moderate drought stress** – The lines are sown during the optimal planting time on raised beds in a moderately drought stressed environment that receives 250 mm of water in two irrigations. The plot size is 4.8 m^2, and the lines are sown in three rows over each of the two beds that are of 80 cm width. (d) **Flat-drip managed-high drought stress** – The lines are sown during the optimal planting time in the flat planting system, with about 180 mm of water supplemented through drip irrigation. The plot size is 5.85 m^2, and the lines are sown in six rows that are 18 cm apart and 4.5 m in length. (e) **Early-sown heat stress-5 irrigations** – The lines are sown on raised beds, about 3 weeks before the optimum planting time (early November) and receive optimal irrigation. The plot size is 4.8 m^2 and the lines are sown in three rows over each of the two beds that are of 80 cm width. (f) **Late-sown heat stress-5 irrigations** – The lines are sown on raised beds about 90 days after the optimal time (last week of February) and exposed to high-temperature stress during entire crop cycle, with optimal irrigation. The plot size is 4.8 m^2 and the lines are sown in three rows over each of the two beds that are of 80 cm width.

Stage 3 GY trials: Lines are evaluated in the raised bed-5 irrigations, flat-drip managed – high drought stress and late sown heat stress-5 irrigations environments, with similar conditions as for the stage 2 environments. The lines in stages 1, 2 and 3 of GY testing are sown in 300+ trials, 39 trials and 10 trials, respectively with each trial comprising 28 lines and two high-yielding check varieties in six blocks.

Box 7.3: Phenotyping of Elite Lines for Resistance to Wheat Diseases and End-Use Quality Traits

Field and Greenhouse Responses to Leaf Rust, Stem Rust, and Stripe Rust. Field response to LR (caused by *Puccinia triticina* Eriks.) is evaluated at CIMMYT's research stations in El Batan and Obregon, SR (caused by *Puccinia graminis* Pers. f. sp. *tritici*) is evaluated at the Kenya Agricultural and Livestock Research Organization, Njoro and YR (caused by *Puccinia striiformis* West. f. sp. *tritici*) is evaluated in Toluca, Njoro and Ludhiana (India). For all the rust evaluations in Mexico, the lines are sown in 0.7 m long paired rows over raised beds that are 30-cm-wide, whereas in Kenya and India, the lines are sown in the flat planting system. Appropriate rust spreaders that are artificially inoculated with a mixture of urediniospores of the most relevant races of the pathogen in the phenotyping fields are sown around the experimental fields, as well as on the hills that are on one side of the plot, in the midst of the pathway. Uredinospores are sprayed on the spreaders four-six weeks after sowing, depending on the field sites in Mexico. In Kenya, urediniospores of the SR pathogen races belonging to the Ug99 lineage are sprayed to create an artificial rust epidemic. The plants within the border rows are also inoculated by injecting a suspension of freshly collected urediniospores in water using a hypodermic syringe, twice prior to booting. However, YR infection in Kenya is from natural infection as the main phenotyping is targeted to SR. Susceptible and resistant checks are sown every 20–30 lines in nurseries and serve as indicators of disease pressure. Rust response is scored twice or thrice between the early and late-dough stages at weekly to 10-days intervals after the severity of the susceptible checks reaches 80–100%. The percentage of infected tissue (0–100%) is assessed using the modified Cobb Scale, in addition to the disease reaction. The lines in stage 2 GY trials are also phenotyped for resistance to LR and YR in the seedling stage at CIMMYT's greenhouses in El Batan, using the standard inoculation method with the most appropriate races.

Field Response to Septoria tritici Blight and Spot Blotch. Field response to STB (caused by *Zymoseptoria tritici* (Desm.) Quaedvlieg & Crous) is evaluated at Toluca. The inoculum for STB consists of a mixture of six aggressive strains, that are used to inoculate the plants 45 days after sowing using an ultra-low volume applicator. In addition, two more applications are made at weekly intervals. A border row of a susceptible spreader and a resistant variety is planted around the field. Disease evaluation is done using the double-digit scale (00–99) which is slightly modified from the Saari-Prescott 0–9 scale for rating foliar diseases. After three to four evaluations, the double-digit scores are used to calculate the disease severity percentages, from which the area under the disease progression curve is obtained. Field response to SB (caused by *Bipolaris sorokiniana* Sacc.) is evaluated at CIMMYT's research station in Agua Fria, Mexico. The lines are sown during November and harvested in March. A mixture of virulent races that occur naturally in Agua Fria are collected from leaves and used for inoculation. Disease evaluation is done similar to STB.

