2021-22

International Wheat Yield Partnership

ANNUAL REPORT

IWYP | International Wheat Yield Partnership

Research to Deliver Wheat for the Future

Contents

Executive Summary

Recent geopolitical events have reminded us of the importance of wheat supply chains and the consequences of grain shortages. This reinforces the value of IWYP as a leading public-private integrator of wheat research for yield enhancement and the urgent need for it to be successful.

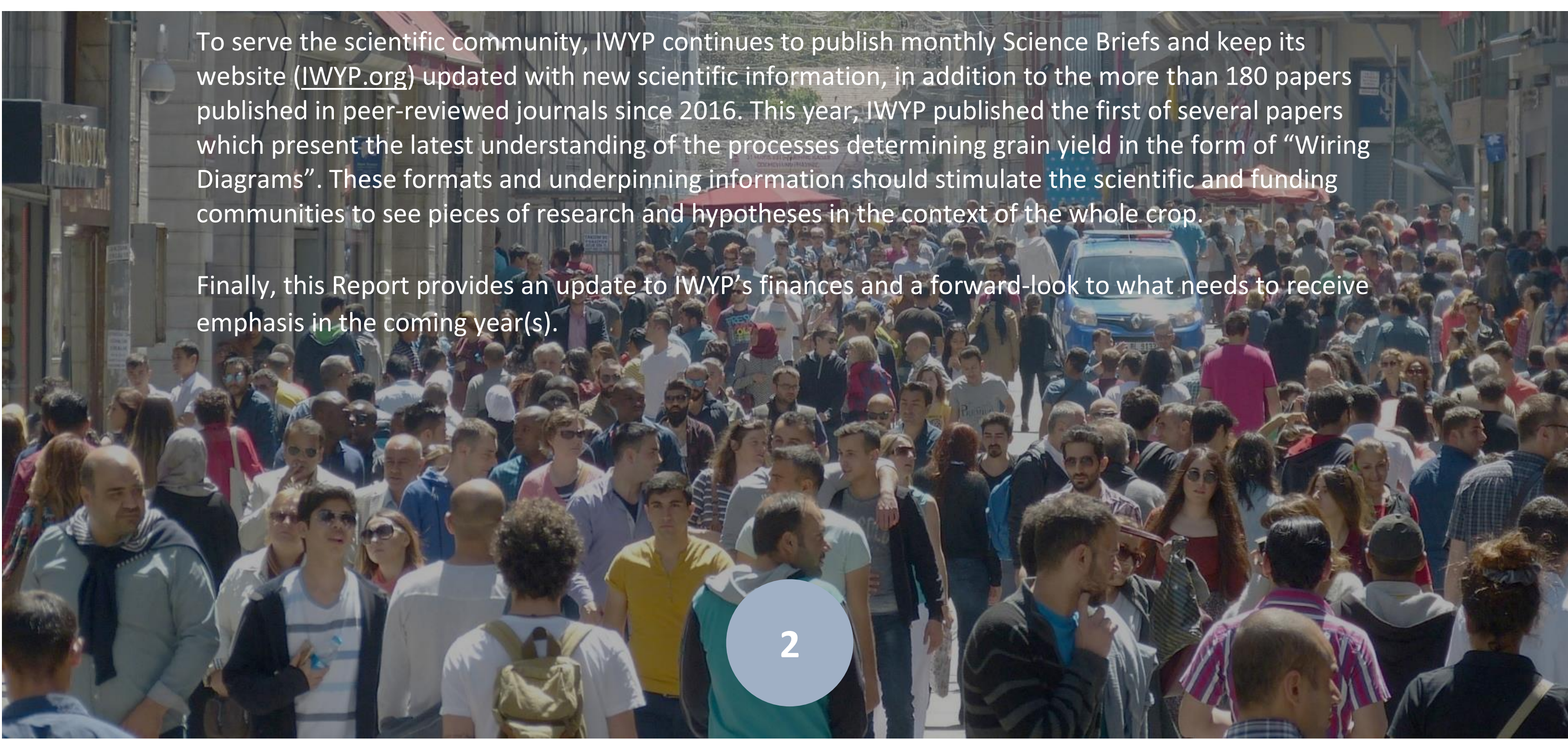
Climate change has also dominated news. Funders now emphasize the need to have wheat varieties that are more resilient to changing climates and be higher yielding. In this Report, we show that wheat lines which are high yielding under good conditions also perform better under poorer growth conditions, although these do not necessarily embody the environmental extremes that can be features of changing climates. The Report also highlights (i) discovery of a chromosome segment that provides significant tolerance to heat which could be very useful in quests to create heat resilient wheats; (ii) knowledge about the combinations of genes that together program flowering times- an important contribution to wheat yield enhancement; (iii) the different physiological processes wheat plants execute before and after midday and (iv) many other discoveries, tools and methods to improve the efficiencies of wheat breeding. Collectively, they add to the toolbox on which future yield improvements depend.

Sections of this Report focus on progress in the IWYP Research Translation and Development Hubs which generate new spring and winter wheat germplasm. These are the jewels in the IWYP crown because they are the places where research discoveries get tested in elite germplasm, in commercial-style agriculture, and if worthy, become assembled together to drive yield gains. This past year, IWYP has further refined its rigorous “Stage Gate process” (detailed in previous Annual Report 2018-19) for tracking and managing the progression of traits through the Hubs’ pipelines from discovery to delivery of high yielding lines. Where some new traits for yield improvements sit in the pipeline are described.

The IWYP Hub at CIMMYT takes the cream of its pre-breeding selections and tests them in different environments around the world. The results provide IWYP with a view on the relevance of variant traits for increasing yield and so provide a measure of progress. Results from the international trials are included and show that each year the IWYP Hub at CIMMYT has produced lines with higher yields than previous years, as new trait sources are tested. The dissemination of these lines, as well as other tools, molecular markers and knowledge are important outputs of IWYP and its contribution to wheat breeding worldwide.

To serve the scientific community, IWYP continues to publish monthly Science Briefs and keep its website (IWYP.org) updated with new scientific information, in addition to the more than 180 papers published in peer-reviewed journals since 2016. This year, IWYP published the first of several papers which present the latest understanding of the processes determining grain yield in the form of “Wiring Diagrams”. These formats and underpinning information should stimulate the scientific and funding communities to see pieces of research and hypotheses in the context of the whole crop.

Finally, this Report provides an update to IWYP’s finances and a forward-look to what needs to receive emphasis in the coming year(s).



Message from the IWYP Board Chair

The members of the Science and Impact Executive Board (SIEB) of IWYP are delighted to provide this Annual Report for 2021-22. This year the shortages of wheat due to the war in Ukraine have hit the headlines worldwide and emphasized the vulnerability of the world's wheat supplies to geopolitical as well as climate changes. IWYP's objectives therefore become ever more urgent and important. It is vital that we continue to deliver to mitigate against inadequate supplies of this staple crop on which the world's population depends.

Wheat plants are complex machines and sensitive to the environment, both as they are being built in the field and when they are operating as mature machines and making grains. Breeders reassemble the machine's parts every breeding cycle in the hope of finding new combinations of parts and control systems that result in higher yielding machines.

The finding or creating of better parts is not a short-term activity. IWYP is now in its 8th year. It has contributed enormously during this period to the scientific knowledge for wheat improvement and provided major growth points for the development of new tools for wheat breeding along with trait-improved germplasm. A quick look down the lists of some of its 170 plus peer reviewed publications and the derived technical outputs on offer to all, reveals the productivity of IWYP-associated scientists and the range of contributions being made. Potential breakthroughs are embedded in the publications, but much remains to be done to provide the breeding communities around the world with the knowhow and tools to make large gains.

IWYP activities continue to be needed for both public and private sector breeding programs because the latter cannot afford to drive breakthrough discovery programs as well as finished varieties for farmers. To sustain their role, IWYP-associated scientists will need added support which remains a focus for the SIEB and wheat scientists in the coming months. New research projects whose outputs can be increased in value by IWYP via its translational Hubs and pre-breeding pipelines, will need to be sought by scientists and funding agencies and brought into the IWYP system.

