2019/20 Annual Report

INTERNATIONAL WHEAT YIELD PARTNERSHIP (IWYP)

IWYP | International Wheat Yield Partnership

Research to Deliver Wheat for the Future

CONTENTS

Executive Summary

This IWYP Annual Report comes at a unique time in history, during the current Covid-19 global pandemic. For IWYP, some key activities had to be cancelled, such as the Annual IWYP Program Conference, while other activities such as communications were enhanced. Throughout the past year IWYP continued to make progress in both the research and development areas of the Science Program and our science team remains dedicated and focused. The Science Program comprises 38 projects conducted in some 60 institutions and 14 countries.

IWYP was founded on a simple yet aggressive goal, of *raising the genetic yield of potential of wheat by 50% by 2035*. To this end, a new model for funding, coordinating, and integrating international science was deployed. Now five years after initiating our Science Program, we have grown in response to need and exciting results continue to emerge. These include discovery of new sources of enhanced traits, molecular genetic markers and tools to measure phenotypes in labs and fields. Many are described in this Report.

During the last year IWYP expanded its output delivery capabilities with the launch of two new Hubs for discovery validation and pre-breeding, one in the US and the other in Europe, to accelerate the development of our research outputs in winter wheat backgrounds. These complement the spring wheat germplasm Hub at CIMMYT in Mexico. The new Hubs were developed as public-private partnerships which further demonstrates the value of IWYP innovations and should quicken delivery to farmers' fields. The management teams of public and private breeders in each new Hub have now selected germplasm and IWYP-validated outputs that can be quickly moved into their own breeding programs as soon the traits are introgressed and assessed. This establishment of a "global" platform comprising networked international discovery pipelines linked to germplasm development and pre-breeding Hubs that provide routes to market for countries in the north and south for spring and winter crops is a major achievement of the Partnership.

IWYP's scientific strategy is based on finding genetic variation that leads to improved traits underpinning yield and combining it in new combinations. From work started many years ago within CIMMYT results this year suggest that it is a promising strategy, based on early examples of high yielding lines that have been selected for both "source" and "sink" traits. Genetic analyses of such selections from multiple crosses have identified which source and sink traits are associated with the higher yields.

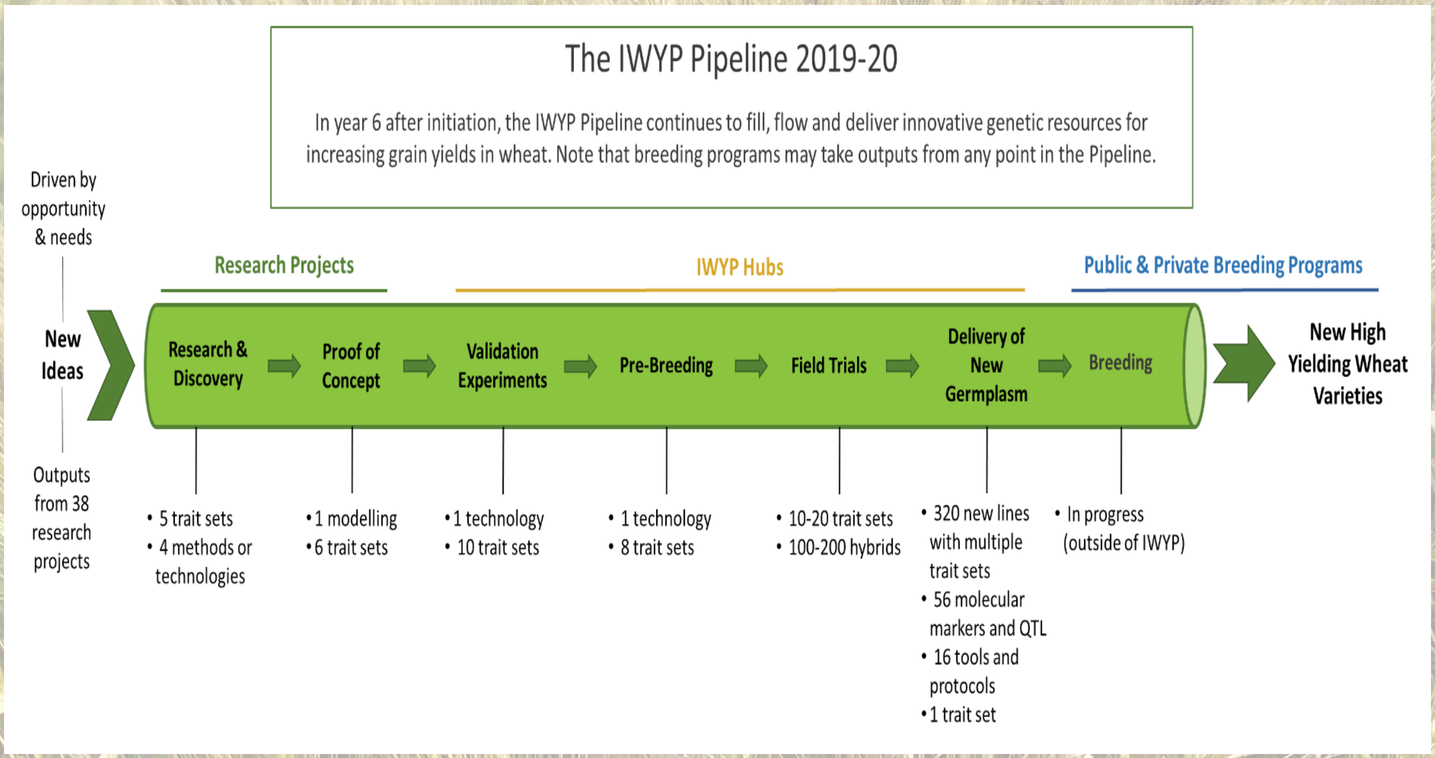
Over the past year, IWYP performed an exhaustive review to catalog the progress and delivery of new innovations from completed and ongoing research projects. This new database reveals a volume of new genetic resources and tools for yield improvement unimaginable just five years ago.

An exciting project that IWYP undertook this year, in an effort to dissect what drives grain yield in wheat, was the development of a "Wiring Diagram for Yield". A team of IWYP scientists is completing work that describes both in words and graphics the known and hypothesized traits, processes and pathways associated with determination of grain yield. The team has identified the critical linkages and relationships among the traits and processes that should reveal which innovations, and combinations thereof, have the highest probability of generating yield increases. The final output will influence strategies for IWYP pre-breeding and trait stacking and should facilitate breeding in other crops, especially other cereals. We expect the outcomes from this project will be published very soon.

The IWYP pipeline is managed and monitored by a Stage Gate system (**see below**) and continues to flow and deliver. For maximum impact and efficiency, it is important to keep the pipeline full and items progressing toward delivery. Over the last year, IWYP research projects have transferred 11 new outputs into the IWYP Hub at CIMMYT for validation. These include new traits and tools for yield components, biomass production, harvest index and radiation use efficiency. 8 research outputs were validated at the CIMMYT Hub and entered the pre-breeding stage. These include canopy, grain size, photosynthesis and phenology traits. From Hub pre-breeding, 150 new higher yielding elite lines were tested, and 32 were selected and sent for international field trials at over 100 locations across the world. These lines were also made available to breeding programs worldwide. Data received and analyzed indicate that several of these new lines significantly out-yielded the elite CIMMYT and local check varieties in most locations. As a result of these trials over the last few years, 4 of these new higher yielding lines have been selected to become varieties in a few countries including Pakistan and Afghanistan.

IWYP has now catalogued around 100 scientific journal publications resulting from IWYP research and this continues to increase. These important research findings aid to broaden IWYP's reach to the scientific community, facilitate uptake of its outputs and add to the knowledge base for crop improvement.

IWYP continually strives to reach beyond the wheat scientific community and communicate our scientific progress to a broader array of scientists, policy makers and organizations that invest in food and nutritional security. This year we began monthly publication of a series of "Science Briefs" which are one-page summaries of IWYP projects and activities. These provide a wide audience with overviews of different facets of the IWYP Science Program in short and easy-to-read summaries that include the "what, how and why" of each topic. The development of the new Asset Catalogue and Wiring Diagram for Yield are other examples of new IWYP communication tools. We continue to work with our partners, e.g., CIMMYT and the Wheat Initiative, to strengthen the types and reach of our messages.



Message from the Board Chair

As Chair of the Science and Impact Executive Board (SIEB) of the International Wheat Yield Partnership, I am very pleased to recognize the substantial progress made this past year in delivering innovations into wheat breeding, to aid and sustain yield increases. IWYP has continued to do things differently and generate innovations that make a difference.

The founding Partners of IWYP came together six years ago to create international teams to discover new sources of enhanced traits and get them tested in elite germplasm under agricultural conditions. CIMMYT was selected as the technical Hub to carry out the trait development and testing for spring planted wheats. This year two additional public-private IWYP Hubs for testing of traits in winter wheat germplasm have been launched, one in the USA and another in Europe. This is a very significant expansion of the IWYP crop improvement program. The new networked group of Hubs not only increases routes to market but also increases efficiency and global coverage.

IWYP seeks to drive upwards the rates of gain in yield, year on year, by continual introduction of newly discovered or created trait improvements, coming from scientific research around the world. Many new sources of improved traits, molecular markers to use them in pre-breeding and new tools to aid finding and measuring traits in labs and the field are reported in this Annual Report, as in previous reports. A catalog of new discoveries to use and/or evaluate now exists for all to explore.