Field Response to Fusarium Head Blight. Field response to FHB (caused by *Fusarium graminearum*) is evaluated at the El Batan experimental station, during the summer season (May to October). The lines are planted in 1-m double rows and five checks that represent a range of resistance to susceptibility responses are included for every 50 entries. A mixture of five aggressive *Fusarium graminearum* isolates are used for field inoculation, which comprise isolates collected from naturally infected wheat spikes in different places at the State of Mexico. Spray inoculation targeted to each line's anthesis stage is done using an inoculum of 50,000 spores/ml and is repeated two days later. From anthesis to the early dough stage, the lines are misted for 10 min each hour, from 9 am to 8 pm, thereby creating a humid environment that is favorable for FHB development. Response to FHB is scored three times at 20, 25, and 30 days post-inoculation, on 10 spikes that had been tagged at anthesis. The FHB index is calculated using the total numbers of infected spikes and spikelets of each spike using the formula: FHB index (%) = severity × incidence, where severity is the averaged percentage of diseased spikelets, and incidence is the percentage of symptomatic spikes.

Field Response to Karnal Bunt. Field response to Karnal bunt (caused by *Tilletia indica*) is evaluated at Obregon. The lines are sown in two planting dates and artificial inoculation is done from January to March during the booting stage, by injecting a sporidial suspension of the fungus with a hypodermic syringe into the boot, when the awns emerge. Overhead sprinklers are used during the inoculation period for five times a day, with 20 min of misting each time, to maintain humidity via intermittent misting. When the plants mature, five inoculated heads are harvested and threshed, and the number of infected and uninfected grains per head is counted. Disease severity is then calculated as the percentage of infected grains in each head and the average infection from five spikes is obtained.

Greenhouse Response to Stagonospora nodorum Blotch and Tan Spot. Seedling resistance to Stagonospora nodorum blotch (SNB, caused by *Parastagonospora nodorum* (Berk.) Quaedvlieg, Verkley & Crous) and tan spot (caused by *Pyrenophora tritici-repentis* (Died.) Drechsler) is evaluated in CIMMYT's greenhouses in El Batan. Inoculum production and inoculation for SNB are done as described in [19] and check varieties Erik, Glenlea, 6B-662, and 6B-365 are planted every 20 rows. Reaction to SNB is scored on the second leaf of each seedling 7 days post-inoculation, with the 1–5 lesion rating scale. For tan spot seedling response evaluation, race 1 or isolate *Ptr*1 of the pathogen is used. Inoculum production and checks are similar to that for SNB evaluation. The seedlings are then rated for tan spot response, seven days post-inoculation, using a 1–5 lesion rating scale.

End-use Quality Traits. In all the quality analyses, grains from the high yielding environment with reduced protein content are used, which allows for better discrimination of lines for quality. Some of the end-use quality traits evaluated in the elite lines include: (a) Mixing time (minutes) that is obtained from a mixograph (National Mfg. Co.) according to the American Association of Cereal Chemists (AACC) method 54-40A. (b) Alveograph W or the work value under the curve and Alveograph P/L (mm mm^{-1}), which is the tenacity vs. extensibility, or the ratio of the height to the length of the curve, both of which are obtained from the Chopin Alveograph (Tripette and Renaud, AACC method 54-30A) and used to analyze dough rheological properties. (c) Flour sodium-dodecyl sulfate sedimentation volume (mL) that is measured using 1 g of flour. (d) Bread loaf volume (cm^3) that is assessed by the rapeseed displacement method according to the AACC method 10-05.01, using pup loaves that are baked as pan bread with the slightly modified AACC method 10-09. (e) Grain protein content which is measured on a 12.5% moisture basis. (f) Grain hardness or the particle size index and moisture content, that are measured using Near-infrared spectroscopy (NIR System 6500, Foss) according to the methods AACC 39-10, 39-70A, and 39-00, respectively. The Brabender Quadrumat Jr. (C. W. Brabender OHG) is used to mill grain samples, that are optimally tempered to 13–16.5%, based on the hardness. (g) Flour protein and moisture content are determined with the Antaris II FT-NIR analyzer (Thermo). Calibration for moisture (AACC Method 44-15A), and protein content (AACC Method 46-11A) are done in the NIRS instruments. (h) Flour yield is obtained as the percentage recovered from milling. (i) Test weight (kg hL^{-1}) is obtained by weighing a 37.81 mL sample. (j) Thousand kernel weight (g) is obtained by weighing the kernels, that were counted using the digital image system SeedCount SC5000 (Next Instruments). (k) Grain color is scored visually as red or white.