IWYP seeks to inspire the scientific communities to find new breakthroughs. To this end, IWYP-associated scientists have generated and published papers defining wheat development and grain production in terms of "Wiring Diagrams." This is novel. It is hoped that better appreciation of the steps limiting grain production via these diagrams and putting these into practice will result in yet more novel ideas, tools and breakthroughs.

As can be seen from this Annual Report's snapshot statistics, IWYP's successes come from many international collaborations in addition to its breeding-based translational Hubs in USA, Mexico and the UK. Much has been achieved. The SIEB thanks all those who have contributed these past years in the service of ensuring supplies of wheat in the decades to come.

Message from the IWYP Program Director

Now in its 8th year, IWYP continues to produce valuable scientific information, innovative research outputs and new higher-yielding germplasm with novel traits edging us closer towards our goal of doubling genetic gain in breeding programs to enable wheat production to meet the demands of a rapidly growing global population. The increasing effects of climate change and need for more sustainable production is making this challenge even harder and requires our discovery and development efforts to account for additional factors. Data collected to date indicate that many of our yield enhancing trait combinations are providing yield benefits under lower yielding conditions which typically involve hotter and dryer environments and/or fewer agronomic inputs.

IWYP is special because of how it is constructed and how it works. Its collection of both public agency and private industry partners have remained focused and committed towards our goals with each doing their part towards aligning strategies, research, pre-breeding development and varietal breeding to address our operational needs. IWYP systems, which span from discovery research to germplasm delivery, are highly functional and efficient. The research outputs and new germplasm developed in the Hubs are being widely transferred and incorporated into public and private breeding programs across the world to create new higher yielding wheat varieties for farmers to grow.

Although the impacts are nascent, they are growing. That said, the momentum needs to accelerate and there is still much that can be done to generate greater impact faster. More intense focus on the rate-limiting steps and bottlenecks in the physiological systems that create higher grain yields is necessary. Filling critical gaps in our trait portfolio will enable us to further capitalize on and amplify the innovations already in-hand. IWYP scientists have recently created an illustrative roadmap (Wiring Diagrams) to facilitate this. Continually implementing the newest technologies can help make our pre-breeding pipelines faster and more efficient. New aligned genomic and “deep learning” research could help with this.

What IWYP seeks to accomplish is extremely difficult. Success relies on a large coordinated global effort and is dependent on novel breakthrough innovations that provide wheat breeders traits and tools that have not been widely accessible, if they existed at all. Breeding programs rely on the infusion of new genetic variation to reinvigorate their breeding pools and make more substantial genetic gains. Because varietal breeding pipelines are driven by capacity and limited by resources, any new genetic variation deployed needs to have proven benefits. The IWYP system, with its validation and translational aspects, its pre-breeding pipeline and environment-rich international field trialing systems helps fill this need and provides breeding programs with the data they require.

Over the last few years, we have learned a great deal, both scientifically and strategically, and have adjusted our pipelines accordingly. It has been exciting to lead the Program from its beginnings to see the superb operational systems and teams that exist today. I look forward to the opportunities that lie ahead when our pipelines deliver more yield-enhancing outputs that are used to create higher yielding heat varieties in farmers’ fields, that uplift economies and provide food security for the global masses.

IWYP in 2022

SOCIAL MEDIA

1941 Twitter Followers
1600 Facebook Followers
110 LinkedIn Followers

PARTNERS

14 Public Partners
11 Private Partners

RESEARCH NETWORK

41 Research Projects
60 Research Institutions
14 Countries

PUBLICATIONS

16 Scientific Publications to date in 2022 (178 since 2016)

RESEARCH OUTPUTS

286 Wheat lines from the CIMMYT IWYP Hub
26 Research Project Germplasm
108 Trait Linked Molecular Genetic Markers
25 Tools and Protocols

CAPACITY BUILDING

47 Research Scientists Trained

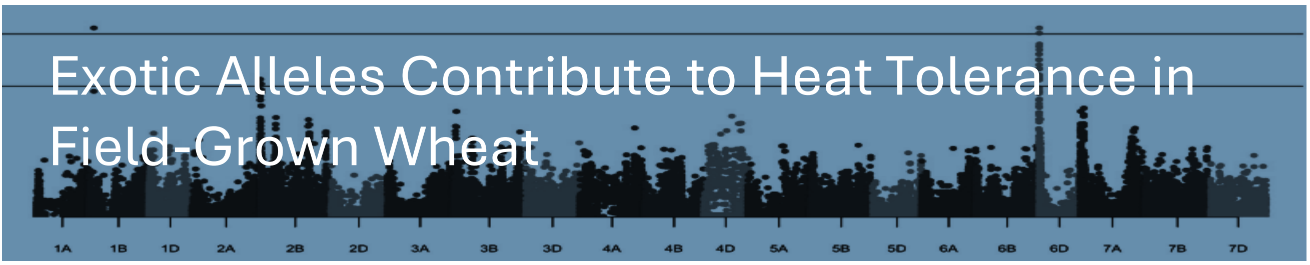
SEED REQUESTS

9th Wheat Yield Consortium Yield Trial (WYCYT) germplasm distributed to 117 collaborators in 42 countries over the 2021/22 cycle
10th WYCYT germplasm distributed to 111 collaborators to date

Research Highlights

Over the past year the portfolio of IWYP Research and Aligned Research Projects has continued to generate the potentially valuable discoveries required by IWYP to be successful and many discoveries have been transferred to the IWYP Hubs for validation under full agricultural conditions, followed by pre-breeding. Below is a snapshot of some of the research highlights. For a more complete overview of the research conducted as part of the IWYP Partnership please visit https://iwyp.org/research-program/ or our collection of IWYP Science Briefs at https://iwyp.org/iwyp-science-briefs/.

Exotic Alleles Contribute to Heat Tolerance in Field-Grown Wheat



A study at the IWYP Hub at CIMMYT identified three marker-trait associations that in combination increased yield under heat stress by up to 50%. A chromosome segment transferred from a wild species, *Aegilops tauschii* Coss. was responsible for much of this effect and underlines the importance of looking beyond the primary gene pool of wheat for novel variation to develop high yielding and more climate resilient wheat cultivars. The discovery validates the current IWYP/CIMMYT strategy of introducing novel genetic variation from exotic material to boost wheat yields beyond current levels. While these alleles are not necessary for raising yield under high yield potential conditions they provide an insurance should the plant experience high heat conditions. Importantly they do not impart a yield penalty under high yielding conditions.

