IWYP International Wheat Yield Partnership

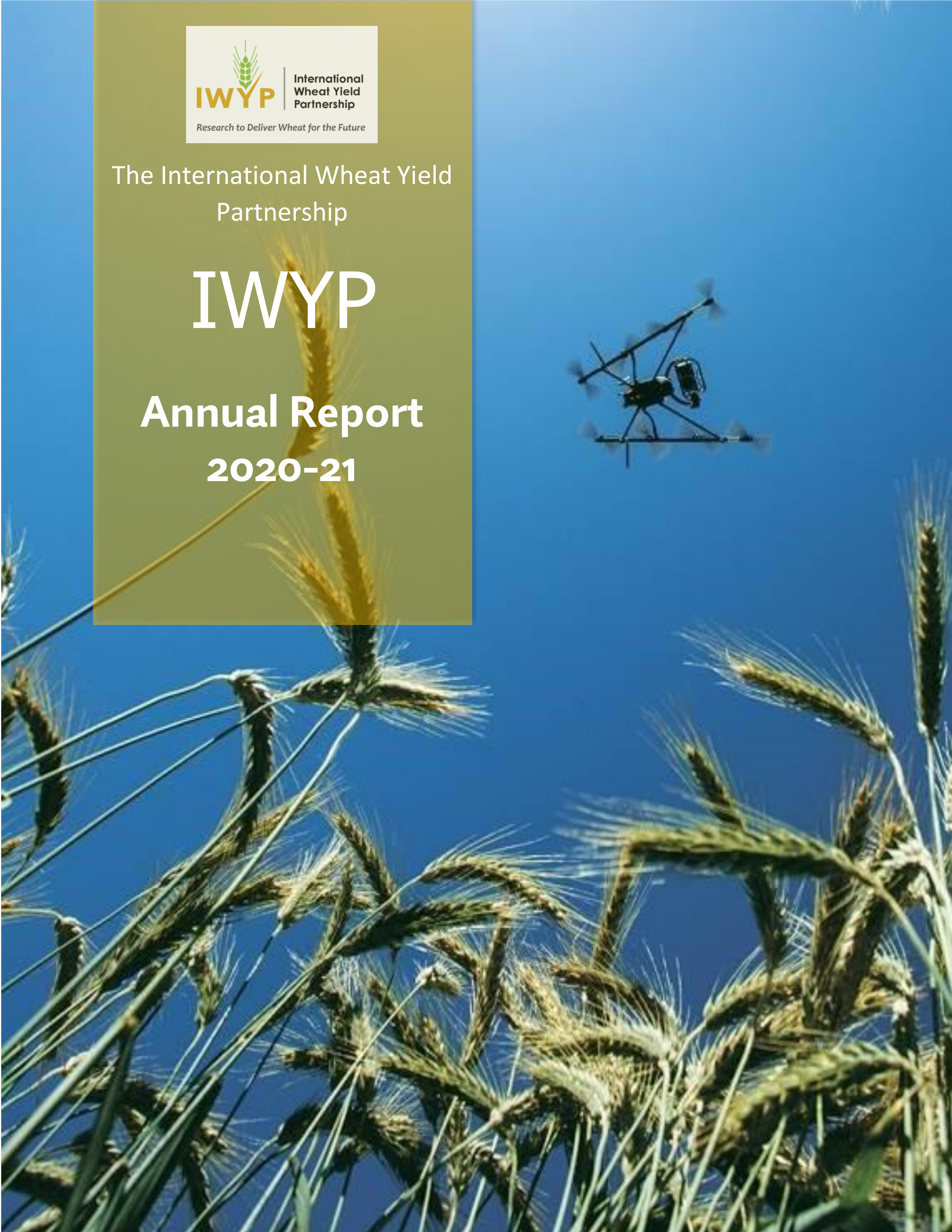
Research to Deliver Wheat for the Future

The International Wheat Yield Partnership

IWYP

Annual Report

2020-21



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Executive Summary

Over the last 7 years, IWYP has been instrumental in bringing together public funding agencies, major research institutions and private companies across the world into an effective and unique public-private working collective. The Partnership has created a shared strategy, co-invested and found ways of working together to address the critical need of global food and nutritional security in the future. Collaborative networks of international science teams have been created that function as envisioned and there is now much value embedded in the know-how of IWYP and all the communities that work within it. The “IWYP system” has been shown to be highly functional, effective and efficient. IWYP has created a pipeline of discoveries that can transform the landscape for future wheat yield increases.

IWYP strategy for impact

The core of the IWYP strategy has changed little since originally developed. The objective is to provide germplasm, knowledge and tools to breeding programs around the world, public and private, to help achieve substantial wheat yield gains in farmers’ fields. To this end, international teams of IWYP researchers work collaboratively to discover novel genetic variation defining trait improvements in key physiological source and sink pathways. Combining such optimized traits is essential to raising yields by our goal of up to 50% by 2035. IWYP scientists also continue to develop the associated tools to facilitate the uptake of these discoveries in breeding programs. Validated outputs are field tested and made available to all wheat breeding programs around the world as soon as possible.

Impacts are primary measures of progress and success for IWYP. During 2021, IWYP has created impact in numerous ways as illustrated in this Annual Report. These include new scientific knowledge and genetic resources, more advanced implementation of integrated systems for research translation into germplasm development and the training of scores of new scientists. Most importantly, international field trials of lines selected for the traits they possess are revealing yield gains over competing commercial checks, which is the ultimate measure of impact that IWYP seeks.

New options for yield improvement through research

Over the last year, a new concept to aid yield improvement design has been finalized. It embodies “Wiring Diagrams” that provide a graphical integrated view of the major traits and subtraits that interact to create grain yield, highlighting the deterministic links (wires) between them as currently understood. The diagrams are supported by detailed explanations and literature citations. We intend to use this as a key tool for filling gaps and identifying opportunities in research, as well as a guide to build higher yielding wheats by combining specific traits. This work has been prepared in several manuscripts that are now being submitted for publication in leading scientific journals.

Research discoveries made around the world feed the 3 translational pipelines in the IWYP Hub Network that validate the discoveries and develop them into higher yielding germplasm that is field tested and delivered to breeding programs. Over the last year, nearly 2 dozen new favorable trait variants, genetic markers and protocols/technologies have been transferred to the Hubs from research projects, illustrating the power of the IWYP model. These new variants enhance photosynthetic efficiency and biomass “source” traits, multiple new “sink” related traits, different root architypes, traits for crop development and floral traits to facilitate hybrid seed production. They will contribute much to the knowledge base of which chromosome segments can drive yield improvement. Important new breeding technologies have also been devised. These include multiple instance deep learning models that fuse phenotypic image data from the field and genomic information to enable yield predictions.