Table 7.5 International screening nurseries and yield trials derived from the spring bread wheat improvement program, their abbreviations, the number of entries, the target mega-environment (ME) and the grain color requirement for that environment

Trial/Nursery	Abbreviation	Entries (No.)	Target mega-environment (ME)	Grain color
Screening nurseries				
International Bread Wheat Screening Nursery	IBWSN	250–300	ME1, ME2, ME5	White
Semi-arid Wheat Screening Nursery	SAWSN	250–300	ME4	White
High Rainfall Wheat Screening Nursery	HRWSN	150–200	ME2, ME4	Red
Disease based nurseries				
International Septoria Observation Nursery	ISEPTON	100–150	ME2, ME4	White/Red
Leaf Blight Resistance Screening Nursery	LBRSN	100–150	ME4, ME5	White/Red
Stem Rust Resistance Screening Nursery	SRRSN	100–150	All MEs	White/Red
Fusarium Head Blight Screening Nursery	FHBSN	50–100	ME2, ME4	White/Red
Karnal Bunt Resistance Screening Nursery	KBRSN	50–100	ME1	White/Red
Yield trials				
Elite Spring Wheat Yield Trial	ESWYT	50	ME1, ME2, ME5	White
Semi-arid Wheat Yield Trial	SAWYT	50	ME4	White
Heat Tolerance Wheat Yield Trial	HTWYT	50	ME1, ME4, ME5	White
High Rainfall Wheat Yield Trial	HRWYT	50	ME2, ME4	Red

7.7 International Screening Nurseries and Yield Trials for Identifying Superior Lines from Multi-environment Phenotyping

CIMMYT's spring bread wheat breeding program has continued to develop and deliver germplasm to best serve the targeted major wheat growing countries through the partnership called International Wheat Improvement Network (IWIN). The spring bread wheat IWIN partners include over 200 public and private sector institutions distributed worldwide in about 80 countries, who currently test approximately 700 new elite CIMMYT spring bread wheat lines annually at over 200 field sites, resulting in a massive exchange of germplasm and valuable phenotypic datasets. These lines targeted to different mega-environments (MEs) with specific biotic and abiotic stresses [16] are distributed through several international screening nurseries and yield trials, that are described in Table 7.5 and details of the yield trials are provided in Box 7.4.

Box 7.4: The Annually Distributed International Yield Trials Distributed by the Spring Bread Wheat Breeding Program

Elite Spring Wheat Yield Trial (ESWYT): The ESWYTs comprise lines with high and stable GY relative to checks in optimally irrigated trials using three years of GY testing data. Parental diversity is also used to ensure that most lines are derived from different crosses. These lines also show good to moderate drought and heat tolerance (most lines with around 90% or higher yields compared to the checks under drought and late-sown heat stressed environments) and have normal heading and maturity. They are targeted to the irrigated environments with mostly favorable temperatures during the crop season (ME1 mega-environment) which include the Northwestern Gangetic Plains of South Asia, most of Egypt, northwestern Mexico (Obregon), various spring wheat growing areas of Turkey, Afghanistan, Iran, etc. Furthermore, the lines with heat tolerance adapt in Sudan, Nigeria, etc. and lines with STB resistance adapt in Ethiopia.

Semi-Arid Wheat Yield Trial (SAWYT): The SAWYTs comprise lines with high and stable GY relative to checks under drought stressed environments and are mostly from different crosses. The GY in optimally irrigated and late-sown heat stressed environments is generally 90% over the checks and the lines have normal heading and maturity. They are targeted to the semi-arid or rainfed or partially irrigated areas in South Asia, West Asia, North Africa and low to moderate rainfall areas of East Africa. In years of good rainfall, STB resistance is also required for these lines.

Heat Tolerant Wheat Yield Trial (HTWYT): The HTWYTs comprise early maturing lines showing high and stable GY among the early maturing group in optimally irrigated trials, with heat tolerance (similar or higher GY than early maturing check Baj#1 in the late-sown heat stressed environment) and drought tolerance (90% or higher yields than the checks under drought). These are for irrigated or partially irrigated environments where temperatures rise fast post-flowering and often the night time temperatures are slightly warmer throughout the crop season (ME5). The main target areas include the Eastern Gangetic Plains of South Asia, Southern Pakistan, Central and peninsular India, etc. These areas require wheat lines that are early heading and maturing (7–9 days in Obregon compared to lines in ESWYTs) to avoid grain shriveling due to hot temperatures.