IWYP uses a stage-gated pipeline process to manage the many discoveries through the long steps of plant improvement. Many new items have moved through stage gates this year which is important and heartening. Some advanced lines emerging from trait stacking in pre-breeding stages have displayed high yield impact in international trials-results which suggest that selecting combinations of traits in targeted, information-driven ways is a useful, progressive approach.

IWYP seeks to demonstrate how breakthroughs can be achieved to help redefine longer term expectations of the genetic yield potential of wheat. While combining a large number of small increments in breeding efficiencies is relevant, necessary and important breakthroughs in yield are most likely to come from the introduction of new variation not in elite breeding programs today. IWYP's demonstration that large yield increases can come from the introduction of genes from wild species and also from highly active *Arabidopsis* and rice genes are powerful examples of this. The creation of novel alleles by gene editing, as achieved this past year, is also destined to create major gains.

The future looks both exciting and promising. However, to exploit its discoveries, make desired trait combinations and validate them for new variety production, IWYP must continue to build and finance the downstream translation pipelines. Good progress has been made this past year with the funding of the USA and European Hubs but such progress needs to be sustained so that the potentials of scientific research for wheat improvement reach the places for which they are intended, namely the farmers of the world.

The Science and Impact Executive Board Members of the Partnership thank all members of the IWYP family for their commitment to the enhancement of wheat production, worldwide, for the benefit of future generations.

Richard Flavell
Chair, IWYP Science and Impact Executive Board

Message from the Program Director

From my perspective as Program Director for IWYP, this last year has been both exciting and challenging. The year began with seeing the data from our international yield trials and new results from the various research projects. It was gratifying to see that some of the new lines resulting from pre-breeding at the IWYP Hub at CIMMYT are significantly out yielding the elite and local check varieties indicating that the yield gain trends we are seeking are being realized. Experiments from the research projects indicate that newly completed discovery and proof-of-concept steps have identified new genetic variation for additional traits that will add to our portfolio and help us to build-out trait sets that propel wheat yields higher. Outputs continued to be delivered to the IWYP Hub at CIMMYT for validation and pre-breeding.

Then Covid-19 hit and the global pandemic began. It was unclear how long it would last and how this could affect the research and delivery activities of IWYP. Adjusting to the constraints imposed to stem the virus flow affected some activities at first, but overall IWYP Management and the science team adjusted and continue to move forward.

Over the last few months, the IWYP Hub Network expanded to include two new Hubs to expedite winter wheat development, one in the US and one in the UK. In all, the pipeline from discovery to delivery is flowing and delivering new genetic resources to the global wheat breeding community. The new Hub teams, which include both public and private partners, are selecting germplasm and traits and beginning work. This is truly an exciting development for IWYP.

What marks this past year as special is the continued persistence of the research and Hub teams to pursue and evolve the science-based decisions and technical plans required to increase genetic gain and push wheat yields significantly higher using novel genetics. IWYP will not reach its goal of increasing the genetic yield potential of wheat by 50% in 20 years by finding one or two traits that give almost mystical and instant game changing results. We recognized from the beginning that attaining this level of performance change would require combinations of multiple traits that optimize how energy is captured, stored, mobilized and utilized. As we continue ramping up activities and scaling innovations, exploring new ways to drive decisions on the “right sets of traits” to combine becomes more critical. IWYP is therefore developing new ways to facilitate these decisions based on science and efficiency, by attempting to dissect the traits and critical pathways that influence grain yield and understand their connections. This new platform for understanding crop yield should be complete by year’s end.

As always, none of the progress reported this year would be possible without the dedication and passion of all of those involved in the IWYP initiative, especially the research scientists of the IWYP international science team and the funding organizations that support them.

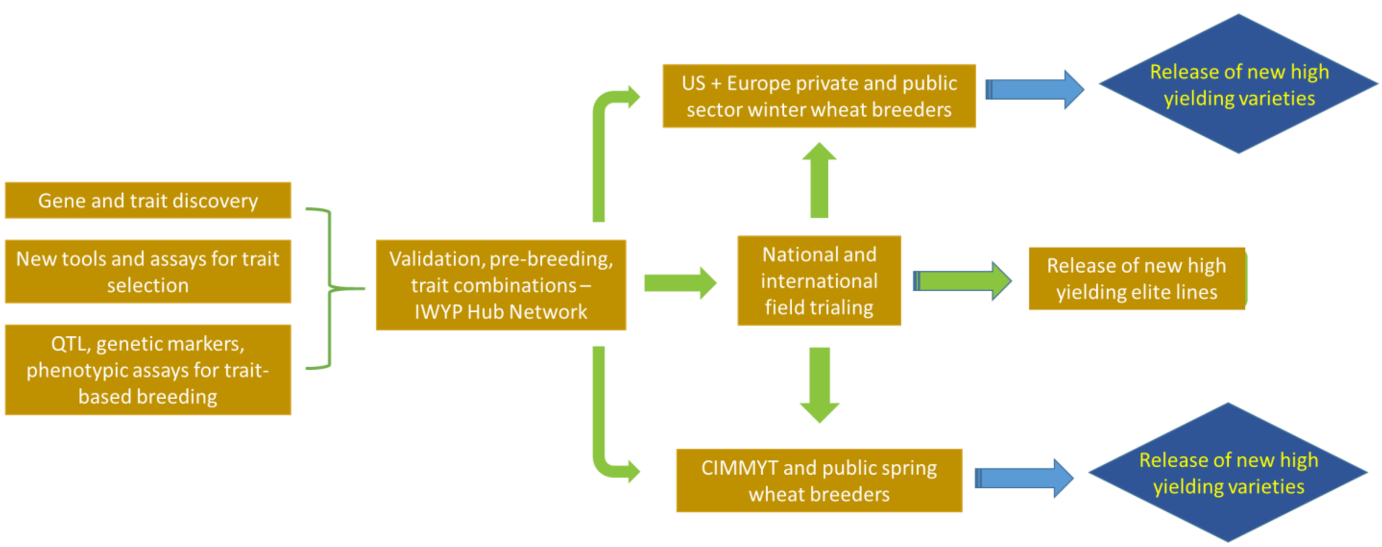
Jefferson Gwyn
IWYP Program Director

IWYP Integrates International Research and Applications for a Global Crop

IWYP is a public-private partnership focused on generating germplasm, tools and methods for the improvement of traits underpinning wheat grain yield. Its outputs serve the breeding programs of the world, public and private, rich and poor. IWYP brings together international projects originating in many countries to drive their discoveries to where they are fit-for-purpose in applied breeding programs. It also generates added value by combining discoveries from different sources to boost wheat yields. In addition to integrating international science underpinning wheat breeding, it also compiles the assets emerging from the scientific discoveries and makes them available to breeding communities around the world.

IWYP has an R&D Hub at CIMMYT in Mexico. CIMMYT has a long history of success in wheat improvement for the world. It has world-class technical skills relating to wheat germplasm improvement and makes selections in environments that are relevant to many wheat growing areas of the world. CIMMYT also catalyzes the testing of improved germplasm around the world to help find the best forms for local environments. Via this Hub, IWYP tests discoveries made in research labs around the world and combines the best in elite spring wheat lines and further develops them through pre-breeding to enhance the efficiency, outputs and impact of wheat breeding internationally.

Many areas of the world grow wheat crops that benefit from a longer growing season that includes a winter. Some of these are the focus of the private sector breeders in Europe and the USA. Such companies therefore also contribute much to feeding the world. This is why this year IWYP has established, with partners, two other R&D Hubs. The diagram illustrates the routes (in brown with green arrows) to products being catalyzed by IWYP, now in its 6th Year of operation. "IWYP in Numbers" is shown on the following page.



IWYP in Numbers

Progress and growth of IWYP is reflected in these selected metrics. Categories and associated values presented on the top left indicate the structure and size of the IWYP Science Program to date. Categories with associated values on the bottom right illustrate selected additional outputs the partnership has generated over the past year and for which more explanation is provided later in this report.