Translational Hub Network

The IWYP Spring Wheat Hub at CIMMYT carries the primary responsibility for validating all new research outputs and building them into elite spring wheat germplasm for testing and dissemination to breeding programs. Importantly, this Hub is responsible for seeking the optimal combinations of different traits to raise yields higher. Over the past year, several new outputs were in the validation stage with nearly 3 dozen different validated traits/genes/markers under development in pre-breeding with the proportion involving trait stacking ramping considerably. International field trials have identified several new IWYP lines with significantly higher yields than the elite check varieties and analyses show that the yield advantage of new lines has increased over the past 5 years. These and other new higher yielding elite wheat lines from this pre-breeding pipeline have been disseminated around the world.

Over the last year, the 2 translational Hubs established in 2020 as public-private partnerships for the development of winter wheat types began introgression of selected IWYP traits into multiple elite wheat lines. The North American Winter Wheat Hub is currently introgressing 7 IWYP traits into 11 different US winter wheat lines. The European Winter Wheat Hub is currently introgressing 3 IWYP traits into 3 different EU winter wheat lines. Each Winter Wheat Hub will add new traits as funding/capacity permits.

Communications

The IWYP management team continues to devise new communication tools to disseminate information on IWYP, its scientific discoveries and to drive uptake of Program outputs by public and private breeding programs around the world. Major communication components include the IWYP website, Annual Reports, monthly Science Briefs, various newsletters, updated Asset Catalogues and over 130 publications in scientific journals.

A successful IWYP Program Conference was conducted online this past year. It was held over 3 half days and attended by more than 90 IWYP members from around the world. Discussion sessions and breakout groups provided the IWYP community with valuable feedback on several topics including new research to feed the pipelines, the Wiring Diagrams, the Hub Network and ideas for increased research funding.

Finances and future priorities

IWYP currently has 14 funding and research institution partners and 10 private industry partners. These Partners represent agencies, institutions and companies from around the world and have made a total investment in the IWYP Program of ~US$71M from 2014 to date. Additional financial resources will be needed year-on-year to sustain IWYP's progress.

As with any organization, it is important that IWYP continues to assess its progress and adjust its strategy according to changing needs. IWYP must continue to feed its translational pipelines with new discoveries and combine them in various ways to find the level of yield gains sought. We will deploy all our systems, assets, tools and scientists to create the genetic building blocks to push wheat yields higher and higher and move them to wheat breeding programs around the world to help facilitate impact in farmers' fields.

Message from the IWYP Board Chair

I recommend this Annual Report in the context of the urgent need to improve wheat yields in most parts of the world, using fewer inputs and less land. It records another year of significant IWYP discoveries and progress and illustrates the continuing contribution IWYP associated scientists are making to wheat science and crop improvement.

Failure to increase wheat yields globally will lead to much human hardship unless other forms of food and feed are substituted. The situation is serious given the short timeframes available to make the essential crop yield improvements and mitigate the effects of changing climates. The work of the International Wheat Yield Partnership (IWYP) therefore becomes more important year-on-year, given its significant international role for discovering and implementing new routes to increase wheat yields.

At the highest level, the IWYP Science and Impact Executive Board seeks impacts of many kinds, some shorter term and others for the longer term. Excellence needs to pervade all aspects of this initiative. IWYP was primarily formed to contribute in a major way to finding new genetic systems that can significantly increase wheat yield potential and stimulate the transfer of knowledge and know-how into the breeding programs of the world. It is recognized that this immense challenge requires novel discovery and innovation through long term translational pipelines. This Annual Report shows that IWYP, as an international integrator of science and know-how, is indeed moving discoveries on yield-enhancing traits down translational pipelines as intended. It also shows that there is much novelty being generated in genetics, methods and elite germplasm that is being assessed in many breeding programs around the world. Young researchers are being trained in significant numbers and scientific excellence is being illustrated by the more than 130 publications in high quality scientific journals.

The IWYP model as a public-private partnership is now validated and the Board recommends it to others who seek innovations from science in areas where the burden is too great for any one funding body or company. However, innovations from the mind and lab to being proven in the many environments of food production of the world require many years of dedicated attention and resources. In these days when the effects of climate change and net-zero carbon releases must be built into the solutions, the needs and urgency are even greater than when IWYP started in 2014. IWYP extended its reach into winter wheats these past 2 years, stimulated by private sector investments. Building the network of three IWYP translational Hubs over the past two years is another feature that the Board sees as transformational in stimulating transfer of scientific discoveries into commerce, public and private, to serve future food production for the global need.

The Board is pleased to see that the IWYP “brand” built over the past seven years remains strong in the scientific community as IWYP continues to play its part to meet future wheat needs of the poor and rich, north and south, around the world.

This past year the home institutions of IWYP’s scientists needed to limit staff activities due to the Covid-19 pandemic. Consequently, scientific progress was limited in some places. The IWYP Board thanks the institutions and scientists for minimizing disruptions while maintaining a safe working environment.

Message from the IWYP Program Director

We began the International Wheat Partnership (IWYP) Program seven years ago with excitement, a handful of public and private partners, a new model and aggressive goals. Our focus, the critical need to significantly increase wheat yields to address food and nutritional security for the future global population. We based our strategy on the core tenet that coordinated, collaborative and integrated international science would be the most effective and efficient way to find and deliver mitigative solutions. We knew from the beginning that making potentially impactful scientific discoveries is hard and takes time. We knew that it takes years to validate, develop and deliver these discoveries into commercial pipelines whose outputs create societal impact. This remains the case.

Over the last few years, through our Science Program we have been reminded that wheat has a large genome, is genetically complex and significant genetic improvement is hard. To achieve the level of yield gains we seek requires ingenuity, technical expertise, collective effort, resources, and time. This continues to drive our systems.

What have we learned? 1) Those who provide the resources for scientific research and the scientists they support continue to believe that a collaborative and integrated international group, has the best chance to provide meaningful solutions. 2) The IWYP "brand" is highly respected by the wheat scientific community. 3) Wheat scientists and funding organizations believe that there is inherent value in what the IWYP model has created by integrating the science, operating internationally and building a community. 4) The wheat scientific community view the IWYP Hub Network and their platforms as a highly valuable and important component of the overall Program. 5) Wheat scientists continue to be committed to IWYP goals and desire more funding to follow new leads and find creative solutions. 6) Overall, maximum transparency and constant communication are valuable and appreciated.

What else has happened in 2020/21? In addition to the significant hurdles to our success known at the beginning, the effect of changing climates on crop production and the need for sustainability is ever increasing and has become a higher priority. This requires additional strategic science to ensure that progress in increasing yields is not relegated to merely maintaining them at current levels. Further, the unforeseen COVID-19 pandemic affected our scientists around the world to differing degrees and has led to new ways of communicating and executing research to maintain progress.