High Rainfall Wheat Yield Trial (HRWYT): The HRWYTs are targeted for rainfed areas requiring red grain color wheat, e.g. Kenya and some other East African highlands (excluding Ethiopia where white grained wheat is required), Central and South American countries.

Considering the screening nurseries, the phenotyping data generated for the lines in stage 2 GY trials including GY, agronomic traits, resistance to diseases and quality are used in selecting about 250–300 white grained lines for including in the international bread wheat screening nurseries, 250–300 white grained lines for the semi-arid wheat screening nurseries, and about 150–200 red grained lines for the high rainfall wheat screening nurseries. In addition, other disease-based screening nurseries like the International Septoria Observation Nursery, Leaf Blight Resistance Screening Nursery, Stem Rust Resistance Screening Nursery, Fusarium Head Blight Screening Nursery and the Karnal Bunt Resistance Screening Nursery are prepared for screening these specific diseases in MEs where they are important.

The GY data generated during the three stages of testing and data from all other phenotyped traits are used in finalizing the international yield trial nurseries, which are prepared in summer and distributed worldwide for sowing in November or later depending on the hemisphere. The international yield trials are replicated (two replications) and comprise 50 entries including one local check added by the cooperator (different for each cooperator), three common CIMMYT checks (consistent over trials and change over years by maintaining overlapping checks) and 46 different entries each year. The 50 entry international yield trials were considered by the most partners to be of adequate size, based on their phenotyping capacity and the frequency of lines retained for subsequent testing, leading to varietal release or use as parents in the local breeding programs. Each year partners request trials and nurseries using https://www.cimmyt.org/resources/seed-request/ and the data returned (recovery rate of 60%) is well-maintained in the database and made publicly available at http://orderseed.cimmyt.org/iwin/iwin-results-1.php.

7.8 Integration of Genomic Selection

The spring bread wheat program constantly evaluates and integrates new breeding methods to increase the rate of genetic gain for key traits. One such promising method that has been integrated in the breeding pipeline is genomic selection (GS) that leverages genome-wide molecular marker information to select individuals based on their predicted genetic merit [20]. While GS has transformed animal breeding by increasing the accuracy of selections, reducing cycle time and phenotyping cost, its application in wheat breeding needs a better understanding of its fit in different stages of the breeding cycle and its comparative advantage over conventional breeding strategies.

Hence, GS research at CIMMYT primarily focusses on: (i) evaluating genomic prediction models for traits with different heritabilities and genetic architectures [21–25]. While the within-nursery cross-validation accuracies were moderate to high for most traits, forward predictions (using a previous nursery/year to predict the next nursery/year) were challenging for low-heritable traits like GY [25] (ii) comparing different marker densities, marker platforms and training population designs for optimizing GS schemes [25–27] (iii) comparing genomic and pedigree-based predictions in populations with different family-structures to understand the relative advantage of genomic predictions over the pedigree [28] (iv) comparing selections made from GS and the baseline phenotypic selections [29] (v) understanding the potential of GS for predicting the performance of lines in the target environments including South Asia [30, 31]. The genomic-estimated breeding values of most traits for all the lines evaluated in stages 1 and 2 of GY testing are routinely obtained each year and integrated in selection decisions.

7.9 Partnerships with National Programs for Variety Identification, Release, and Dissemination

CIMMYT maintains effective partnerships with the National Agricultural Research Systems (NARS) who are leaders in developing, releasing, and disseminating varieties to the farmers. Their responsibilities include managing the required multisite yield trials before variety release, providing seed of new varieties at the time of release, promoting new varieties and maintaining basic seed. The NARS partners' local and regional breeding programs also develop new varieties, derived from elite CIMMYT lines. Targeted NARS partners in India, Pakistan, Bangladesh and Nepal also have an early access to a larger set (540 lines and checks) of spring bread wheat lines called the South Asian Bread Wheat Genomic Prediction Yield Trials (SABWGPYTs) that was initiated as part of the U.S. Agency for International Development's Feed the Future project, for local phenotyping, selection and use in breeding. Similarly, NARS partners in Kenya and Ethiopia have early access to elite lines combining good yields, quality and resistance to three rusts and STB.

As an outcome of the very successful partnerships between CIMMYT and NARS, at least 183 direct CIMMYT-derived spring bread wheat varieties have been released by 24 partner countries during 2015–2021 (Table 7.6), replacing older lesser productive and disease susceptible varieties and ensuring adequate wheat production and affordable food for low income wheat consumers.