13
Public Partners

10
Private Partners

60
Scientific Institutions

14
Countries

38
Research Projects

IWYP Metrics

3
IWYP Hubs

320
Wheat Lines Available

250
New Strategic Crosses

4
Wheat varieties released

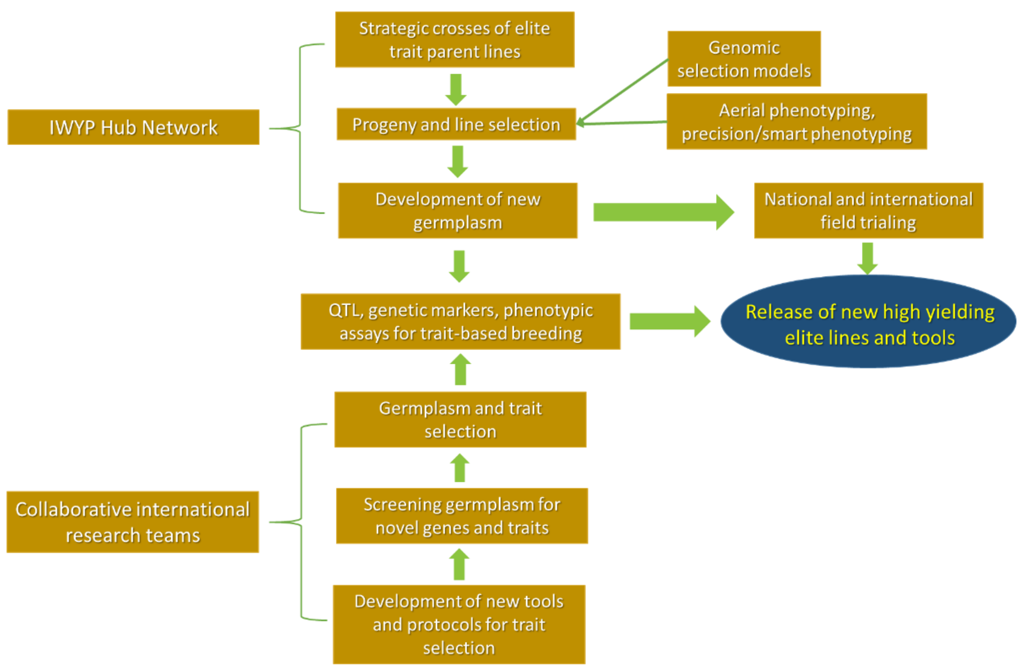
>90
IWYP Publications

>250 Scientists in Training & Capacity Building

>2K
Social Media Followers

IWYP Scientific and Delivery Strategies

IWYP seeks to improve the genetic resources and efficiency of breeding higher yielding wheats. Two general strategic approaches are used, as shown in the diagram below. In the top half of the diagram the approach entails creating higher yielding germplasm by combining parental lines with novel and improved traits found and evaluated using physiological and other assays. The performance of the traits as well as overall grain yield is then assessed across many diverse environments. Tools such as aerial evaluation of phenotypes in the field trials using cameras on drones have been developed and deployed to improve efficiencies. Analyzing the genetic and physiological basis of the improvements identifies those traits that have the most influence on grain yield, and when confirmed, the ways to assay these traits more efficiently at scale. Many of the trait stacks combine high efficiency photosynthesis and radiation use efficiency with spike and grain formation/filling traits. Trait stacking to combine different "source" and "sink" traits has become primary to our strategy. Genetic analyses of the traits that are associated with higher yields provide QTLs and/or molecular markers to aid recapitulation of the trait combinations in wheat breeding around the world via marker assisted breeding and genomic selection.



The other approach in the IWYP strategy is to survey extant genetic variation in germplasm populations, including unimproved germplasm and wild species, seeking novel variation that is associated with traits likely to increase grain yields. This is illustrated in the lower half of the diagram. Discovery of such germplasm displaying traits that are better than those found commonly in breadwheat enables linkages between the traits and QTLs/molecular markers to be discovered to aid breeding around the world. These discovery programs are conducted by international teams via grants awarded after competitive review. The enhanced traits can then be incorporated into elite germplasm and tested across many environments, in combination with other traits in pre-breeding programs.

All the outputs and assets generated by the IWYP programs are available to all breeding programs, free from exclusive intellectual property constraints, whether they be germplasm, molecular markers, tools, software or methods to assay traits. IWYP does not release varieties. This is done by breeders and national agencies.

Science Program Highlights

IWYP seeks to improve the genetic resources and efficiency of breeding higher yielding wheats. This entails creating higher yielding germplasm with novel and improved traits then evaluating its performance by measuring different characters or traits across diverse environments. Analyzing the genetic and physiological basis of the improvements identifies those traits that have the most influence on grain yield, and if confirmed, the ways to assay these traits more efficiently at scale. Over the past few years IWYP scientists at the CIMMYT Hub have been selecting lines from targeted crossing programs in which specific high value traits are stacked to assess the value of specific trait combinations to higher yields. Progress here has been significant both in terms of the germplasm created and the learnings about trait stacking. Many of the trait stacks combine high efficiency photosynthesis and radiation use efficiency with spike and grain formation/filling traits. Traits that are associated with higher yields have been identified by genetic analyses. Trait variants that contribute to higher yields are providing molecular markers for the genetic sources of the improvements for the benefit of wheat breeding around the world.

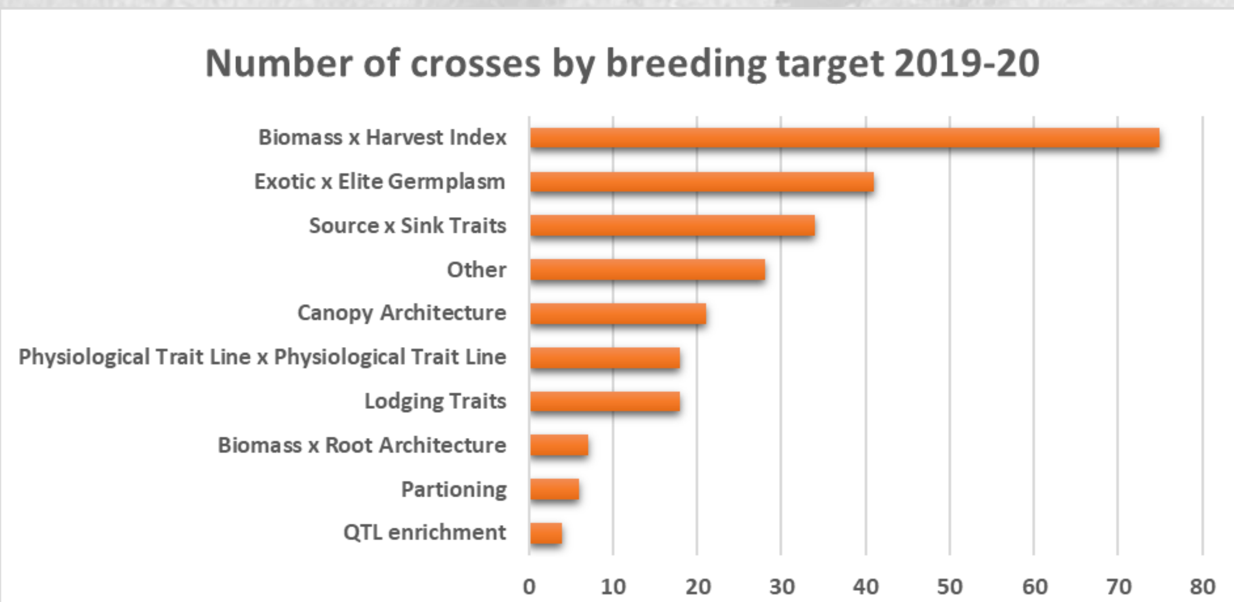
- A greater understanding of the contribution individual and combinations of physiological traits make to genetic yield potential is refining our pre-breeding strategy.
- Strategies for trait stacking continue to evolve. New tools such as the “Wiring Diagram” presented later in this Report, will serve to further define the options with the best potential.
- Our strategy of introducing novel genetic variation linked to targeted physiological traits continues to be validated with additional data.
- New molecular genetic markers for many “source” and “sink” traits continue to be delivered from the research projects and are being validated and applied in the IWYP Hub at CIMMYT.
- New phenotyping assays that are more efficient and higher throughput continue to be designed.

Trait Stacking

Trait stacking has continued at the IWYP Hub at CIMMYT as part of the pre-breeding activities, based on the wealth of knowledge generated over years on the target traits and relationships between them. Different numbers of traits having a positive effect on the source (e.g., biomass, photosynthesis, RUE) and development of a more demanding sink (e.g., spike development, fruiting efficiency, grain size and weight, etc.) are combined to produce wheat plants that display highest yields.

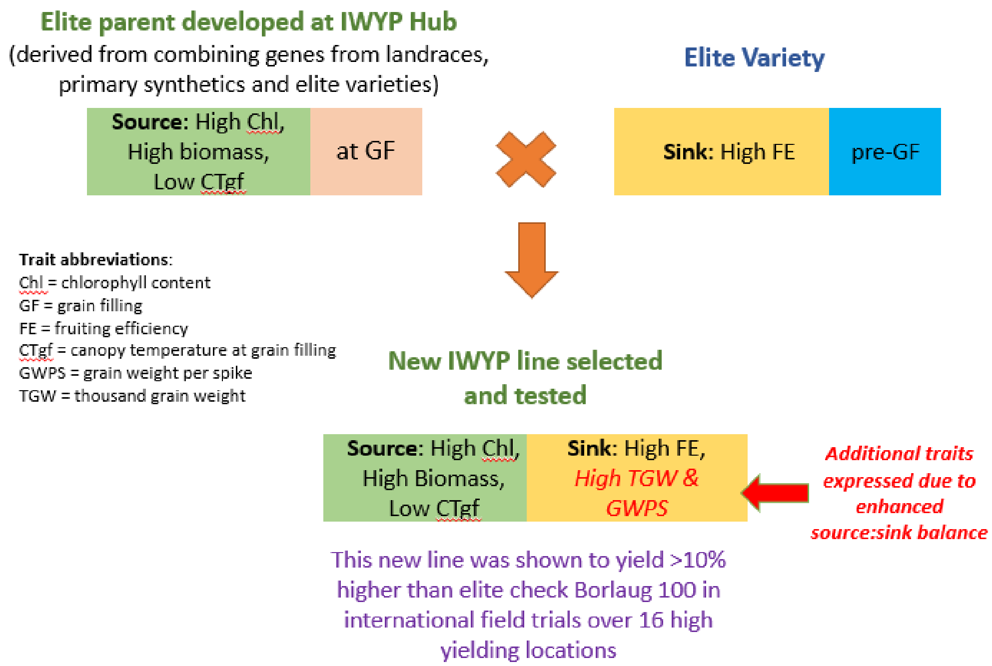
During the last annual cycle at the IWYP Hub at CIMMYT (2019-20) several hundred crosses were made based on multiple trait combination scenarios, by using either phenotypic data to select the parents or, in some cases, knowledge of the gene variant they possess that is responsible for the trait, and for which the trait is difficult to phenotype (**See Figure below**). In several instances, exotic germplasm, including synthetic wheats and landraces have provided a basis for the best expression of these traits. The traits considered when the crosses were made include:

- Biomass at different growth stages
- Biomass/day
- Canopy Temperature (gf)
- Chlorophyll content at different growth stages
- Fruiting Efficiency
- Grains per square meter
- Grain number
- Grains per spike
- Grain weight at position 4 in a spike
- Grain weight per spike
- Harvest Index
- Internode diameter
- Internode wall width
- Normalized difference vegetation index (NDVI) at vegetative state
- Peduncle length
- Plant height
- Ratio analysis of reflectance spectra-chlorophyll a
- Radiation use efficiency at different growth stages
- Spikes per square meter
- Spike number at 7 days after anthesis
- Spike partitioning index
- Spike dry weight at 7 days after anthesis
- Spike length
- Spikelets per spike
- Thousand grain weight
- Photosynthetic capacity
- Grain yield



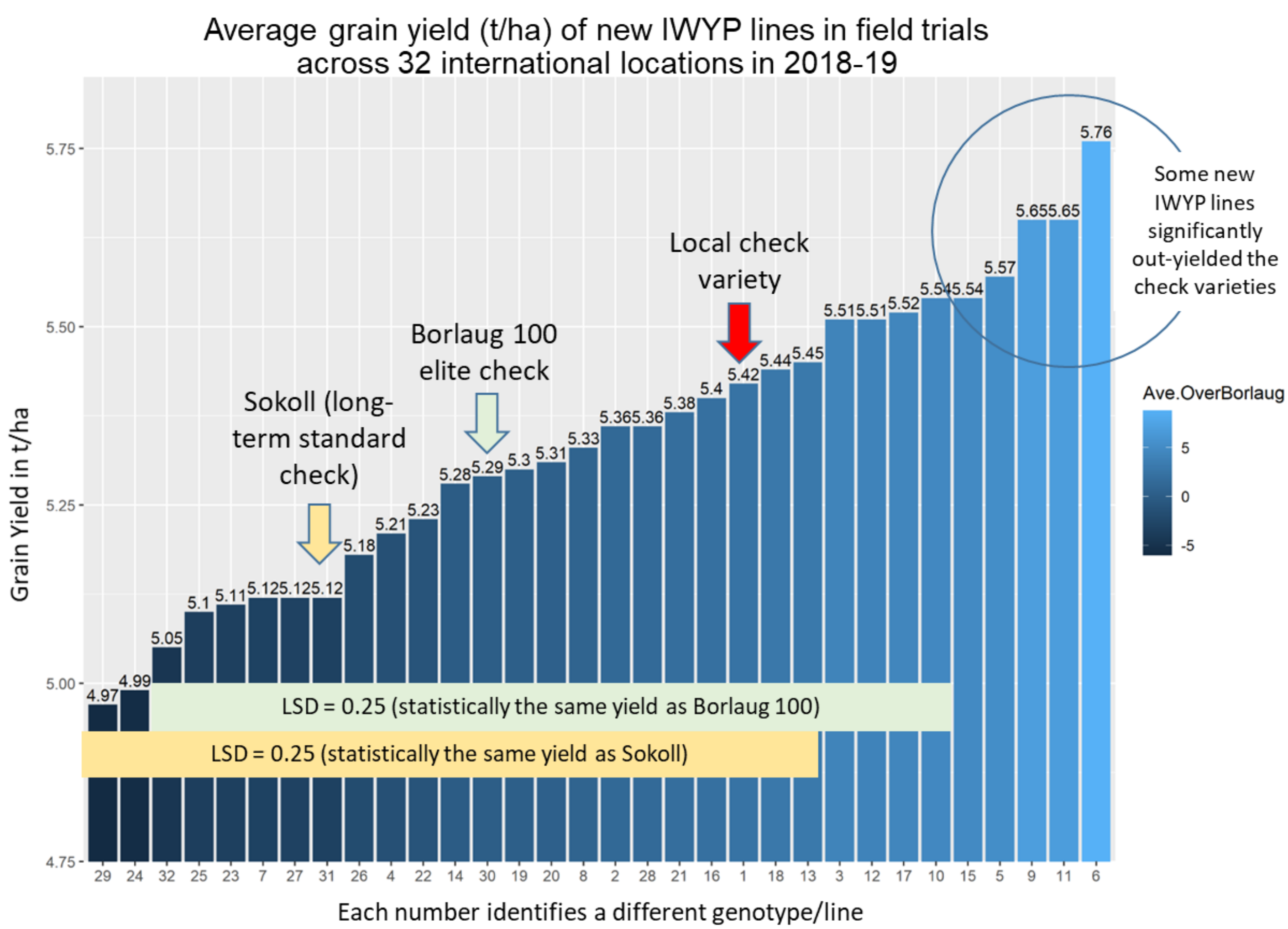
In the example shown below, an elite variety with high fruiting efficiency (sink strength) was selected as a parent to cross with a line that had a good expression of source traits (high chlorophyll content, high biomass and low canopy temperature) and which had exotic germplasm in its pedigree. From selections made in later generations, several sister lines were chosen and included in 16 international field trial locations in 2018-19.

One line had ~15% higher yield than Borlaug 100, the current elite check variety used at CIMMYT. This result demonstrates that the exploitation of novel genetic variation from landraces, primary synthetics, and other sources, when combined with traits from elite varieties, can result in an enhanced balance of source:sink traits that leads to increased yield, in this case thousand grain weight and grain weight per spike.



Genetic Gains of New IWYP lines Containing Combined Traits

IWYP is testing the hypothesis that wild species, landraces and synthetic wheat possess untapped variation for key traits such as biomass and radiation use efficiency, and in combination with the targeted selection of physiological and grain formation traits, this will lead to significant increases in genetic yield potential. Following several years of applying this strategy, IWYP continues to amass data that indicate that the hypothesis is valid and progress is being made against our goals. Some of these results are shown below.



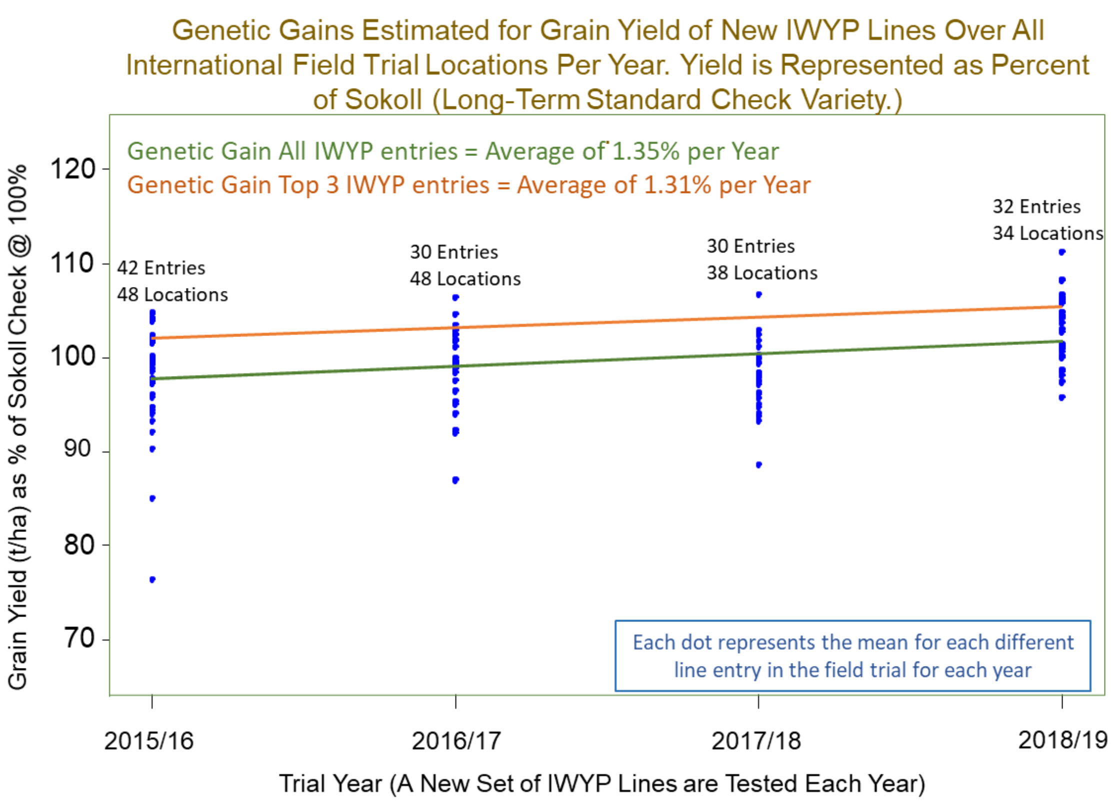
The graphic above provides a snapshot of the overall performance of some new IWYP lines tested in many locations around the world for one year. For comparison, three check varieties are also presented, two of which are CIMMYT standard checks (Sokoll and Borlaug 100) and a variety that is grown locally. While most of the new IWYP lines have yields comparable to the CIMMYT and local check varieties, some new lines significantly outperformed the checks across many environments. Pedigree analyses indicate that the traits selected in the new germplasm are contributing to the yield gains. Therefore, we believe this strategy of trait selection should continue to increase yields at a higher rate than other strategies.