Are we on track to deliver a 50% yield increase by 2035 as planned? In short, we believe that we are. The critical need remains. IWYP's focus and commitment of the science team is strong. Our scientists continue to make new discoveries to overcome the rate-limiting steps to creating higher yields. The IWYP Hubs are delivering new higher yielding germplasm each year. The newly created Wiring Diagrams now provide IWYP with an integrated view of how to build higher yielding wheat plants and have enabled us to identify the major gaps and opportunities in our research portfolio more easily and precisely. This will help us to address the major physiological bottlenecks more comprehensively, add to our rapidly expanding toolkit of assets and continue to build higher yielding lines and deliver them to commercial pipelines.

IWYP Strategy: Discovering, Assembling and Disseminating the Genetic Building Blocks to Increase Yield Potential

IWYP scientists seek yield enhancing trait variants of leaf and canopy architecture; stem thickness and length; timing of flowering and other key developmental stages; photosynthetic and radiation use efficiency; responses to changes in light levels; photosynthetic differences between upper and lower levels in the canopy; grain number, weight and size; determinants of sugar accumulation versus its use for building new molecules; respiration; stomatal size changes that control carbon fixation rates; roots; and many more. While nowhere near comprehensive, IWYP research projects arguably represent the largest integrated compilation of wheat yield trait discovery and analyses achieved to date.

The germplasm in which these trait variants are sought is the key to finding novelty. IWYP scientists therefore screen many diverse and uncommon sources of germplasm, including wheat wild relatives, to discover these new trait variants. In some instances, molecular genetic markers closely linked to the traits are discovered which facilitate the introduction of the traits into elite global germplasm. Details of all these activities are noted elsewhere in this Annual Report, the IWYP Science Briefs and many publications in the scientific literature (see below).

The value and impact of the IWYP Program will be greatest when single trait variants are assembled in novel combinations and selected in breeding programs. This requires sustained pre-breeding over many years within the IWYP Hubs and elsewhere. Nevertheless, new lines selected with higher rates of photosynthesis, increased radiation use efficiency, optimal flowering times and other traits have already demonstrated enhanced yield in elite lines in agricultural trials as noted in this Annual Report. Furthermore, lines with enhanced yields and traits have been disseminated around the world for use by others as parents for breeding or varieties. This strategy of discovery, validation, pre-breeding, trialing and dissemination through research projects and Hubs is illustrated in the diagram below.

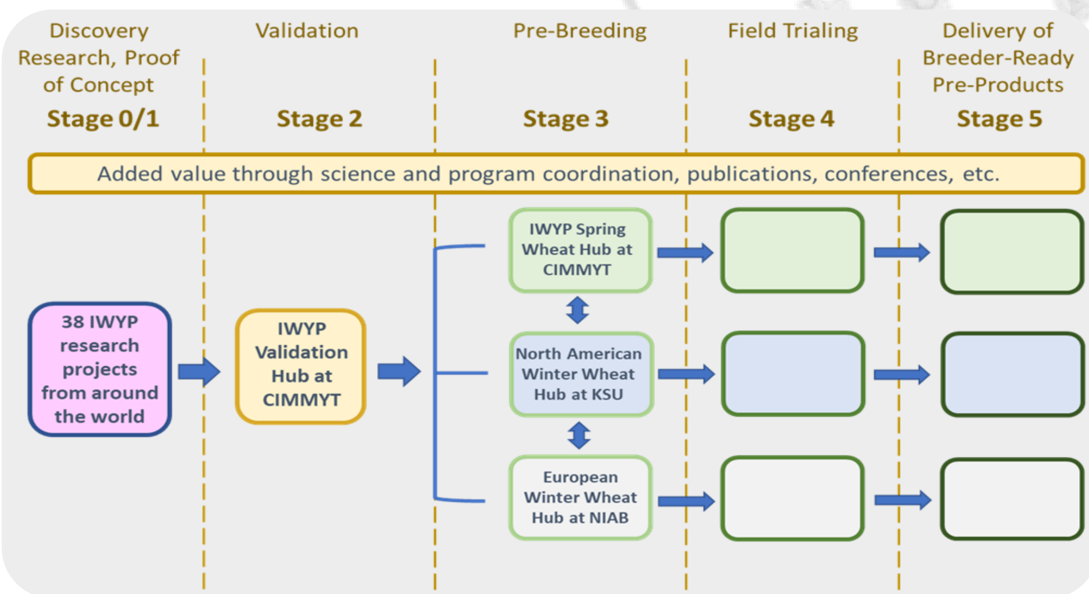


Figure 1. Overview of the IWYP Program

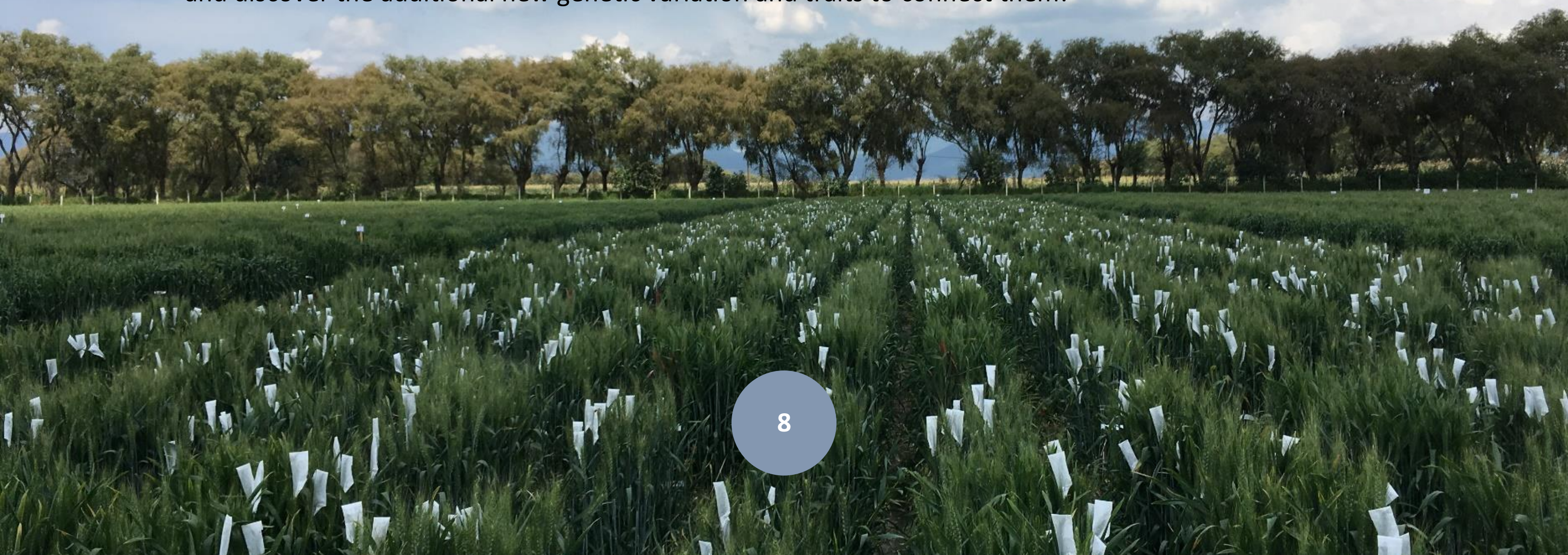
IWYP in Perspective: What has been Accomplished?