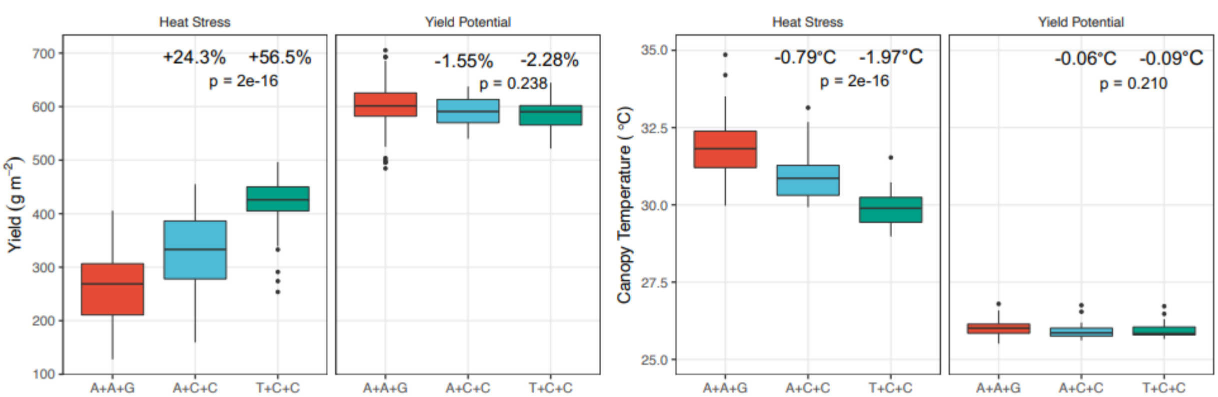
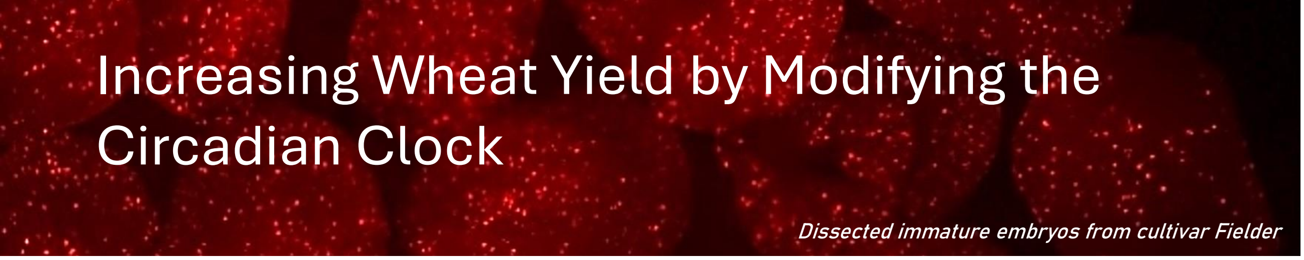


Figure 1. Under heat stress the haplotype T+C+C confers more than 50% improved yield over the haplotype A+A+G while showing no significant yield penalty under high yield potential conditions. Similarly for canopy temperature, an important adaptation for heat tolerance, heat stressed plants with the same haplotype remain cooler (a desirable trait) which again causes no significant negative effect under high yield potential conditions. (Taken from Figure 3b "Genome-wide association study reveals genetic markers underlying heat tolerance traits", Molero et al. (2022)

Increasing Wheat Yield by Modifying the Circadian Clock



Dissected immature embryos from cultivar Fielder

The circadian clock widely influences gene expression that in turn affects plant development and responses to the environment. Several alleles of circadian clock (CC) genes have been selected through breeding. Now, characterization of the wheat transcriptome over a 24 hour-cycle has shown that midway through the day wheat plants undergo a change in gene transcription with transient up-regulation of thousands of genes, revealing that the plants have reached photosynthetic saturation and have transiently activated photorespiration, a carbon wasteful process. Many different metabolic activities occur on either side of this split. The new knowledge generated by this research will be important in wheat breeding for optimizing photosynthesis and radiation use efficiency by the exploitation of novel variation in more CC genes.

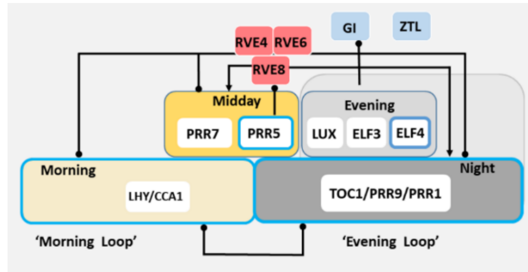


Figure 2. A circadian clock gene model for wheat. Unpublished. Courtesy of A. Laroche & J. Laurie, AAFC.

Optimizing Phenology for High Yields

Crop development needs to align with environmental conditions for high yields to be achieved. Over the years, genes determining major developmental flowering time responses to environmental changes in temperature and daylength during the growing season have been recognized. More recently, additional allelic variants of these genes and many new genes with more minor effects have been found, facilitating the knowledge that yield potential results from interactions between all these developmental genes/alleles. This past year a series of papers have emerged from IWYP-associated scientists linking allele combinations to yields and different environments. The reports provide detailed strategies for using these genes/alleles to breed high yielding varieties for different environments and describe the molecular marker tools needed to simplify the construction and selection of the required combinations of alleles. It represents a major contribution of IWYP- associated science to wheat breeding.

Figure 3. Illustrating the critical phenological timepoint for flowering time in wheat. Courtesy of S. Griffiths, John Innes Centre.

Exploiting Variation in Floral Characters for Hybrid Wheat

A possible solution for significantly raising wheat yields is by exploiting heterosis, also known as hybrid vigor. The production of hybrid seed requires a “female parent” plant to be pollinated by a genetically different “male parent” plant. However, wheat has evolved as an “in-breeder” and therefore does not possess floral characters that facilitate cross pollination at high efficiency. In past years wheat wild relatives have been screened for suitable variation in these traits. Now, introgression lines of breadwheat containing chromosomal fragments from wild wheat relatives have been selected with altered flowering morphologies that include smaller pollen grain size, longer anthers, longer filaments, longer stigmas, extended stigma receptivity and floret gaping. Several introgression lines with these potentially useful floral characteristics have been requested by hybrid wheat breeders and the characters are also being validated in the IWYP Hubs.

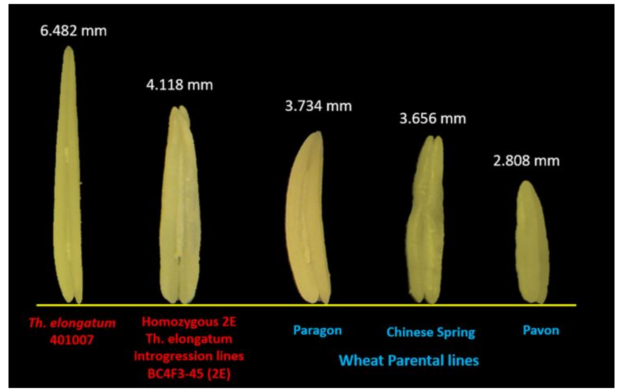


Figure 4. Introgression line identified with larger anthers from the wheat wild relative *Thinopyrum elongatum* (Host) D.R. Dewey. Courtesy of J. King, University of Nottingham.

Phenotyping Single Plant Characters using UAVs

Efficient and robust integration of phenomics and genomics data is a key to revolutionizing plant breeding. Analyses of data collected from field plots and single plants from drones (UAVs) have been progressed further. It was possible to detect variation in numbers of spikelets per spike in both plots and spaced single plants and the two correlated well. This is particularly useful because evaluation of single plants is typical in the early generations of a breeding program when full plots are difficult to screen because insufficient seed is available. Therefore, being able to select individual, high yielding plants in early segregating generations using UAVs should enhance the efficiencies in breeding programs.

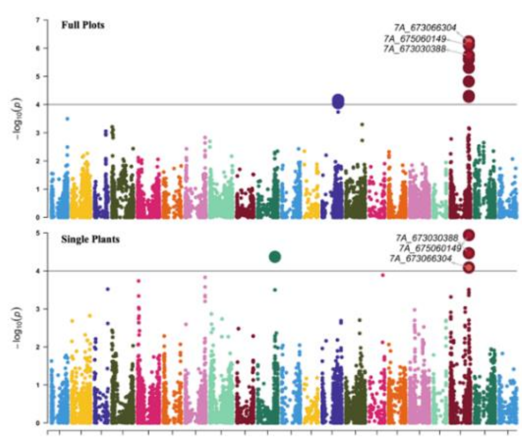


Figure 5. Manhattan plot of spikelets per spike in full plots (top) and single plants (bottom). Common significant markers on chromosome 7A have been highlighted. Adapted from [Crain et al. (2022)](#).