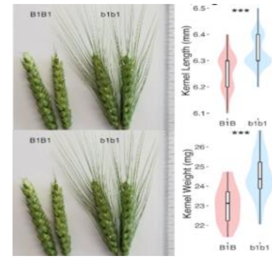
Genetic Gains of New IWYP Lines Over Time

The graph below illustrates progress made over time using the IWYP pre-breeding strategy. The results show the percent genetic yield gain achieved by new IWYP lines over many locations (numbers indicated on the graph) beginning in 2015, the year IWYP was initiated. The yield performance of all lines is presented as the percent of the long-term standard check variety (Sokoll), in order to normalize year-to-year comparisons.

The graph plots all lines evaluated in each year as blue dots, demonstrating the variation observed between the different sets of lines. Some lines outperformed the standard Sokoll control while others performed similarly or less well. There is an upward trend over time with an average genetic gain of ~1.3% over years for the new IWYP lines (green line) as well as for the best three new IWYP lines for each year (orange line).

It takes many years for determinations of rates of gain to become highly reliable. The estimated annual genetic gain in wheat yields from breeding is commonly accepted to be <1% but any estimate is challenging to infer as the data do not come from experiments specifically designed to capture this. The annual rate of genetic gain reported here of ~1.3% is an improvement upon this estimate and suggests that the strategy of combining selected new trait combinations is valid. These preliminary results are based on new selected lines from initial crosses made five years ago. The expectation is that newer crosses using the same pre-breeding strategy, and with the introduction of new IWYP Research Project outputs, will lead to additional increases in yield gain per year. To meet IWYP's goal of increasing the genetic yield potential of wheat by 50% will require breeding programs to achieve 1.7-2% gain per year.



Discovery and Enhancement of Traits

- 3 grain size genes (Ta*GW2*, *QTL5a*, *QTL6a*) have been introgressed into high biomass lines to test their effect on grain yield.

- Several wheat lines were identified with up to 27% higher biomass than elite checks from four years of field trials of ~5000 lines. Many had primary synthetics, synthetic-derived lines, landraces or combinations of these in their pedigree.

- The *GW-A2* mutation for larger grains and the *TmElf3* allele for increased grain number were introduced into the elite variety Kingbird and 3 IWYP high biomass lines. Results revealed a significant (2.4%) increase in yield, associated with an increase in spikelet number per spike, for the lines containing *TmElf3*. The *GW-A2* mutation was not associated with an increase in grain yield in all lines but did induce increases in grain size and protein content.

- Strong positive correlations were found between stem soluble carbohydrate, harvest index and grains per meter square, and between fruiting efficiency and stem soluble carbohydrate 7 days after anthesis, suggesting stem soluble carbohydrate amounts are associated with yield.

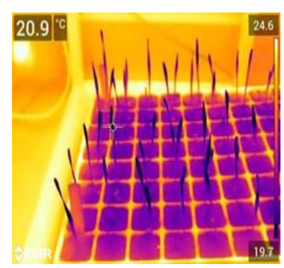
- Advanced populations combining high biomass and harvest index with different combinations of flowering time genes were evaluated. Two novel candidate genes were found to fine-tune wheat phenology and provide a stabilizing effect on yield and harvest index in specific environments.

- Newly identified native alleles for genes *TaVP*, *TaPSTOL* and *TaNAS* that have been shown when very highly expressed to increase plant biomass production and grain yield were crossed into elite Australian wheat variety “Scepter” for evaluation in field trials in Australia and at the IWYP Hub at CIMMYT.

- High biomass lines with high RUE exhibit higher heat tolerance in hot irrigated conditions and generate much higher yields. The higher yields were significantly associated with 3 new QTL for yield potential on chromosomes 6D, 1B and 2B.

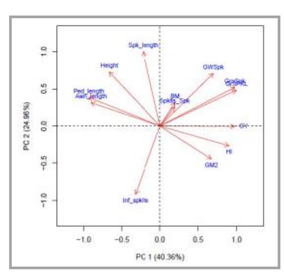
- Spike partitioning index (SPI) was found to be highly negatively correlated with internode 3 length, implying that a shorter internode 3 can be used as a proxy for selecting lines with highest SPI.

- Reducing the photosynthetic kinetic transition rate following periods of shade is associated with higher grain weight. 15 genotypes showing genetic variation in rates of photosynthetic induction (shade-to-sun transition) were selected from an initial screen of 200 lines.



- 23 accessions from 9 wild wheat species were selected for significant genetic variation in floral morphology. These may have potential for hybrid wheat breeding.

- Wheat lines containing mutations in orthologs of barley root angle and enhanced gravitropism genes have been identified. These lines which have an extremely narrow seminal root angle are being tested for yield enhancing effects.




Trait-Linked Markers and QTL

- An analysis of selected gene allele frequencies in the IWYP Wheat Yield Consortium Yield Trials (WYCYTs) revealed that the major proportion of favorable alleles came from CIMMYT elite wheats, while some rare favorable alleles came from landraces and synthetics. Most of the favorable alleles, including known major genes for phenology and plant height, increased in frequency (approaching 100% in some cases) in the final international nurseries and can be used to guide future breeding decisions, while landrace and synthetics may provide untapped novel variation not present in the CIMMYT main breeding program.

- Marker-assisted selection was used when deriving new candidate IWYP lines in the Hub at CIMMYT to fix several alleles together with the targeted yield component gene *TaGW2*.

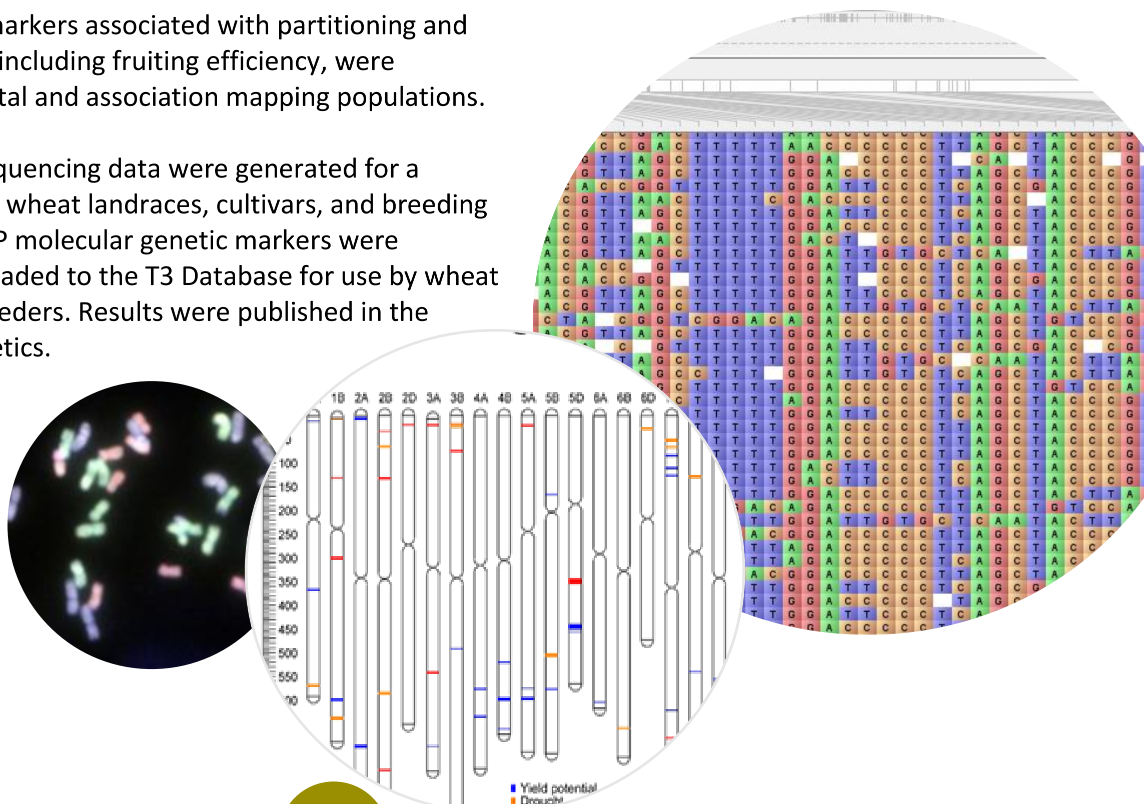
- QTLs on chromosomes 6A (Grain width) and 5A (grain length) have been combined to assess the effect of these grain size QTL on grain yield and to test their potential use as selectable markers in wheat breeding.

- KASP molecular markers for major seedling root traits, such as seminal root angle and biomass, have been developed and validated. One was used in combination with visual estimation of root biomass to select high and low root biomass lines and test if it is a useful selectable marker in breeding for specific root traits.

- SNP markers for both trehalose phosphate synthase (TPS) and trehalose phosphate phosphatase (TPP) genes were found to be significantly associated with key yield component traits. These may offer new routes to improve genetic yield potential.