Over the last seven years, IWYP has been instrumental in bringing together public funding agencies, major research institutions and private companies into an effective and unique public-private collective. The Partners have created a shared strategy, co-invested and found new ways of working together to address a critical need. New collaborative networks of international science teams have been created that join forces scientifically on a variety of research targets using state-of-the-art technologies.

The “IWYP system” is functioning as envisioned and there is clearly much value embedded in the know-how of IWYP and all the communities that work within it. IWYP has demonstrated that it is highly functional, effective and efficient. With over 130 journal publications to date, numerous outputs entering product-driven pipelines and with new trait-led breeding strategies emerging, the potential impacts are many. Also, large numbers of young scientists have been trained in wheat genetics and breeding via the projects and Hubs to help fill the need for more scientists to pursue applied aspects of plant science.

Overall, IWYP can already claim to have made a significant and important difference to wheat science. A deeper understanding of the mechanisms underlying the creation of grain yield and the limiting steps of the processes underlying high yields has been gained. New sources of improved traits in germplasm are available for use by all, as are new methods to measure and select the traits, along with new knowledge regarding their genetic control. Germplasm with enhanced yield traits is already being transferred around the world to enrich public and private breeding programs and some lines have been converted to varieties.

IWYP has also created a pipeline of discoveries and opportunities that transform the landscape for future yield increases. There now exist multiple new platforms of knowledge, germplasm, genetics and genomics for wheat improvement. The list of potentially limiting traits, the physiological, developmental and biochemical processes underlying these traits, as illustrated by the Wiring Diagrams (see below), can now become a new framework for future research. IWYP is already well along the path in the deployment of more efficient photosynthesis and the traits necessary to build bigger spikes with more and larger grains by numerous ways. Both knowledge-based and tangible outputs have increased breeding efficiencies and are beginning to positively influence the rate of yield gain. As these outputs become rapidly adopted by others, we expect this influence should grow. Much more needs to be done not only to capitalize and build on the discoveries made so far, but also to fill the critical knowledge gaps and discover the additional new genetic variation and traits to connect them.



IWYP's Impact in 2021

119 SCIENTISTS TRAINED

45 SCIENTIFIC PUBLICATIONS

2900+ FOLLOWERS ON SOCIAL MEDIA

298 NEW WHEAT CROSSES

4 WHEAT VARIETIES

104 GERMPLASM SETS DISTRIBUTED

320 AVALIABLE WHEAT LINES

14 PUBLIC PARTNERS

10 PRIVATE PARTNERS

14 COUNTRIES

38 RESEARCH PROJECTS

3 IWYP HUBS

60 RESEARCH INSTITUTIONS

Sustaining the IWYP Translational Pipelines

IWYP now has 3 translational Hubs: the large principal Hub at CIMMYT in Mexico, the North American Winter Wheat Innovation Hub and the European Winter Wheat Hub. The IWYP Hubs rely on outputs from the IWYP Research and Aligned Projects to make the gains in genetic wheat yield potential that we seek. The Hubs test the effects of these outputs on yield performance and if confirmed the outputs are combined in different ways to maximize yield gains before being offered to wheat researchers and breeders worldwide. Yield enhancement is a continuous process, year-on-year and not all discoveries are expected to add yield to existing leading varieties. Therefore, the Hubs need to be sustained with a continual supply of new research outputs. Furthermore, many different sources of enhancements for each trait are needed to build and realize maximum trait potential.

Over the past year, many of the planned project activities, particularly those conducted in the field or laboratory, were hampered or even curtailed due to the Covid-19 pandemic. Despite this, most researchers were able to generate discoveries and demonstrate potential outputs likely to make their way to the IWYP Hubs. Some highlights are presented below.

Photosynthesis and Radiation Use Efficiency

- Several molecular markers were found to be genetically linked with a response in photosystem II efficiency and located close to the *Rca* (Rubisco activase) gene involved in carbon fixation. These genetic markers show variation in wheat. This raises the possibility of utilizing these markers in breeding to select wheat plants with improved photosynthetic efficiency.

- Bioinformatic analyses identified wheat genes likely to control leaf development and stomatal characters. Lines with mutations in these target genes showed differences in stomatal number, distribution, dimensions and gas exchange/transpiration without any apparent negative effects on plant growth. These lines are a novel resource for testing the effect of altered stomatal phenotypes on yield, water use relations and photosynthetic rates.

Biomass (Source)

- Field data of Canadian winter and spring wheats suggest that establishing a large crop canopy early and maintaining it to anthesis results in higher yields. Furthermore, under drought conditions a positive relationship between high biomass accumulation and seed protein content was found. This work provides insights on what traits to select in breeding for higher yielding wheats.

Yield (Sink)

- Several genes (trehalose phosphate synthase and trehalose phosphate phosphatase genes) involved in the biochemistry of trehalose, a sugar signaling metabolite, were found to be linked to several yield component traits. One gene was strongly linked to the interaction of plant height with grain number. Exotically derived wheat germplasm that has not undergone breeder selection for trehalose phosphate phosphatase genes may contain novel variation useful for enhancing grain-related traits such as the number of grains per m^2.

- The strategy of backcrossing 16 previously identified loci that affect defined sink-based yield components into germplasm expressing exceptional source-related traits (biomass, root architecture, spikelet number per spike) continued. In addition, 3 wheat genes affecting either plant growth, metabolism of carbon, nitrogen or nutritional quality (iron and zinc) were selected for gene editing of their promoter regions to create an edited allelic series for each of these genes.

- A transcription factor regulating spikelet architecture and grain quality traits by modifying vascular bundle development was identified following analysis of a population of wheat mutant lines. As well as regulating spikelet number, this transcription factor was also found to be associated with a 25% increase in grain protein content.