7.10 Outlook to Further Accelerate Genetic Gain

The annual genetic gains reported in several studies from the evaluation of CIMMYT's international nurseries in the target environments, serve as good indicators of the progress made from the current breeding strategies at CIMMYT. For example: in the optimally irrigated ME1, annual GY genetic gains of 1.63% and 0.72% (compared to the long-term check PBW343, and local checks that are continuously updated with new varieties by NARS partners, respectively) have been reported, using the ESWYTs evaluated from 2006 to 2014 [8]. Similarly, in the low yielding rainfed or partially irrigated ME4, an annual GY genetic gain of 1.8%

Table 7.6 The 183 direct CIMMYT-derived spring bread wheat varieties released by 25 partner countries during 2015 to March 2021

Country	Name of variety
Afghanistan	Daima-17, Lalmi-17, Shamal-17, Garmser-18, Pakita 20, Jowzjan 20, Nasrat 20
Algeria	Ain El Hadjar, Bordj Mehis, El Hachimia, Nif Encer
Argentina	BIOCERES 1008, MS INTA 815
Australia	Borlaug100, SEA Condamine
Bangladesh	BARI Gom 31, BARI Gom 33, WMRI Gom 3
Bhutan	Bumthang kaa Drukchu
Bolivia	Cupesi CIAT, INIAF Tropical, Yotau, INIAF Okinawa
Egypt	Misr 3
Ethiopia	Amibara 2, Deka, Kingbird, Lemu, Wane, Bondena, Hadis, Hibist, Ga'ambo 2, Balcha, Boru, Dursa, Adet 1
India	Ankur Shiva, DBW107, DBW110, DBW168, DBW93, HI1612, HI1605, HS562, PBW658, PBW677, PBW1Zn, Pusa Kiran, Pusa Vatsala, Super 252, Super 272, Super 404, WB2, WH1142, DBW187, HI1620, DBW222, NIAW3170, HI1628, HD3249, DBW252, HI1621, HUW711, Mucut, Tarak, VL Gehun 967, DBW303, WH1270
Iran	Baharan, Barat, Ehsan, Mehrgan, Rakhsahn, Sarang, Talaei, Tirgan, Torabi, Mearaj, Kelateh, Paya, Kabir, Sahar, Farin, Araz, Arman
Kenya	Kenya Deer, Kenya Falcon, Kenya Hornbill, Kenya Peacock, Kenya Pelican, Kenya Songbird, Kenya Weaverbird, Kenya Kasuku, Kenya Jakana
Jordan	Ghweir 1
Mexico	Bacorehuis F2015, Conatrigo F2015, Ñipal F2016, Ciro NL F2016, RSI Glenn, Noroeste F2018, Noeheli F2018, Hans F2019
Nepal	Chyakhura, Danphe, Munal, Tilottama, Zinc Gahun 1, Zinc Gahun 2, Bheri-Ganga, Himganga, Khumal-Shakti, Borlaug 2020
Nigeria	Lacriwhit 9, Lacriwhit 10
Pakistan	Anaaj-17, Barani-17, Borlaug 2016, Ihsan-16, Israr-shaheed-2017, Khaista-17, Kohat-17, NIFA-Aman, Pakhtunkhwa-15, Pasina-2017, Pirsabak-15, Shahid-2017, Sindhu-16, Ujala-16, Wadaan-2017, Zincol 2016, Ghazi 19, Markaz 19, Bhakkar 19, Gulzar 19, Fahim 19, NIFA Awaz, Aghaz 2019, Umeed-e-Khass 2019, Akbar 19, MH-2020, Subhani 20, MA 2020, Bhakkar20, AZRC Dera 2020, IV-2, Swabi 1, Zarghoon 2021, Pirsabak 2021, NIA Zarkhiaz 2020
Paraguay	Caninde 31, Itapua 90
Peru	INIA 440 K'ANCHAREQ
Rwanda	Cyumba, Gihundo, Keza, Kibatsi, Majyambere, Mizero, Nyangufi, Nyaruka, Reberaho, Rengerabana
Spain	Tujena, Santaella, Montemayor, Setenil
Sudan	Ageeb, Akasha
Tajikistan	Haydari, Roghun
Turkey	Altinoz, Ekinoks, Kayra, Koc 2015, Nisrat, Polathan, Karmen, Kirve, Sahika, Simge
Zambia	Falcon

(compared to the mean of four long-term checks) has been reported, using the SAWYTs evaluated between 2002 and 2013 [32]. Furthermore, in the high-rainfall and low rainfall environments of ME2, annual GY genetic gains of 1.17% and 0.73% (compared to the local checks), respectively were reported using the HRWYTs evaluated between 2007 and 2016 [33]. All these studies clearly indicate that continuous genetic gain for GY is achieved in the target environments, where the international spring bread wheat nurseries distributed by CIMMYT are evaluated.