Variation among Homoeologous Genes Selected in Breeding Programs

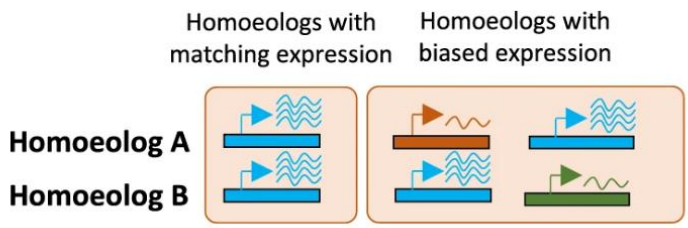


Figure 6. Taken from Figure 1a "Relative expression of homoeologous genes in the diverse panel of wheat lines", [He, et al. (2022)]

Wheat is a hexaploid crop species containing 3 genomes (A, B and D) and therefore 3 copies of each of the 7 chromosomes. A seminal study published early in 2022 found that while the majority of copies of triplicated genes are expressed at similar levels, there are a subset of genes that exhibit unbalanced, biased expression, i.e., one or more copies has a very different level of expression from the other copies (see **Figure 6**). Such unbalanced, biased expression has in some cases a positive effect on several yield traits, e.g., grain size, weight and number. It is postulated that plant breeders have unknowingly positively selected combinations of unbalanced genes over time that impact agriculturally relevant traits. This knowledge emphasizes the importance of the interactions of homoeologous alleles in yield improvement in polyploid crops.

Better Spike Development for Higher Yields

The dwarfing genes that led to the "Green Revolution" enabled varieties to be bred that moved more fixed carbon into growing grains instead of stems. That principle can be exploited in additional ways. IWYP scientists have generated a new strategy for yield enhancement through the preferential movement of more nutrients into spikes and grains by optimizing the timing, duration and rates of spike, floret and grain growth that better fit different environments. The crucial timing for initiation of these events is between when the spike wrapped inside the stem is <1 cm and when it reaches anthesis. This strategy is being put into practice based on known sources of genetic variation, moving us along the path to higher yields. Further, deep analyses of early spike development will lead to more detailed models of the processes of spike growth, spikelet formation, floret growth and survival leading to deeper modelling using AI and machine learning to find new genetic variation for optimization of these traits.

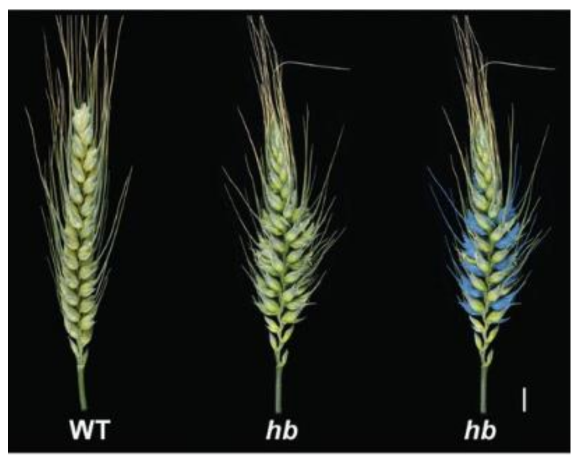


Figure 7. Wild-type (WT) and *hb* (highly branched) inflorescences (blue indicates secondary spikelets). Taken from Figure 1a, "Inflorescence Architecture and Development and Tiller Number Are Modified in *hb* Plants", [Dixon et al. (2018)].

A Year at the IWYP Hub at CIMMYT

Phenocart multisensor (version 2.0)

Tools and Protocols

Research collaborations have been strengthened to improve the efficiency and accuracy of aerial and ground phenotyping using high-resolution imagery. The latest advances include:

- Improvements made to a custom-made imaging platform, the "Phenocart", to allow the simultaneous acquisition of data from multiple sensors, which have been correlated with several yield related phenotypes.
- A new root index based on the relationship between canopy temperature (CT) and root biomass which provides a more integrative assessment of root capacity than conventional destructive methods.
- New machine learning models to automate image-based quantification of traits such as spike and spikelet count, heading date, ground cover and stay green.
- A Classification and Regression Tree (CART) determined the different paths a crop takes to achieve a certain ideotype made up of multiple traits. Using harvest index as an example, an ideotype having a harvest index = 0.5, would need more than 13,000 grains per m^2, a thousand grain weight larger than 40g and a grain weight per spike larger than 2.4g. These models can be used to test and develop further the Wiring Diagrams underpinning grain yield.
- Two new protocols based on the application of Trehalose 6 Phosphate (T6P), a key biochemical regulator of yield-enhancing pathways. The first is a method to boost photosynthetic metabolism using topical application of T6P and the second is a chlorophyll fluorescence protocol that measures photosynthetic activity shortly after T6P treatment. When calibrated, these protocols help confirm source and sink potential in parental and selected lines.
- A new protocol for high-throughput characterization of chlorophyll fluorescence kinetics in photosynthetic analyses of leaves.
- Significant marker-trait associations for stem water soluble carbohydrate (WSC) across multiple germplasm sets.
- 17 molecular genetic markers validated for physiological traits and ready for use in marker-assisted selection schemes.

Germplasm Development

- 296 new strategic crosses were made in 2022. The most commonly followed crossing strategy included exotic parents (synthetics and landraces) and new IWYP lines from Wheat Yield Consortium Yield Trial (WYCYT) or candidate lines that showed good performance in IWYP Hub field trials.
- Candidate lines for the 10th WYCYT, selected from crosses made in 2018, had the following composition:
    - 90 lines introgressed with a grain size QTL from an IWYP Research Project
    - 49 lines from combinations of high grain weight and number
    - 23 lines from combinations of high harvest index (HI) and final biomass
    - 18 lines from crosses with primary synthetics and synthetic derivatives with high expression of final biomass

    - 8 lines with high expression of photosynthesis, 8 lines from strategic source and sink combinations and 3 lines from parents with high lodging resistance
    - 30 lines (15% of 199 lines) with 13.3% to 0% higher yields than the check Borlaug 100
- Lines with cooler canopies (during vegetative and grain filling phases), early canopy closure and longer stay-green considered for selection of the 10th WYCYT nursery, along with other key traits such as yield, yield components and disease resistance
- The best new IWYP line from the new WYCYT candidates was REEDLING-GL5A_1/QUAIU (918 g/m2), a line introgressed with a grain size QTL on chromosome 5A from an IWYP Research Project. Such lines expressed up to 6.3% higher harvest index and 11.3% more grains than the Borlaug 100 elite varietal check.
- 25 pre-breeding lines with high expression of physiological traits were selected for the final 10th WYCYT international nursery for distribution and field trials. All lines had a relative grain yield of 95.6 to 113.4 % compared with the best elite varietal check (Borlaug 100). 11 of the 25 lines possessed the introgression for a new grain length QTL on chromosome 5A discovered in an IWYP Research Project.

Genetic variants for important traits in the IWYP Pipeline

The IWYP Stage Gate Plan is a planning tool used in all IWYP Hubs to track R&D as new genetic innovations are translated through validation, pre-breeding, wide area field testing and delivery to potential users. It is therefore a useful tool to manage trait development in elite germplasm as well as pipeline capacity. The figure to the right illustrates a few examples of the many genetic variants that are in the pipeline. Some are also in international public and private breeding programs. The pre-breeding steps in the R&D pipeline follow a well-defined strategy in which source strength traits and sink strength traits are combined to maximize the probability of increasing harvest index and grain yields before being subjected to yield tests in different environments.