- New knowledge was generated on the role a phenology gene has in accelerating plant maturity, particularly through the genetic and environmental regulation of the transition to flowering. The results also illustrate how optimizing the timing of developmental stages can improve spikelet numbers and hence the number of grains.

- Candidate genes were identified, validated and/or published for 11 QTL involved in grain size, number of spikelets/spike and awn number. These discoveries will greatly aid exploitation of new variants of these genes for yield enhancement.

Roots

- A gene known to determine the angle at which roots grow, and is evolutionarily conserved in barley and wheat, was cloned. An orthologue of this gene in durum wheat produced an even stronger phenotype, confirming its role in regulating root growth angle. This gene could be a valuable target for creating improved root systems in cereals.

- 3 candidate genes localized at a root growth angle QTL on chromosome 6A were submitted for gene editing in durum wheat at NIAB, UK to help validate their role.

Development

- Genes for the circadian rhythm clock that enables plants to sense daily environmental changes which control developmental processes influencing grain yield were identified. An analysis of genetically edited circadian clock genes confirmed their characteristic oscillation patterns and their differential expression in the 3 constituent wheat genomes. The circadian clock genes were found to regulate plant defense genes with one gene regulating the oscillating expression of jasmonate synthesis genes, and another regulating the expression of salicylic acid biosynthesis genes.

Hybrids

- 5 wheat lines containing chromosomal segments from the wild wheat relative species *T. timopheevii* produced smaller pollen grains than those found in bread wheat. This is a desirable trait for hybrid seed production because it can increase the distance of pollen movement and thus fertilization frequency. An additional line showed extended stigma receptivity, another useful trait likely to increase pollination frequency in hybrid wheat seed production.

- A group of abundant pre-meiotic 24-nt reproductive phasiRNAs were discovered in the anthers of wheat and barley. These may open the door to develop novel genetic methods to induce male-sterility for use in hybrid wheat seed production systems. Disruption of the biogenesis of these phasiRNAs is being carried out to discover their effect on conditional male-sterility.

Technologies

- The T3/Wheat breeding database, part of the Wheat CAP project and supported by IWYP through a USDA NIFA grant, has continued to load more phenotypic and genotypic data, including new IWGSC Refseq physical map assemblies, genotypic data from several different populations and phenotypic data from several trials. It also now includes more analytical functionality.

- Haploid production is an important tool in wheat breeding, but current approaches are laborious and expensive. Alpha and beta-*CENH3* mutant combinations in different wheat homeologs were created and are being tested for their ability to induce haploids. The *CENH3* gene is involved in determining the position and function of the centromere. In parallel research, wheat lines containing mutations in the *MATRILINEAL* gene have been generated to also test their effect on haploid induction.

- A new protocol has been designed for PhotosynQ and MultispeQ devices to measure the induction of photosynthesis, including the identification of genetic variation in components of photosynthesis, thus better assessing the effects of Rubisco activase (*Rca*) which regulates the activity of ribulose 1,5-bisphosphate carboxylase/oxygenase, the enzyme involved in photosynthetic carbon fixation.

- A trehalose 6-phosphate precursor spray application elicited a significant and diverse response in grain yield in wheat lines 10 days post anthesis with strong positive effects on spike grain weight. Large-scale amounts of this precursor will soon be ready for testing of its effect on final grain yield in the field.

- Vegetation indices collected with unmanned aerial vehicles (UAVs) in small plots have been found to be more predictive of grain yield than univariate genomic selection. Multi-trait genomic selection approaches combining genomic information with the aerial phenotypic indices were found to have the highest predictive capabilities. The data suggest that aerial HTP phenotyping may facilitate selection by breeders for many different traits that are difficult to measure in early generations and therefore has to the potential to increase the rate of genetic gain.

- Initial results using a single crop model suggested a relatively large positive response in yield (up to 34%) were related to with an increase in canopy RUE in locations in India, Canada, some parts of China, Russia, Mexico, Argentina and Brazil. Conversely, the data suggested a negative response to an increase in RUE in most of Europe possibly due to limitations on the use of nitrogen fertilizer to promoting further growth and yield. Scaling these results to all countries suggested that an overall global yield increase of 9.4% could be achieved by increasing RUE.

- A new transgenic transformation technology based on the developmental *GRF4-GIF1* genes was developed that increases efficiencies of transgenic plant production from tissue culture explants.

Assembling the Building Blocks to Boost Wheat Genetic Yield Potential by Integration of International Discoveries

A founding feature of IWYP was to not only promote scientific discoveries related to yield improvement but also to integrate them for the purposes of crop improvement around the world. To that end, IWYP has established 3 translational Hubs as detailed later in this Annual Report. Now that many of the Projects have achieved outputs with potential use for yield enhancements, their integration at the Hubs can be assessed. In the panel below, the trait outputs assembled into pre-breeding at the IWYP Hub at CIMMYT are listed. Their contribution for pushing wheat yields higher, singly and in combination, are being evaluated. The list provides an important measure of IWYP's contribution to wheat improvement as an integrator of international science.

Yield

- Total grain yield (elite lines and parents)
- Total grain yield (markers)

Photosynthesis and RUE

- High biomass at different growth stages
- Total biomass
- Biomass (markers)
- Radiation Use Efficiency (RUE)
- Chlorophyll content in the third leaf
- Photosynthetic capacity & efficiency
- Photosynthetic capacity & efficiency (wild relatives)
- Speed of sun-shade photosynthetic transitions

Grain size and number

- High harvest index
- Canopy architecture
- Grain weight
- Thousand grain weight
- Grain length
- Grain Number
- Number of grains M^2

Spike traits

- Spikelet number per spike
- Spikelet number mutants
- Number of grains per spike
- Number of spikes M^2
- Fruiting efficiency

Partitioning

- Spike partitioning
- Length of internode 3
- Length of internode 2

Other

- Decreased canopy temperature
- Optimized stomatal dynamics
- Phenology
- Tiller number
- Vigor
- Hormones
- Floral characters for hybrid production
- Roots
- Lodging resistance

BLACK = Traits from CIMMYT Aligned Projects; BROWN = Traits from IWYP Research Projects; BLUE = Traits from international IWYP Aligned Projects

Figure 2. Traits Assembled in the IWYP Hub Pipelines from International Discovery Projects

Wiring Diagrams – An Integrated View for Building Higher Yielding Wheat Plants

IWYP Management and a team of IWYP-associated scientists (crop geneticists, physiologists and modelers) have collaborated this past year to generate a comprehensive framework for approaching wheat yield improvement. Bringing together decades of crop research into a visual tool, this novel product, composed of wiring diagrams (WD), describes trait interactions using a set of "wires" to link traits and genetic yield determination. The links between multiple traits and yield are easily identified and described in corresponding explanatory text. By displaying the links between traits, organs, physiological functions, developmental stage and grain yield using coded wires, the tool facilitates the identification of connections that may not have been previously apparent. The WD also aids the development of new and more integrative research hypotheses and approaches. What makes the WD different from crop simulation models which are based on a similar concept, is that the WD makes no assumptions and are based largely on empirical evidence.