- Molecular genetic markers associated with partitioning and spike fertility traits, including fruiting efficiency, were validated in biparental and association mapping populations.

- Whole exome re-sequencing data were generated for a diverse collection of wheat landraces, cultivars, and breeding lines. 8.8 million SNP molecular genetic markers were discovered and uploaded to the T3 Database for use by wheat researchers and breeders. Results were published in the journal Nature Genetics.

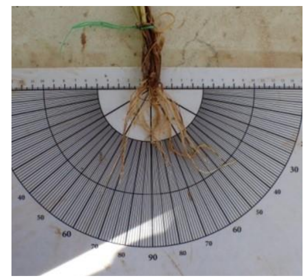


Tools and Protocols

- The IWYP Hub at CIMMYT developed a more reliable assay for determining how limited a genotype may be by the source, sink or both during grain filling and further how to quantify the balance between source and sink.

- A simpler and more rapid method to estimate fruiting efficiency was found to be highly correlated to an alternative but slower and more labor-intensive method that had previously been reported.

- A mobile LiDAR platform (phenotyping cart) was built to enable more rapid screening of approximately 300 plots per hour for biomass and plant structural traits.



- Automated pipelines for data extraction and processing of UAV image data were implemented (source code is available online (github.com/xwangksu/bip)) which will dramatically increase data compilation and analysis.

- Some yield component data collected by UAVs can be used to assay single plants. A genetic analysis using data on single plants vs. full yield plots identified the same genomic position (QTL) for spikelets per spike and spike length.

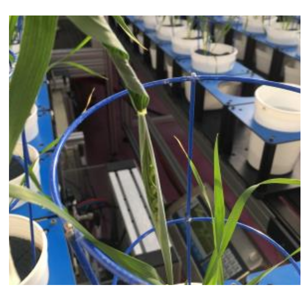
- An improved, low-cost platform designed and built to estimate the distribution of root biomass through a soil core profile by imaging the broken interfaces of soil cores was developed and validated.

- Data from the wheat "T3 Database" started being migrated to the BreedBase platform, which has more functionality for applied breeding. Practical Farmers of Iowa and the T3 team have begun the development of a variety selection tool to be used by growers to predict the top-yielding varieties for their local environment.

- Users can now search the "T3 Website" for gene, protein, and molecular pathway information contained in the Ensembl Plant BioMart. They can also download a subset of the 1000 wheat exome project by selecting specific chromosomal intervals

- More than 10,000,000 mutations in the coding regions of the wheat genome were re-mapped to Chinese Spring RefSeq v1.1, and the mutation effects on all genes annotated. This creates a very useful tool for plant breeders.

- The utility of normalized difference vegetation index (NDVI), canopy temperature (CT) and water indices for high throughput, indirect estimations of in-season biomass and Radiation Use Efficiency (RUE)-related traits has been tested. CT and NDVI had the highest correlation with biomass, particularly at the grain filling stage. This approach has the potential to greatly increase the efficiency of selecting for high biomass and RUE in breeding programs.



Creating a New Framework for Wheat Breeding

Over the last few months, a group of IWYP associated scientists, led by IWYP Management, have come together to generate a new, and as comprehensive as possible, framework for approaching wheat improvement. This has led to the creation of “Wiring Diagrams” that define the major steps and variables determining yield, as currently understood. The purpose is to describe and link all the known and hypothesized developmental/physiological/biochemical features that determine the “source and sink” traits underlying grain yield of wheat from emergence to harvest. Such a comprehensive, integrated framework does not exist at present. We believe that only when all these phenotypic traits are understood, and in genetic terms, can more efficient approaches to wheat improvement be formulated, especially in terms of trait combinations that act additively or synergistically.

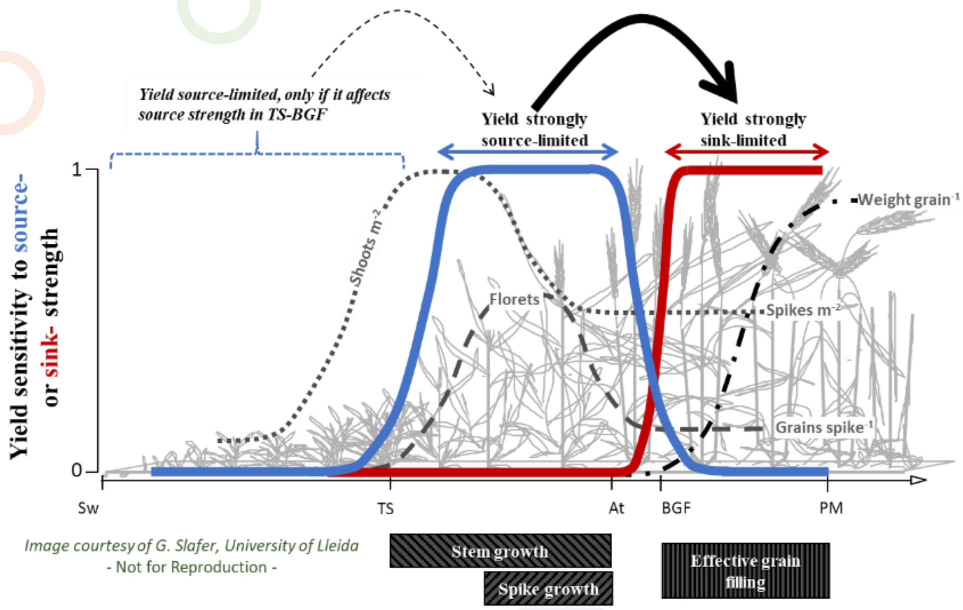


Image courtesy of G. Slafer, University of Lleida - Not for Reproduction -

These “Wiring Diagrams” will enable more comprehensive and targeted assessments of germplasm for each of the traits underpinning grain development at several steps of plant development. Further, they can help drive discovery, pre-breeding, selection and breeding programs for varietal development. They are enabling IWYP to address specific questions such as:

- Which traits are likely limiting yields in breeding pools?
- What are the known or anticipated trade-offs between traits and processes?
- What is the genetic control of each trait and what sources of genetic variation are known?
- Can new genetic variation and traits likely be measured easily and readily tracked efficiently in breeding programs, including the use of proxy assays?
- What needs to be done to fill critical knowledge gaps?

The IWYP associated scientists will be publishing the completed framework (Wiring Diagrams) and its supporting literature in the coming year, for the benefit of all wheat breeding programs. We consider this to be a significant contribution to prioritizing future research, translation of discoveries and pre-breeding for major yield gains in wheat and likely many other crops.

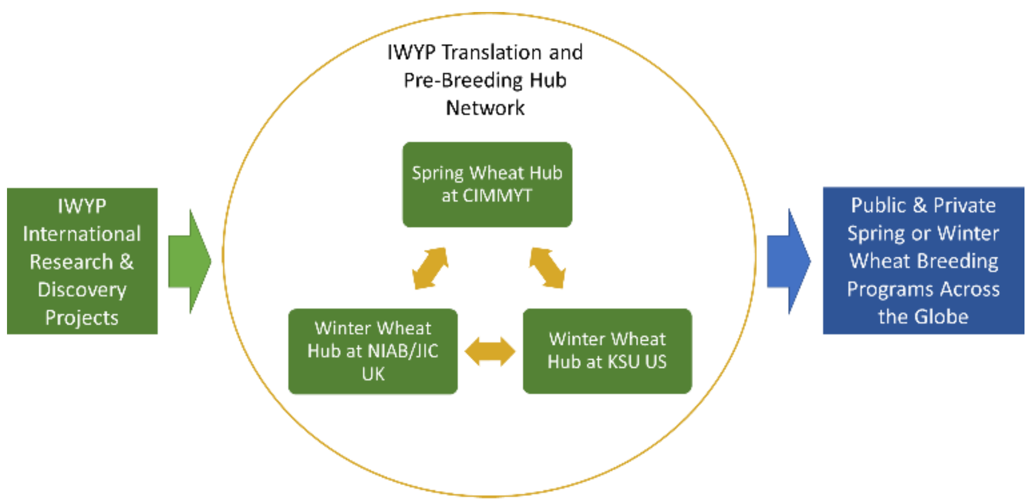
Improving Evaluation of Trait-Selected Lines & Delivery Systems

IWYP Hub at CIMMYT - Refining Germplasm Evaluation

To select and deliver the most promising new elite lines from pre-breeding requires the best data and information possible from international field trialing systems. The IWYP Hub at CIMMYT has utilized the existing International Wheat Improvement Network (IWIN) for field evaluations at 30-40 sites across a variety of countries each year. IWIN is a voluntary system that relies on offers to carry out trials in exchange for return of data. Thus, trials in some environments and collection of some types of data not normally collected for yield trials, are not routinely possible. Therefore, the CIMMYT-based IWYP Hub is developing a dedicated trialing system called the "IWYP Yield Potential Trait Experiment" (IYPTE) network specially for IWYP. Once operational, this will enable the IWYP Hub to contract trials at specific locations, prescribe agronomic practices and have specific phenotypic data collected. 10-12 sites are targeted this year to assess the reliability of the system. Next season we intend to expand this to 20-30 locations based on experiences gained in this first season.

Adding two Hubs to the IWYP Hub Network

A very important achievement for IWYP over the last year is the establishment of two new IWYP Hubs for the development of winter wheat germplasm to complement the IWYP Hub at CIMMYT that is focused on spring wheat germplasm. These additions to the IWYP Hub Network provide IWYP with three interconnected validation and pre-breeding Hubs to develop both major categories of wheats grown across the world, thus expanding IWYP's reach into more breeding programs globally and thereby increasing potential impact.