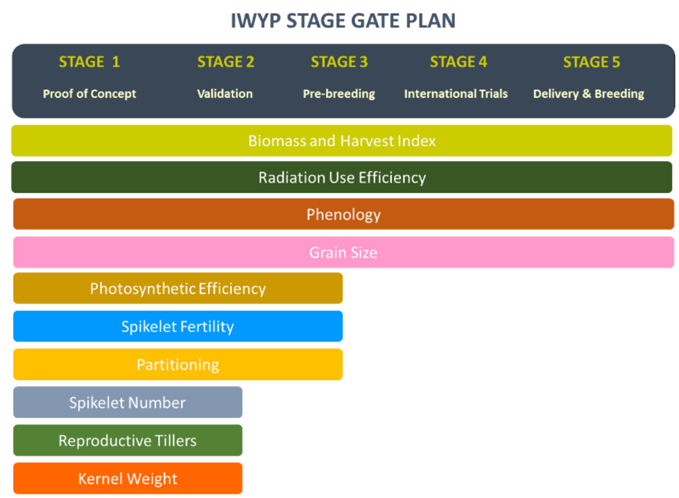
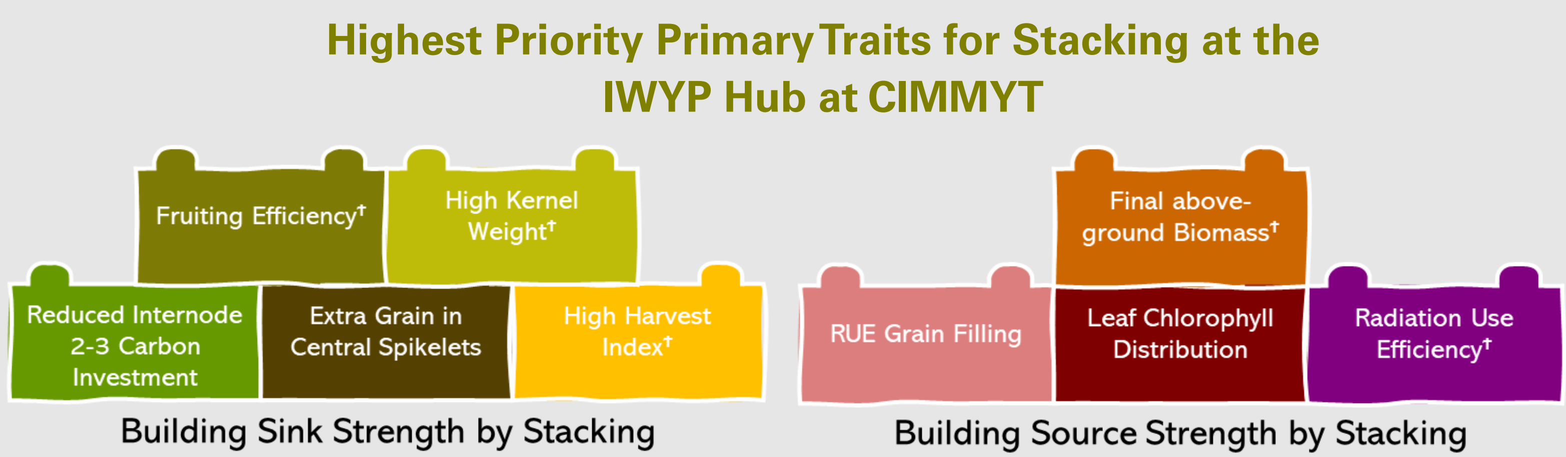


Figure 8. Example of some of the traits in the IWYP Stage Gate Plan



† Traits with associated marker available or under validation

Validation of Traits Giving High Yield Potential

Validating and stacking traits using the most efficient pre-breeding approaches is a primary objective of the IWYP Hub at CIMMYT. The outcomes of pre-breeding are assessed via the International Wheat Improvement Network (IWIN) in which pre-breeding products are grown and yields measured in many environments around the world. In addition, the “IWYP Yield Potential Trait Experiment” (IYPTE) network enables the IWYP Hub at CIMMYT to collect more robust and accurate data by contracting trials at specific locations, which adopt prescribed agronomic practices and collect specific types of phenotypic data. The 2nd IWYP Yield Potential Trait Experiment (IYPTE) was distributed to 15 collaborators worldwide in 2021. Two of the physiological traits on test were canopy chlorophyll gradient which showed a positive association with yield across locations, and the length of stem internode 3 which showed a negative association with grain yield across locations. These now-validated yield potential traits have been added with confidence to the trait toolbox to aid selection of lines with high yield potential.

Delivery of IWYP Germplasm

The dissemination of IWYP germplasm from the IWYP Hub at CIMMYT is coordinated by the International Wheat Information Network (IWIN) at CIMMYT. Seed is sent to international collaborators each year who request specific germplasm sets for field trials and uptake in breeding. Following the trials, many collaborators return performance data to CIMMYT which is used to inform breeding decisions. Since 2012 when the 1st Wheat Yield Consortium Yield Trial (WYCYT) was assembled at the Hub, interest in this germplasm, improved for many source and sink traits, has increased. In the last 3 years, the requests for new sets of IWYP germplasm is the greatest it has ever been, due in part to increased interest coming from the private wheat breeding sector. The latest WYCYT germplasm set (10th WYCYT) has been sent to 111 requestors to date.

Starting in 2019, the IWYP Hub at CIMMYT has also been distributing IWYP wheat lines (many as pre-candidate lines for WYCYT germplasm sets) via the IWYP website. This acquisition route can be used by anyone. The current list contains over 280 lines with associated phenotypic and genotypic data to help users select individual lines for breeding.

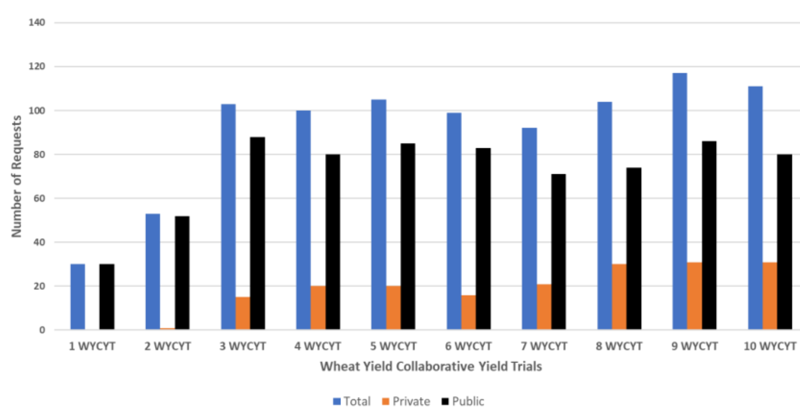


Figure 9. Number of Requests for New IWYP Lines via the WYCYT International Nurseries (2012-2022). Source CIMMYT.

IWYP North American Winter Wheat Breeding Innovation Hub (USA)

Initiated in 2020, the IWYP North American Winter Wheat Hub is located at Kansas State University, funded by a grant from USDA NIFA and supported by several IWYP Private Partners as well as 5 US State wheat commodity groups.

10 trait enhancements (phenology, grain size, photosynthetic efficiency, biomass, yield and floral traits) were selected by the Innovation Hub to be introduced into US winter wheat elite lines representing several market classes, as detailed in last year's IWYP Annual Report (https://bit.ly/3SLnjw5). The newest of these trait enhancements are the products of gene editing (GE) done in a NIFA-IWYP Research Project. Marker-assisted backcrossing of the traits to 11 selected recipient elite parents (hard red winter, soft red winter and soft white winter wheat market classes) has continued this year. For the non-GE crosses, several rounds of backcrossing have already been achieved. The majority of these new populations are not yet at a stage where the effects of the individual trait on yield potential can be evaluated. This is planned in the next 2 years.

European Winter Wheat Hub at NIAB (UK)

Initiated in 2020, the European Winter Wheat Hub serves the European winter wheat market areas. The National Institute of Agricultural Botany (NIAB) in the UK is contracted by IWYP Private Partners to conduct defined trait introgressions in alignment with other trait introgressions being done as part of the Designing Future Wheat (DFW) project in the UK funded by BBSRC.