IWYP Wiring Diagrams

Provide a synthesis of trait interactions during crop development from seedling to maturity

Identify traits that create grain yields in breeding pools

Identify known or anticipated trade-offs between traits and processes at different crop development stages

Identify the genetic control of traits and sources of genetic variation

Identify easily measured traits for efficient tracking in breeding programs

Identify critical knowledge gaps for further study

Multiple versions of the WD could be customized for specific environments and for other species where there is a sufficient knowledge base since most of the same kinds of traits and processes are conserved across crops.

The WD will become an essential tool for IWYP as it helps direct the IWYP research and pre-breeding strategy by aiding the identification of new research targets to explore. It also acts as a check for verifying the current research approaches taken by IWYP such as exploiting genetic variation in source and sink physiological traits and combining these in targeted and novel ways to boost wheat yields.

The completed framework and supporting literature will be published in scientific journals in the coming months.

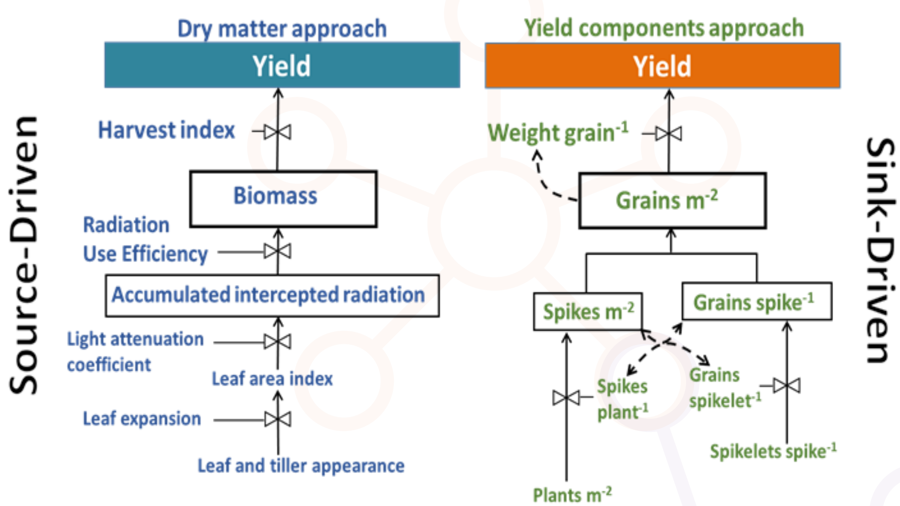


Figure 3. The Established Concept on which the Wiring Diagram was Conceived

Update on the IWYP Hubs' Translational Pipelines

The following pages provide highlights of the progress made by the three IWYP Hubs over the past year in identifying and evaluating the many "building blocks" of yield and in combining them to boost the genetic yield potential. The IWYP Hub at CIMMYT in Mexico serves as the primary entry point where research project outputs are validated and then, if warranted, enter the pre-breeding stage to develop higher yielding elite wheat lines. Successfully validated discoveries and wheat lines stacked with combinations of these discoveries are then shared with others. The IWYP Hub at CIMMYT also conducts a limited amount of discovery research to support the pre-breeding platform and develop methods necessary for efficient validation and pre-breeding. Some of these key activities are described below.

IWYP Spring Wheat Hub at CIMMYT

Research and Platform Development Outputs

- A molecular genetic marker correlated with canopy strength and lodging susceptibility has been found. This marker will aid in selecting lines with increased yield protection.

- Significant genetic variation for decreased chlorophyll content in leaves at the top of the canopy relative to lower parts of the canopy has been characterized. This trait may increase light distribution throughout the canopy and thus raise total radiation-use efficiency (RUE).

- A correlation often exists between stem water soluble carbohydrates (WSC) at anthesis and yield, grain number and radiation use efficiency. Significant genetic variation was found for WSC in CIMMYT germplasm. The adopted screening protocol for WSC is useful for selecting lines with high stem sugar concentration. The trait may also lead to improved fruiting efficiency and grain number as well as provide a buffer for assimilate supply during short periods of mild stress.

- A phenotyping robot and image processing scheme based on deep learning algorithms was developed via a collaboration. This technology has the capacity to measure traits such as spike number, spikelet number, heading date, canopy cover, internode diameter and spike morphology in field plots. Advances in digital phenotyping at CIMMYT and by other IWYP research projects are the future of plant breeding and should lead to greater efficiencies in wheat breeding.

- Trait measurements such as those measured by NDVI and other important indices have been retrieved from satellite imagery illustrating that this approach may have the capability to accurately capture and standardize data from small plot field trials in multiple locations and thus more efficiently characterize GxE effects.

- An improvement of the aerial platform involving simultaneously acquired data from multiple sensors of the Phenocart (land-based phenotyping platform) increased the number of useful remote sensed traits and improved the functionality of the Phenocart. A new version of the Phenocart (v2.0) is planned to be operational for use in the field in the 2021-22 cycle.

Phenology Genes Impacting Yield

Validation of major phenology genes at the IWYP Hub at CIMMYT, originally a focus in an IWYP Research Project led by Simon Griffiths at the John Innes Centre (JIC) UK, confirmed significant impact on yield and harvest index (HI). The insensitive allele of *Ppd*, *Ppd-D1a* had the most significant positive effect on yield in CIMMYT germplasm panels. Further, lines with alleles at *TaTOE-B1* and *TaFT3-B1* had between 3.8% and 7.6% higher yield with 4.2% and 10.2% higher HI respectively. The favorable allele at phenology gene *TaTOE-B1* showed positive effects on several sink traits related to grain number. The favorable alleles at *TaFT3-B1* produced positive effects on traits related to grain weight. Lines with combinations of these alleles have been selected for inclusion in international testing and several of the favorable alleles are being tested in one winter wheat Hub.

Validating Research Project Outputs

Over the last year, IWYP Research Projects have transferred many new outputs to the IWYP Hub at CIMMYT. These include new phenotyping assays and germplasm with enhanced yield traits including biomass production, spikelet architecture, grain protein content, speed of induction of photosynthesis, productive tiller number and spikelet number per spike. About 2 dozen traits are currently being validated or progressing through the translational pipelines in the IWYP Hubs. Several are being tested in combination for their effect on improving yield.

Impacts of the Trait Stacking Strategy

The long-term strategy of combining different physiological traits (both source and sink traits) continued during the 2020-21 pre-breeding cycle. Nearly 300 new crosses seeking to create different trait combinations were made.