The new Hubs are geographically located to serve the two major winter wheat germplasm pools, one in the US and the other in Europe. Both Winter Wheat Hubs have been launched as public-private partnerships. The US Hub is being led by Kansas State University scientists, supported by a grant from USDA NIFA, and supplemented by the private sector. The European Hub is being led by IWYP private sector members and aligned with the BBSRC funded Designing Future Wheat Institute Strategic Programme (ISP) (8 research institutes and universities across the UK are involved) and the National Institute of Agricultural Botany (NIAB) in the UK. The resource support and assistance in technical management of these new Hubs provided by companies is evidence that the IWYP Science Program is generating value that is commercially relevant.

Communications / Promoting IWYP Outputs

IWYP uses a variety of ways to promote its assets and encourage broad uptake by public and private breeding programs of the defined discoveries made by its researchers and Hubs. Examples of how IWYP is striving to reach a diverse audience of stakeholders are described below.

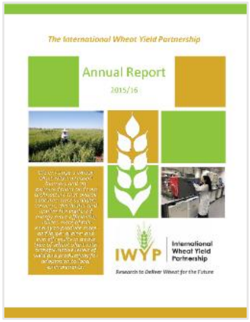
Science Briefs

In 2020 IWYP began to produce a series of monthly “Science Briefs”. These are designed as one-page summaries of research projects, Hub outputs, notable achievements, or other Program deliverables and are written to be of interest to both scientists and non-scientists. For those Science Briefs that focus on a scientific research project the reader is provided with an insight into what discoveries have been transferred into the translational pipelines for development of pre-products. (https://iwyp.org/iwyp-science-briefs/).

Annual Report

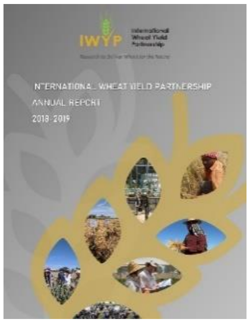
IWYP publishes an Annual Report where progress towards achieving major increases in yield potential are described. This is an important publication for all interested in wheat breeding and crop enhancement. It also informs readers of future plans for the Partnership. Each Annual Report is published in late Autumn and circulated in a variety of ways to reach our stakeholders. This Annual Report along with all past IWYP Annual Reports is available from the IWYP website https://iwyp.org/annual-report/.

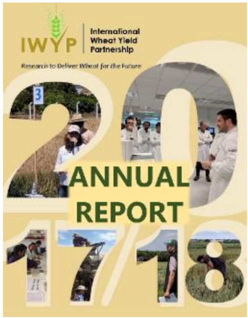
Beginning last year, IWYP also publishes a 1-page version of its Annual Report to highlight its main features. The 1-page summary of last year’s Annual Report is available at https://iwyp.org/annual-report/.



Member Newsletters

IWYP regularly generates a newsletter as part of its commitment to keep our Private Sector Members updated on IWYP activities and news. It highlights advanced details of recent scientific accomplishments and other news about the Partnership.



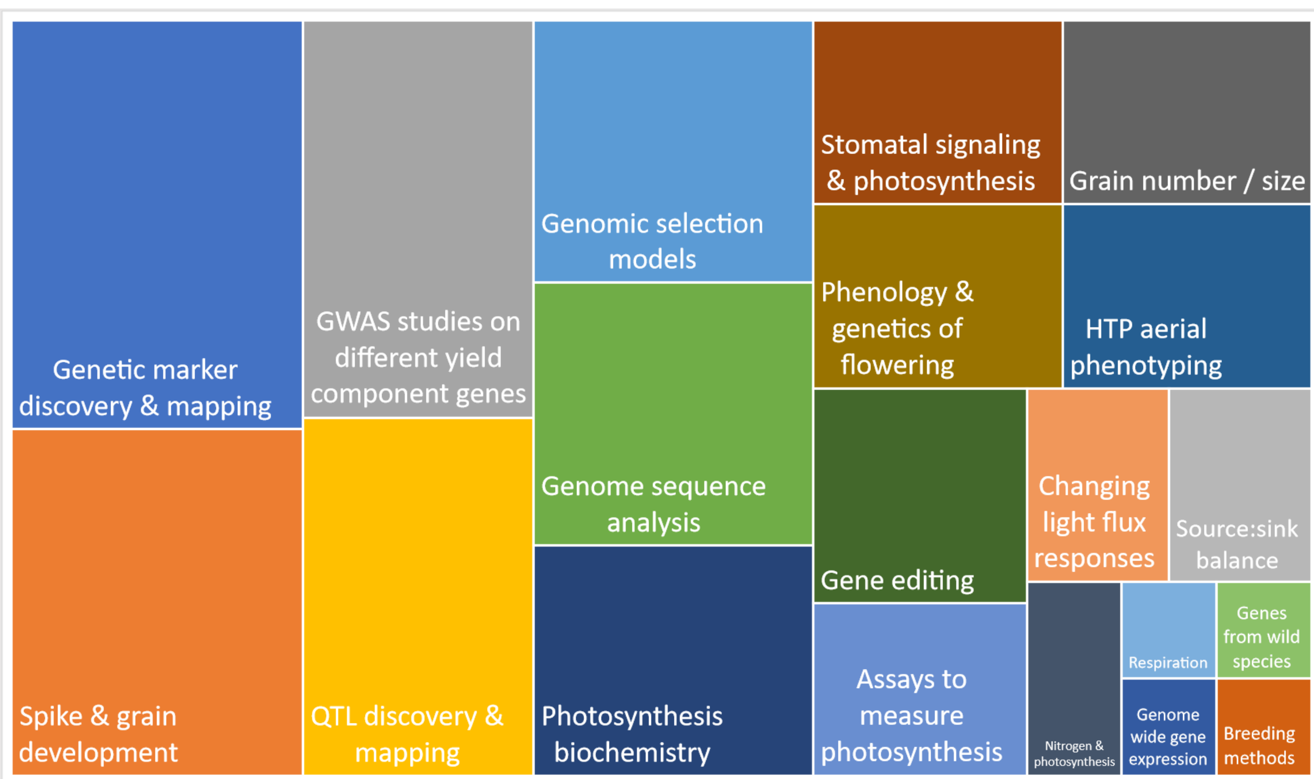


Delivering IWYP Assets for Global Uptake & Impact

IWYP this year has promoted the tangible outputs coming from its research projects and the IWYP Hubs by production of a major “Asset Catalogue”. The informative lists within it are grouped into 1) Trait-Linked Markers, 2) Tools and Protocols, and 3) Germplasm. Lists are made publicly available from the main page of the IWYP website (www.iwyp.org) and are updated as new discoveries and germplasm become available. Sufficient details are included in the lists to alert potential users of the utility of what is available. Details for gaining more information and ordering specific assets are included. IWYP has also this year compiled a Trait List for use by the Hub Management Committees to aid them in prioritizing trait development and stacking. This list comprises detailed information on the traits which has come especially from IWYP-associated research and its assets.

IWYP Associated Scientific Publications

IWYP tracks and compiles the scientific publications made by the IWYP associated researchers resulting from their IWYP Research Projects. Almost 100 scientific articles have been published since 2016. These exemplify both novel groundbreaking scientific discoveries and practical knowledge for genotyping and phenotyping potential yield traits more effectively. The majority of research articles focuses on traits such as yield and yield components (spike and grain development), photosynthesis and biomass production, flowering and harvest index as well as technologies such as high throughput phenotyping, genetic analysis (association mapping, QTL mapping, genomic selection) and genome sequence analysis. The quality of the science produced is reflected by the number of high impact factor journals that have



published these findings. These include Nature Plants and Science. A full list of IWYP acknowledged scientific publications over the years from 2016-2020 can be viewed and downloaded from https://iwyp.org/publications/. The categories of research areas and/or tools reflected in these publications, as shown in the graphic, reflect the chosen areas of investment and exemplify the range of outputs becoming available to breed better yielding wheat plants.

The promotion and dissemination of IWYP documents and lists described above are facilitated using a variety of tools and platforms. Some of these are described below.

The IWYP Website

The IWYP Website (www.iwyp.org) has remained the predominant way to communicate what is happening in IWYP to Funders, researchers and the broader community of wheat breeders and other interested parties. It is the main portal for publishing IWYP documentation, communicating news of IWYP Calls for Research proposals and generally promoting IWYP-related news and scientific progress. It is also used to provide access for IWYP Members to a secure workspace (Members Space Portal and shared drive) that allows sharing of confidential and/or embargoed technical information. Over the period December 2019 to September 2020, 3450 users visited the IWYP webpage, many of whom were first time visitors. This is a 15% increase on the same period last year.