Chapter 30 describes the methods for accelerating breeding cycles. In the current CIMMYT breeding program, it takes a minimum of five years from making simple crosses to obtaining stage 1 GY trial results and six years to obtaining stage 2 GY trial results, which contributes most of the parents for recycling. There are opportunities to accelerate generation advancement by growing 4 generations/year in a greenhouse/screenhouse/speed breeding facility, as well as expand stage 1 trials to multiple selection environments and shortening the breeding cycle time has the potential to accelerate genetic gain. Hence, the spring bread wheat breeding program has initiated piloting and optimization of two breeding schemes that will permit 3- and 2-years breeding cycle time for simple crosses and an additional year for top/BC_1. These schemes will attempt to ensure that the loss from not selecting in early segregating generations can be compensated by selection in later generations. Intensification of data-driven decisions for choosing parents by incorporating the genomic-estimated breeding values of parents and using them to eliminate populations and advanced lines at an earlier stage are also considered useful to accelerate genetic gain in the new breeding schemes. The two breeding schemes are briefly described in Sects. 7.10.1 and 7.10.2.

7.10.1 ‘Rapid Bulk Generation Advancement (RBGA) Scheme (Three-Year Breeding Cycle Time)

In RBGA scheme simple crosses will be made in a field screenhouse in Toluca with sowing of parents initiated in late May, soon after the completion of Obregon season, and F1–F3 generations advanced as bulk in the same screenhouse within one year. In year 2, the F4 populations will be grown in Toluca field for the selection of space-sown plants having the required agronomic traits and disease resistance (YR and STB). Individual spikes will then be harvested and selected for grain characteristics, and head rows will be sown in Obregon in November for selection as small plots for agronomic traits and resistance to diseases (LR, SR). In year 3, the harvested advanced lines with good grain traits will be sown in El Batan and Toluca for seed multiplication. Phenotyping for resistance to LR, YR and STB, while simultaneous genotyping will permit genomic selection, thus, advancing fewer lines to stage 1 trials in Obregon. Seed produced in El Batan will be used to conduct stage 1 trials in 4–5 selection environments in Obregon and phenotyping for resistance to rusts, spot blotch and other diseases in Mexico, Kenya and South Asia. All data will be used for selecting elite parents for recycling using breeding values.

7.10.2 'Rapid-Cycle Recurrent Selection (RCRS)' Scheme (Two-Year Breeding Cycle Time)

Although RBGA is potentially a powerful scheme, opportunities exist to further reduce breeding cycle time by growing F3 derived F4 head rows in Toluca field and then using the seed from selected harvested plots to grow stage 1 yield trials in Obregon in 2–3 selection environments. LR phenotyping and genotyping for estimating breeding values using all data will be used for selecting the best parents for recycling. The 2-year RCRS scheme is especially useful in decoupling population improvement from elite lines (product) extraction and has the potential to simultaneously accelerate genetic gain for a few traits such as grain yield and grain zinc.

7.11 Key Concepts

Delivering genetic gain in farmers fields requires a well-targeted breeding program that needs to select high value parents for hybridization, maintain and add new genetic diversity for relevant traits in breeding populations, conduct accurate phenotyping and select for a range of relevant traits to build the trait package for the development of farmers and market preferred varieties. New methods, such as speed breeding, genomic selection and gene-editing are expected to further enhance the current rates of genetic gains by improving the selection accuracy and reducing the breeding cycle length.

7.12 Conclusion

In this chapter, we have provided an overview of the CIMMYT spring wheat breeding program and discussed several successful breeding strategies like effective parental choice, the selected-bulk breeding scheme, the shuttle-breeding program, rigorous multi-environment phenotyping, international nurseries, and partnerships with national programs. These strategies and their optimization over time, have been instrumental in building a strong spring wheat breeding program at CIMMYT that continuously delivers genetic gains for GY along with other key traits. Moreover, we have also provided descriptions of new breeding schemes that offer promise to accelerate genetic gain by shortening the breeding cycle time, while delivering superior varieties.

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