An analysis of the best IWYP lines from several consecutive Wheat Yield Consortium Yield Trials (WYCYTs) demonstrated that many of the best new IWYP lines containing combined IWYP targets out-yielded the parental lines, including grain yield (28% of new lines), final biomass (45% of new lines) and harvest index (24% of new lines). Other target traits similarly positively impacted yield improvement. In contrast, new IWYP lines scored lower than the check varieties for spike number and canopy temperature traits at the vegetative stage.

Yield Gains of New IWYP Lines Containing Combined Traits in International Trials

The Wheat Yield Consortium Yield Trials (WYCYTs) in the International Wheat Information Network (IWIN) is the primary mechanism used by IWYP for disseminating and promoting new IWYP lines to interested parties, and most importantly for collecting the data necessary to assess the yield performance of new IWYP lines across a range of diverse environments.

An analysis of data received from over 26 international environments showed the best new IWYP lines from the 7th WYCYT conducted in 2019/20 had more than 6% higher grain yield than the elite CIMMYT varietal check Borlaug 100 and 9% higher grain yield over the CIMMYT long term standard check Sokoll. The best new IWYP line was 4 to 27% higher yielding than Borlaug 100 and 2 to 28% higher yielding than Sokoll when analyzed in different clusters of similar environments. We are still awaiting final data for the 8th (2020/21) and 9th (2021/22) WYCYTs. However, preliminary data show the same trends.

New candidate lines for the 10th WYCYT trials (2022/23) will be selected and multiplied for future IWIN distribution based on their performance at the IWYP Hub at CIMMYT during the 2021/22 growing cycle. The lines will be distributed accompanied by information on grain yield, grain weight, grain number, days to anthesis, days to maturity, plant height, and major known genes for disease and agronomic traits.

Yield Gains of New IWYP Lines Over Time

The graph below presents the progress in increasing grain yield that has been made year-on-year for the new wheat lines developed at the IWYP Hub at CIMMYT in comparison to the long term CIMMYT elite check Sokoll. Grain yield progress is presented as the performance of the best overall new IWYP line (in green) or the average performance of the 3 best new IWYP lines (in blue). Grain yields are shown as percentage grain yield over Sokoll, set at 100% (in red). The results indicate that new IWYP lines yielded higher than Sokoll across many international field trial locations. It is both notable and encouraging that the yield gap between the best IWYP lines and international checks continues to widen over time, indicating that IWYP is building on the successes of previous years. It is also noteworthy that the lines evaluated in 2020/21 are the product of crosses made 5+ years ago and selected during the last few years, and therefore do not yet contain many of the new traits and combinations from the IWYP-funded research projects that are currently in the pipeline. It is expected that these new traits and combinations will also contribute to and potentially elevate this upward trend in grain yield.

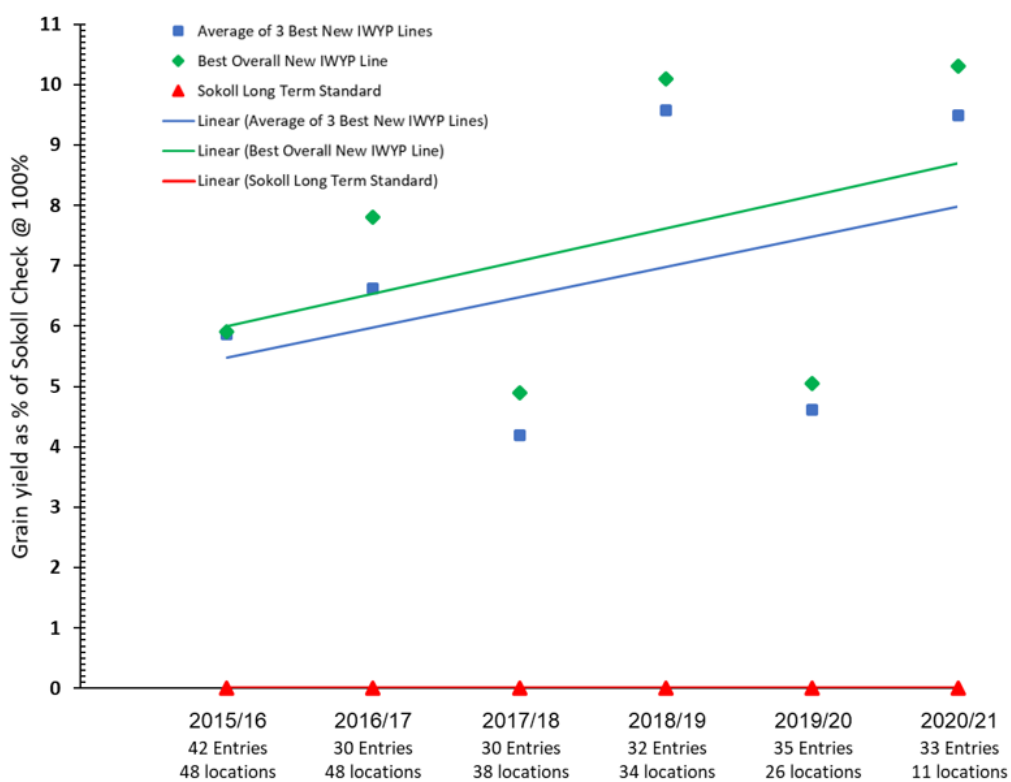


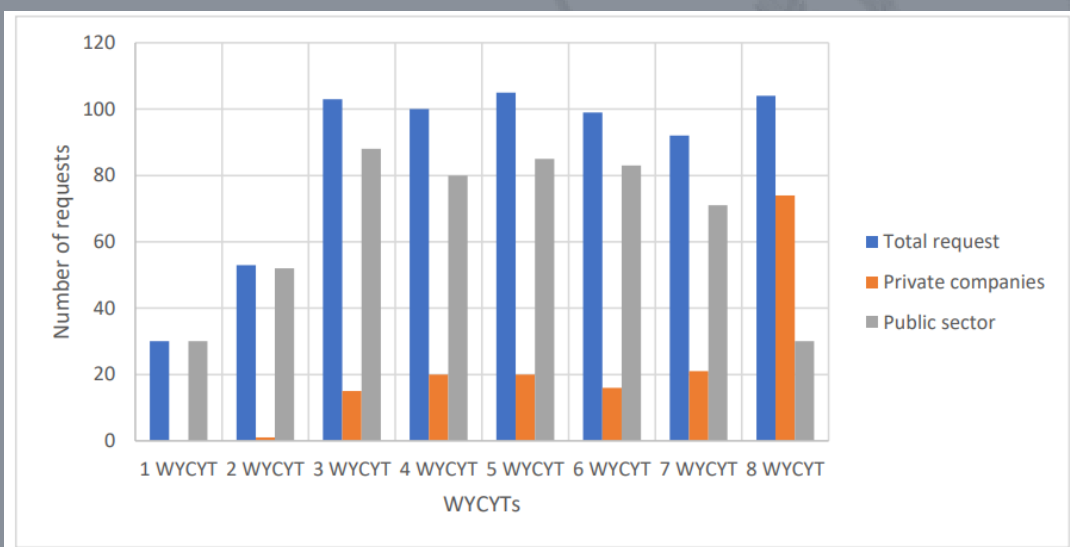
Figure 4. Relative Mean Grain Yield of the Best New IWYP Lines Over All International Field Trial Locations Per Year. Yield is Represented as Percent of Sokoll (Long-term Standard Check Variety)