Social Media

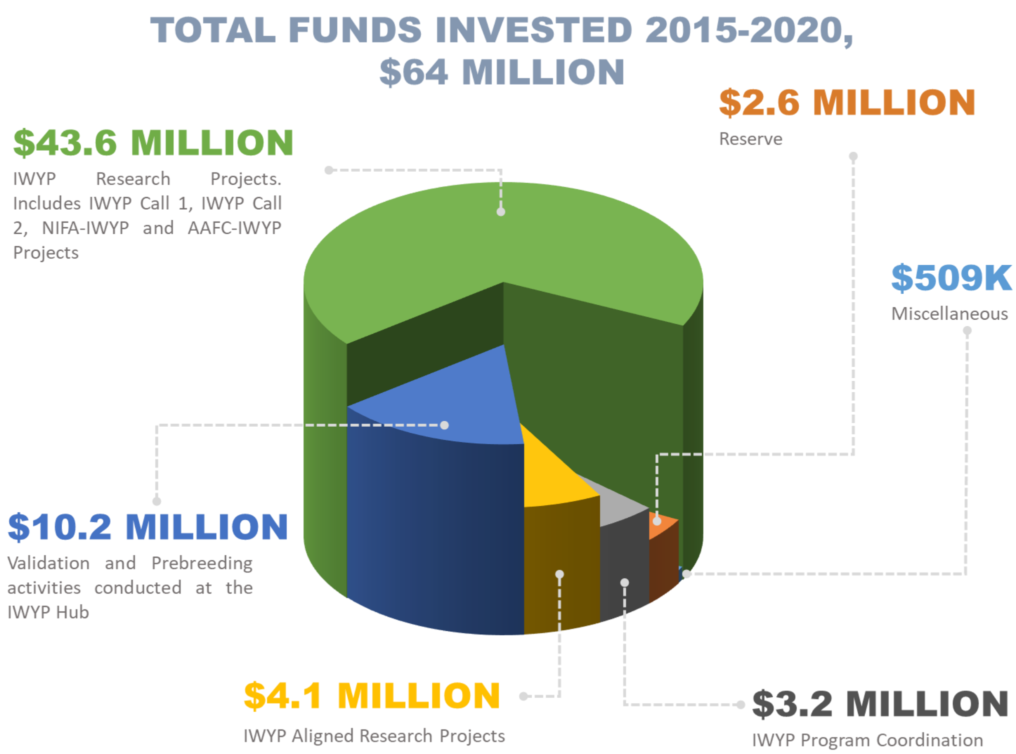
IWYP continuously evaluates how well it reaches its target audience and works with partners such as CIMMYT (www.cimmyt.org) and The Wheat Initiative (www.wheatinitiative.org) to further develop or modify its communications strategy. Social media tools are being increasingly used as an informal and rapid way to promote IWYP and encourage visitors to the IWYP Website to learn more information. Of the various social media platforms available, Twitter is the most valuable and is used by many IWYP research scientists, IWYP funding organizations and other IWYP stakeholders. Our Twitter account continues to attract new followers, reaching a total of approximately 1361 to date, an increase of 18% from November 2019. Similar increases are noted for the IWYP Facebook account.

Email Distribution

IWYP maintains a large distribution list of Partners and others involved in wheat research and breeding. This list is used to communicate important information about IWYP directly to those in the wheat scientific community.

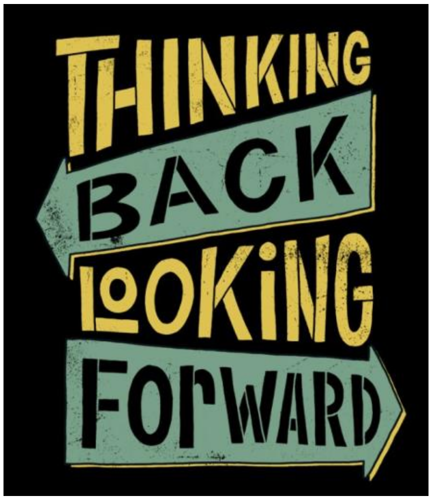
Financial Overview

Over the first 5 years since its founding, IWYP has demonstrated that our model of coordinated and integrated research, coupled with a centralized system of downstream development, is a highly efficient and cost-effective way to make targeted discoveries and deliver them in validated elite germplasm for breeders. The model has enabled several significant advances to be achieved that were never anticipated in the original research plans, especially those driven by the new genomic technologies. These have generated new opportunities and added significant value.



The IWYP Science Program is funded primarily by a group of IWYP Partners (BBSRC, USAID, GRDC, USDA-NIFA, SFSA and AAFC). The total investments raised, directly or indirectly, since the inception of IWYP amount to $64 million. These partition out as shown in the Figure above. During this year monies have continued to be spent on completing the projects funded via the IWYP Call 2 (BBSRC, USAID, GRDC) and the NIFA-IWYP Awards and the AAFC Aligned Call (AAFC, BBSRC, GRDC) together with the CIMMYT Spring Wheat Hub as well as on the necessary associated coordination, scientific management and communication needs. Some additional projects were added to the IWYP portfolio this year, as "Aligned Projects". Management of these projects occurs outside IWYP but results are shared with IWYP. About $2.6 million remains in reserve. This reserve, additional promised funds and new funds that must be raised during the coming years will be used to continue to validate, transform and scale the already achieved innovative discoveries into significantly higher yielding wheat germplasm and breeder-friendly tool kits, for direct transfer to varietal breeding programs that serve both developed and lesser developed nations.

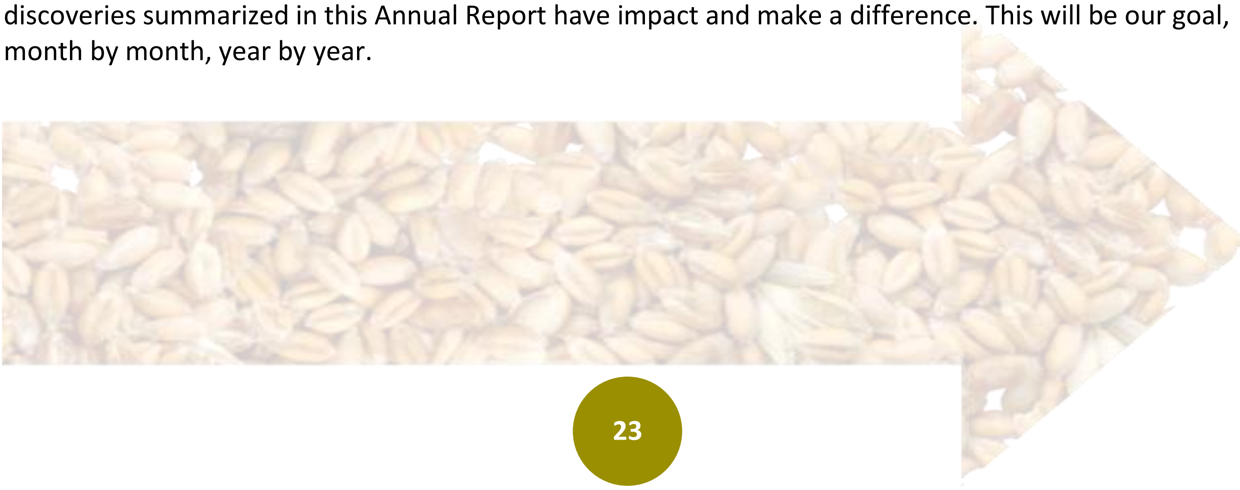
Looking Forward:
Focus on Urgency, Efficiency, and Impact



The global need for additional wheat on fewer hectares becomes more urgent with the passage of every year because of the time it takes to develop the varieties which generate higher yields in farmers' fields. IWYP was established to enable breeders to create wheats with much higher yield potential. Now many discoveries have been made that potentially aid this, the urgent need is to translate the best into elite germplasm and validate their potential around the world. By adding this past year two winter wheat translational Hubs in liaison with private sector breeders, in addition to the major spring wheat hub in CIMMYT, IWYP has made a major step towards boosting the translation of discoveries into forms easier for breeders to adapt to the needs of farmers around the world.

Urgency and cost demand that this translation is made with maximum efficiency. Thus, during the coming years IWYP will focus on bringing maximal efficiency into the Hubs by exploiting Stage Gating and other systems to manage and drive pipeline processes forward. Such efficiency is also demanded because wheat breeding of tomorrow should not be as wheat breeding in the past. New assays, better knowledge of the genetic basis of yield improvement, rapid cycling through generations and new tools to screen germplasm in the field, combined with many digital management tools should boost efficiencies and save time. This will take additional investment, so IWYP will continue to seek and deploy funds to convert known discoveries into impact in agriculture.

IWYP was founded and financed on the principle that outputs from discovery programs are available to all because many discoveries are likely to be relevant to all wheat breeding programs. IWYP will put more emphasis this coming year on making sure that all potential users know what new tools and opportunities are available. Farmers of the world, in richer and poorer countries, are served by public and private breeding programs. IWYP's oversight Board, comprising public and private institutions from many countries and its scientists operating in so many countries, are well positioned to make IWYP's discoveries summarized in this Annual Report have impact and make a difference. This will be our goal, month by month, year by year.



Partners and Funders

IWYP was founded on a collaborative approach bringing together public and private research organizations from many countries. Importantly, IWYP is a partnership between funding and private organizations who are critical to the success of IWYP and play multiple roles in the organization. These include defining strategic direction through to active engagement in the utilization of IWYP Research Project outputs both within their own organizations but more importantly working together to bring new wheat varieties to farmers via the new IWYP validation and pre-breeding Hubs. As of today IWYP relies on support and strategic direction from 14 public funding and research organizations and 10 private industry partners.

FUNDING AND RESEARCH ORGANIZATION PARTNERS

PRIVATE INDUSTRY PARTNERS

Visit us at https://iwyp.org/

@IWYP_wheat

@IWYPnews

International-wheat-yield-partnership