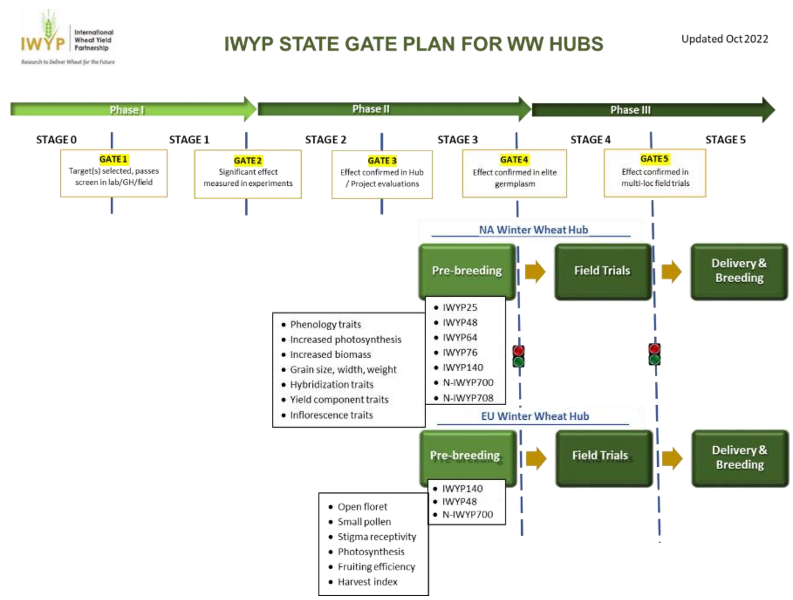


Figure 10. Stage gate plan for the Winter Wheat Hubs

Also using a marker-assisted backcrossing scheme, the first cycle of gene introgressions involving two trait targets for floral traits for use in hybrid seed production began in 2021. The recipients are UK, French and German elite wheat varieties. Seed of lines converted for these traits will be made available for evaluation and validation in 2023-24. A second cycle of trait introgressions, also using a marker assisted backcrossing scheme, began in 2022 when three new IWYP yield traits for photosynthetic efficiency, fruiting efficiency and harvest index were selected. The converted lines will be made available to wheat breeders for testing and breeding towards the end of 2025.

IWYP-the International Integrator of Wheat Yield Discoveries and Germplasm Enhancement

As indicated in the 2022 graphic on page 5, IWYP has successfully continued its mission of integrating discoveries and their translation into advanced germplasm for the breeding programs of the world. During the 8 years since IWYP was founded, understanding of the genetics, genetic variation, physiology and biochemistry of the wheat crop has been transformed. IWYP-associated scientists have played a major part in this, as evidenced by their more than 170 publications in peer-reviewed journals. From these scientific contributions it is now known how to boost photosynthesis and increase radiation use efficiency to build more biomass and larger organs, seek the optimum partitioning of nutrients between vegetative and reproductive parts to generate the highest grain yields and describe the most desirable crop architecture for maximum yields. IWYP translation Hubs are bringing this knowledge and many of the discoveries into new advanced lines through complex pre-breeding systems. The challenge is great because of the complexity of generating wheat crops that are higher yielding year-on-year, but IWYP has well-defined development pipelines to meet this challenge (IWYP Development Pipeline). Many items in the pipelines are illustrated in this Annual Report.

Measuring our Success

While the overall impact of IWYP's work is measured in many ways, one vital metric is the extent to which improved wheat lines developed by the trait-based pre-breeding programs at the IWYP Hubs are adopted by breeders globally, either as varieties or as parents for use in developing locally adapted, high yielding varieties. Another important way that IWYP assesses impact is via the international field trialing programs organized by the IWYP Hub at CIMMYT. This past year the yield results obtained from these trials since the establishment of IWYP have been reanalyzed by new statistical methodologies endorsed by the CGIAR. The analyses shows that since 2017 the yield performance line remains on an upward trend and IWYP continues to make the progress necessary to meet its goal of delivering higher yielding lines, year-on-year. Two main conclusions can be drawn from the results presented in the graph and table below:

- A clear trend in yield improvement at all sites is seen from 2017-2020 where a WYCYT germplasm set was grown. A 2.3% yield improvement was observed year-on-year relative to the average yield in year 1. While this trend remains to be confirmed with additional data in future years, this figure meets the IWYP goal of doubling the current rate of yield gains typically reported by wheat breeding programs. The average yields achieved by new IWYP lines are now greater than the 2 wheat varieties that are used as standard elite checks, Sokoll and Borlaug 100. These yield gains are related to the introduction of multiple validated traits for yield potential. IWYP realizes that breeders need to consider a wide range of agronomic traits and environments for varietal development and so will not attain the total gains exhibited by IWYP lines. Therefore, IWYP targets a larger increase to enable breeders to realize a final doubling of gain in products.

Figure 11a. Trend in IWYP wheat yield annual improvement. Source CIMMYT.

- Improvements in yield are also observed in environments classified as high, medium or low yielding. When grown in optimal/high yielding environments, the rates of yield improvement exceed the average over all sites with a year-on-year improvement of 2.8%. Perhaps the most gratifying results relate to IWYP lines grown under low yielding environments where an increase of 1.4% yield improvement is observed. These data suggest that IWYP outputs have a positive impact on yield in environments that experience greater variation in heat and drought or where agricultural inputs are less.
- Overall, these results provide promising evidence that the new traits being selected in advanced IWYP lines are contributing to grain yield potential and that the strategic crossing of lines with physiological traits related to source and sink potential significantly boost yield potential.

Sites	Improvement (t/ha/year)	Improvement (% per year)
All	0.12	**2.30**
High Yielding	0.20	**2.83**
Medium Yielding	0.06	**1.25**
Low Yielding	0.05	**1.45**

Figure 11b. Yield improvement of IWYP lines in different environments. Source CIMMYT.

IWYP Wheats Perform well in Diverse Conditions

The end goal of IWYP is to provide wheat breeding programs around the world with wheat germplasm that has higher genetic yield potential under optimal growing conditions, together with the tools and know-how to breed the improved traits into local varieties. The strategy for doing this is to combine target traits that have been identified as having the greatest likely impact on yield; for example, by combining traits that contribute to source (e.g., biomass, photosynthetic efficiency) with those that contribute to sink (e.g., grain size, spikelet number). The responsibility for developing wheat lines expressing these traits in combination lies with the IWYP Hubs at CIMMYT, Mexico, Kansas State University, USA and NIAB, UK. For more information about IWYP please visit https://iwyp.org/overview-about-us-2/

The highest IWYP yielding spring wheat lines developed at the IWYP Hub at CIMMYT for high yielding environments are often the highest yielding lines when grown in stressed environments. This implies that improved wheat lines coming out of the IWYP development pipeline are likely to be high yielding in more challenging locations (**Figure 12**) and therefore have a low CV-see Figure 12- when cultivated in different environments, including less favorable climates. This suggests that IWYP may have a broader impact than was originally envisioned.

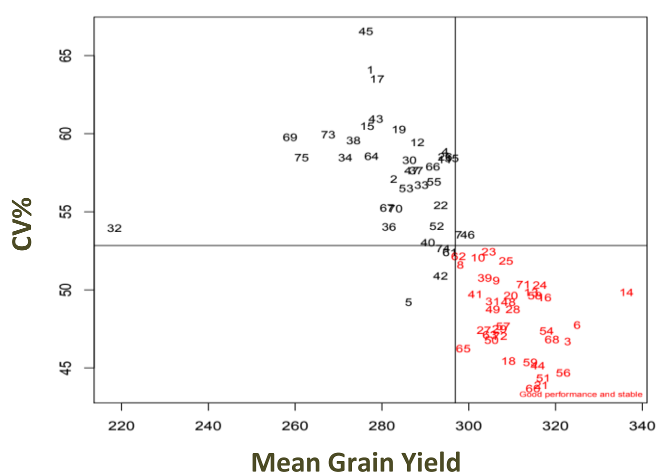


Figure 12. Combined stability analysis (CV) and grain yield for IWYP lines under irrigated, heat and drought conditions in Obregon, during 2019-20 and 2020-21 wheat cycles. Entries in red are both better performing and stable across a range of environments. Source CIMMYT.

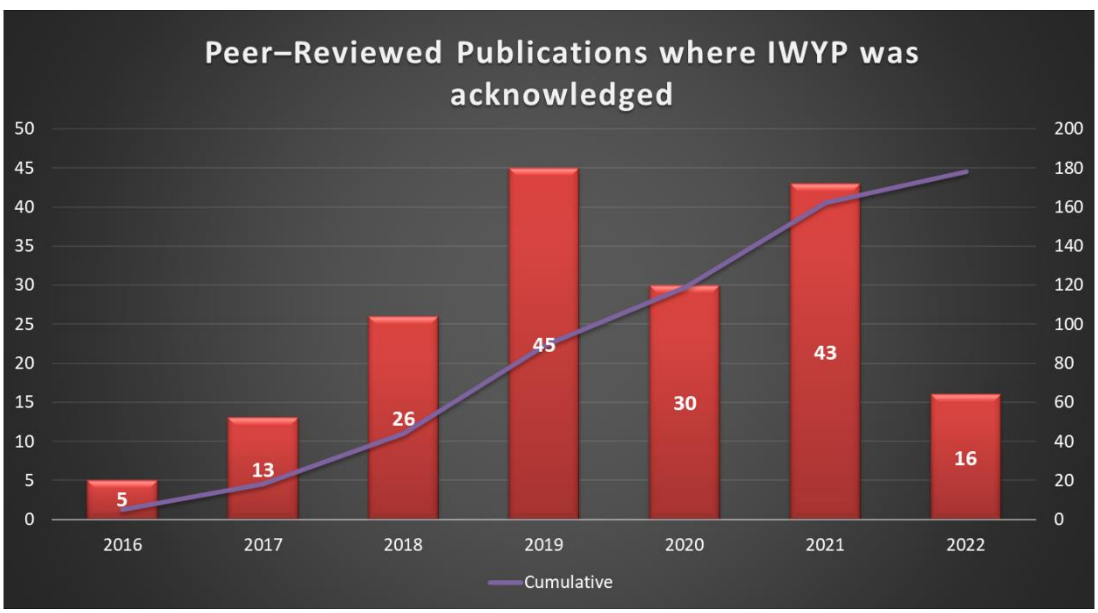
Promoting the Work and Role of Wheat

IWYP Science Briefs

- This last year, IWYP continued to publish monthly IWYP Science Briefs. Each Brief provides a summary of exciting discoveries from IWYP Research Projects, the IWYP translation Hubs or other special topics. This past year's topics included integrating genomics and high throughput phenotyping data, hybrid wheat, manipulating the response of stomata and chemical applications to boost photosynthesis, new trialing networks, circadian clock manipulation and new wheat research projects. All Science Briefs can be downloaded from https://iwyp.org/iwyp-science-briefs/

IWYP Research Publications

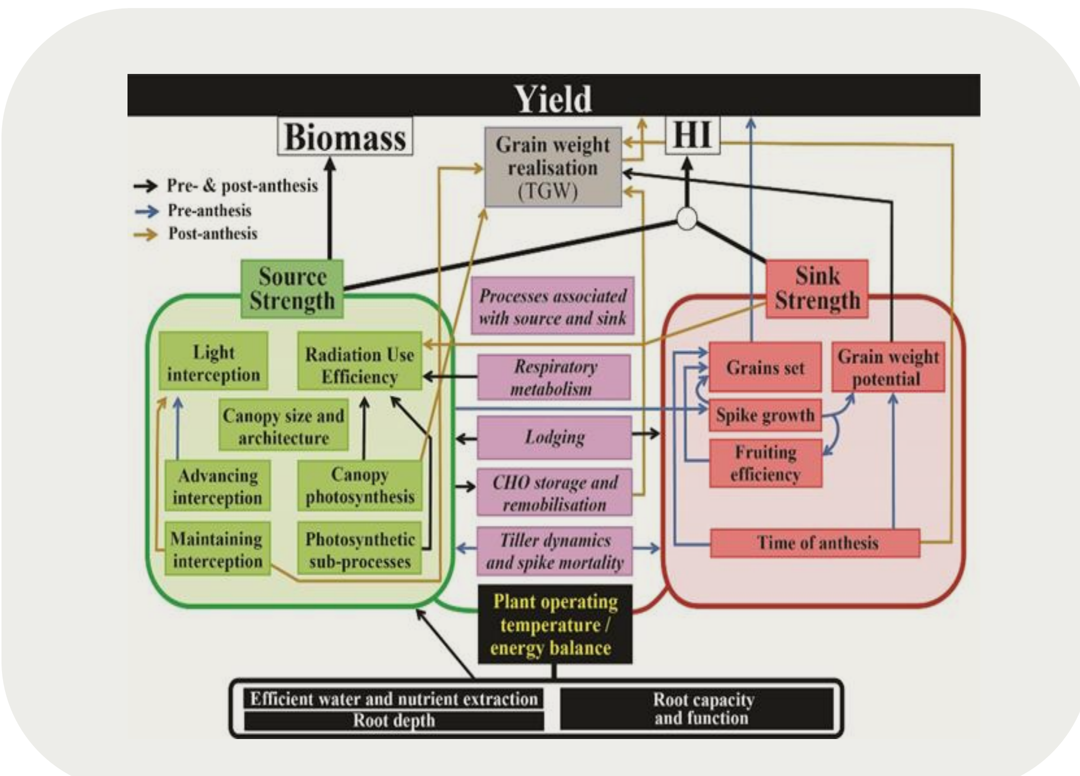
- Almost 60 new peer-reviewed scientific articles from IWYP researchers were published in 2021/22 with many in high impact journals. The list of ~180 + peer-reviewed articles published since the inception of IWYP is available at https://iwyp.org/publications/). The number of publications reported for 2022 is still preliminary and will increase. The discoveries embedded in these publications have contributed to major changes in wheat science since IWYP was founded. They document the large impact that IWYP has had on knowledge of the determinants of yield potential in wheat. They also reveal the power of research collaborations across continents and disciplines, things at the heart of IWYP.



Determining, Analyzing and Prioritizing the Determinants of Wheat Yield

Events throughout the life of a crop influence final yields, including those related to the environment and agronomic management. The large number of events involved complicates defining the most vulnerable critical rate-limiting steps that need to be improved or optimized. IWYP has therefore facilitated the description of steps in crop development in the form of illustrated “Wiring Diagrams”. These diagrams, and the supporting evidence from the literature, have been designed to aid breeding and research as well as the targeting of new potentially high value research by funding agencies. They provide, for the first time, a more comprehensive description of where variation in specific steps and traits can result in loss/gain of grain yield and therefore where to target improvements for commercial gains. The first paper has been published and two others have recently been accepted for publication. The first, an introduction to the Wiring Diagrams, is available from Nature Food (Reynolds MP, Slafer GA, Foulkes JM, Griffiths S, Murchie EH, Carmo-Silva E, Asseng S, Chapman SC, Sawkins M, Gwyn J, Flavell RB, 2022 - *A wiring-diagram to integrate physiological traits of wheat yield potential*, Nature Food https://www.nature.com/articles/s43016-022-00512-z). Scientists participating in the recent IWYP Program Conference unanimously agreed that the wheat scientific community should capitalize on the power of the Wiring Diagram in identifying new targets to accelerate yield gains.

An IWYP Wheat Wiring Diagram



2022 IWYP Program Conference

The 2022 Conference was organized as a virtual event spread over 2 half days to accommodate IWYP Members attending from other time zones. A “by-invitation only” event, the Conference theme was “Scientific and Integration Strategies to Generate Greater Impact Faster” and was structured as a mix of short presentations and discussion panels. Due to time constraints, it was not possible to provide an opportunity for IWYP researchers to give scientific updates of their projects. However, they were invited to send in advance a short presentation/poster that could be circulated among all participants. It was satisfying to see the level of interest in attending the Program Conference. There were over 80 participants for each of the half days that included IWYP researchers, invited guests, Funders and private industry members. The strong interest shown by the wheat scientific community, representatives from funding agencies and private sector partners signifies that IWYP is seen as essential and relevant to the goal of boosting the genetic yield potential of wheat.

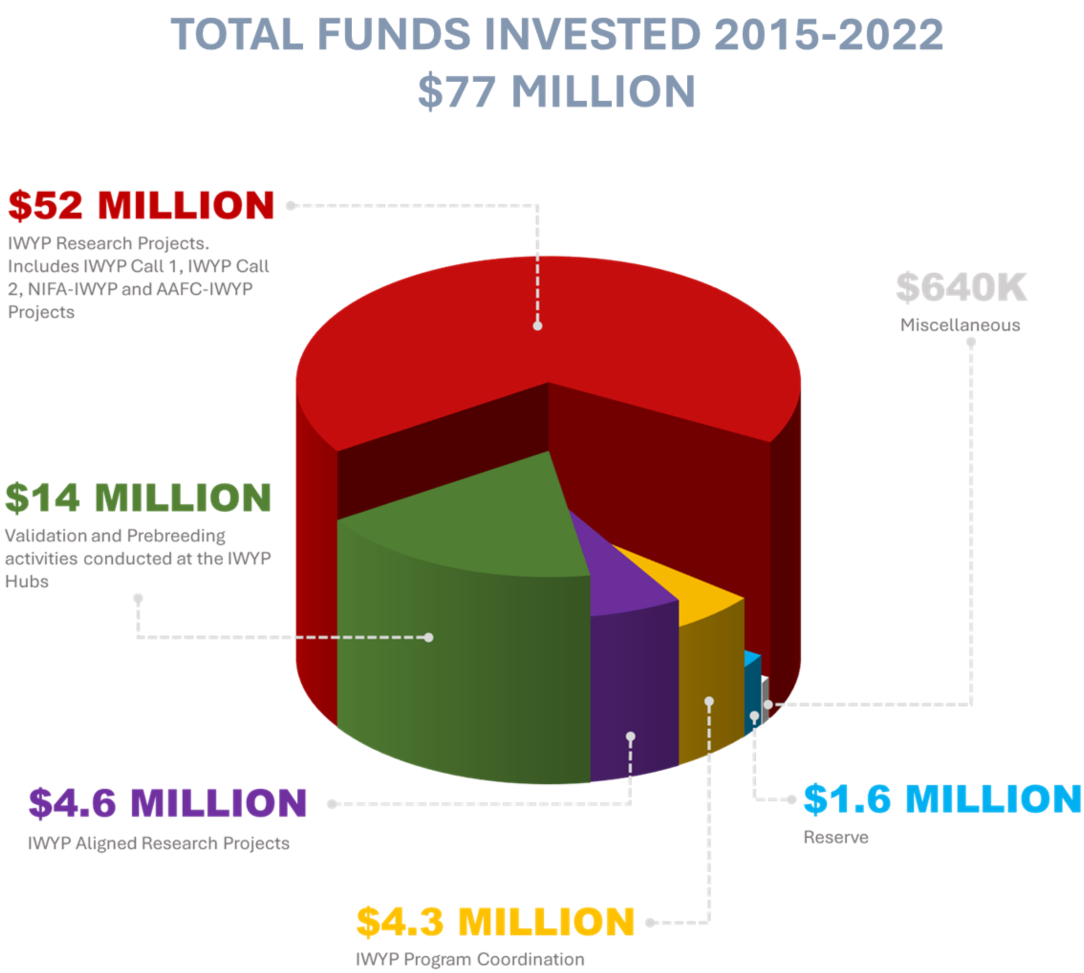
The content of the Program Conference was established with help from a committee of IWYP members. Topics covered included updates from the 3 IWYP translational Hubs revealing progress for trait development in elite germplasm, an examination of different traits that contribute to a high yielding wheat crop, new technologies to increase breeding efficiencies, new tools for managing huge amounts of information to support breeding programs, how IWYP discoveries benefit breeding for stress tolerance and what IWYP’s strategy should address in the coming years. Panelists of experts were asked to provide their views on many of these topics.

It is planned to hold the 2023 IWYP Annual Program Conference in April at the IWYP Hub at CIMMYT in Obregon, Mexico where the latest germplasm advances will be seen.

Financial Overview

Since the founding of IWYP in 2015, the working model created by IWYP of coordinated and integrated scientific research tied to centrally coordinated pipelines of downstream development has been managed via a centralized accounting system.

The IWYP Science Program is largely funded by a group of IWYP Partners (BBSRC, USAID, GRDC, USDA-NIFA, SFSA and AAFC). IWYP also accounts the large in-kind contributions made by a variety of activities within the Program. The total investments made by the range of partners, directly or indirectly since the inception of IWYP, amounts to ~US$77M. Over the period 2021-22 the total funds invested in IWYP were ~US$5M. During this past year, funds have continued to be spent on research projects from the second IWYP Call (BBSRC, USAID, GRDC), the NIFA-IWYP grants and the AAFC Aligned Call (AAFC, BBSRC, GRDC), the CIMMYT Spring Wheat Hub, The NA and EU Winter Wheat Hubs, and the value-adding coordination, scientific management and communication activities. About $2 million remains in reserve for next year. This reserve with additional pledged funds and new funds that must be raised during the coming years will support the continued validation, pre-breeding and scaling up of the current research discoveries into significantly higher yielding wheat germplasm and breeder-friendly tools for transfer to varietal breeding programs globally.



The Year Ahead

There are several important components to consider as IWYP assesses the progress and changing needs of its Science Program. Firstly, fully assessing the potential of past discoveries to yield enhancement must be completed as fast as possible. Secondly, continuing to feed the IWYP pipelines with new discoveries that can fill gaps in knowledge or trait enhancement is also essential. That means we need to work harder in finding or stimulating new research projects being funded around the world to align with IWYP so that their outputs can be applied and bring value into major breeding programs and thus farmers. Thirdly and most importantly, we need to continue to decipher which traits combine to result in the largest boosts to grain yields and how to make those trait combinations as efficiently as possible. This is a complex task, especially considering the need to identify and make the optimal trait combinations for driving yields even higher across different environments and ensure they are as climate resilient as possible. Fourthly, we must link advanced traits with high throughput phenotyping methods and more detailed molecular markers/haplotype segments to make their selection in breeding programs as facile as possible, particularly in early breeding generations. We will continue to refine our international field trialing system and scale it as necessary to evaluate newly created elite germplasm possessing novel traits and trait combinations. We will continue to maximize the uptake of the many outputs from IWYP into breeding programs around the world where appropriate.

IWYP will remain diligent in applying the wealth of growing knowledge about specific traits, trait sets, tools and protocols to bring new gains to breeding systems. The Wiring Diagrams will be a key tool in this endeavor. They will be useful for identifying new high value research targets that can add to or enhance existing yield potential traits in our portfolio. The Wiring Diagrams will also guide the design of more efficient trait stacking strategies to increase yields faster.

We expect that further modelling of yield, linked to the Wiring Diagrams, will become a more valuable tool for predicting trait performance in different environments. It will be necessary to gain more financial resources to bring the full benefits to breeding programs around the world.

Partners and Funders

IWYP operates as a public-private partnership with members from many countries. The Partners provide strategic direction and advice on the means of translating crop-based research discoveries into new wheat varieties for farmers. As of today, 14 public funding and research organizations and 11 private industry partners provide financial support and strategic advice.

Public Partners

CIMMYT International Maize and Wheat Improvement Center

GRDC Grains Research & Development Corporation

INRAE

syngenta foundation for sustainable agriculture

USAID From the American People

CGIAR

UKRI Biotechnology and Biological Sciences Research Council

Wheat Initiative

सत्यमेव जयते Department of Biotechnology Ministry of Science & Technology Government of India

Agriculture and Agri-Food Canada / Agriculture et Agroalimentaire Canada

USDA United States Department of Agriculture Agricultural Research Service

UKaid from the British people

SADER

USDA United States Department of Agriculture National Institute of Food and Agriculture

Private Partners

BASF We create chemistry

Corteva agriscience

Limagrain from earth to life

Seed Co The African Seed Company

Intergrain

KWS

RAGT 2n

INARI®

LongReach

syngenta.

mahyco® Every Seed Counts

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Research to Deliver Wheat for the Future