Delivery of New IWYP Lines to Wheat Researchers and Breeders Worldwide

Since the creation of the 1st WYCYT (Wheat Yield Consortium Yield Trial), there has been a steady increase in the number of collaborators requesting WYCYT germplasm sets from the International Wheat Information Network (IWIN) system administered by CIMMYT. Few requests were received for the 1st and 2nd WYCYTs (pre-IWYP). However, the total number of requests has jumped since the 3rd WYCYT onwards post initiation of IWYP. The total number of germplasm sets requested has remained steady since the 3rd WYCYT when IWYP was founded, but there has been a growing proportional interest from the private sector suggesting that commercial parties see value in this germplasm as a source of new genetic variation and traits for their breeding programs. In contrast, there was a significant reduction in requests for the 8th WYCYT from the public sector. While the reason for this reduction is unknown, it is possible that the Covid-19 pandemic had an influence.

Germplasm Requests made to IWYP

Total number of germplasm sets requested by collaborators since the 1st Wheat Yield Consortium Yield Trial (WYCYT) in 2013 and numbers requested since the inception of IWYP in 2015 (3rd WYCYT)



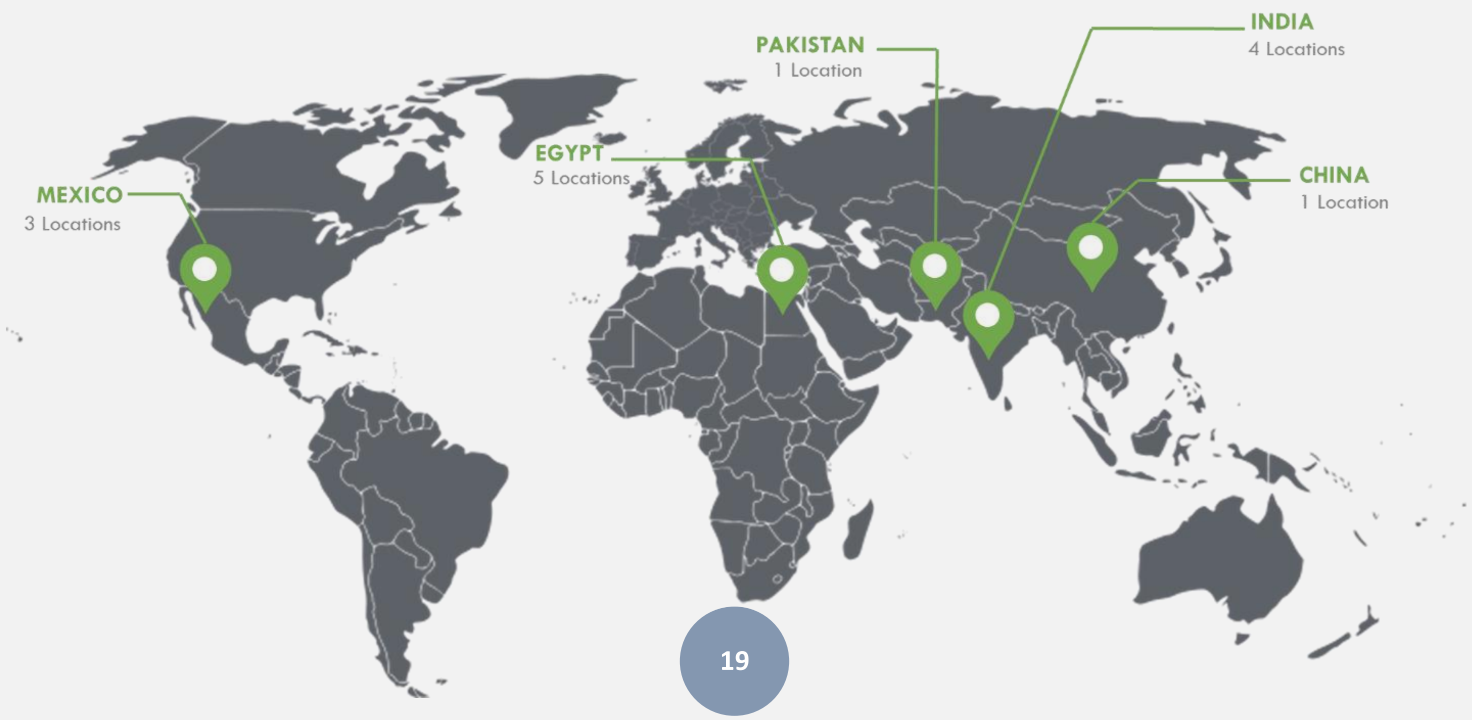
Pakistan 2021


Egypt 2021

New International Trialing System to Evaluate Trait Effects on Yield

Accurate data and information are required to select and deliver the most promising new elite lines from pre-breeding. International field trialing experiments are typically used to supply these data. The IWYP Hub at CIMMYT has utilized the existing International Wheat Improvement Network (IWIN) for field evaluations at 50+ sites across multiple countries each year. IWIN is a voluntary system that relies on offers to carry out trials in exchange for return of data. In this system, trials in some specific environments and collection of some types of phenotypic data are typically not possible. To address this, the CIMMYT-based IWYP Hub has developed a dedicated trialing system called the “IWYP Yield Potential Trait Experiment” (IYPTE) network. This enables the IWYP Hub to contract trials at specific locations, prescribe agronomic practices and have more and specific types of phenotypic data collected.

The 1st IWYP IYPTE was distributed to 14 selected collaborators worldwide in 2020. The objective for this first year was to confirm the relationship of yield potential traits with grain yield under high yielding and well-managed agronomic conditions. The results validated several yield potential traits including biomass, harvest index, grain number, canopy temperature and chlorophyll content in the 3rd leaf and confirmed the utility of these traits in the IWYP strategy for boosting wheat yields.



Bringing Enhanced Traits into Winter Wheat Hubs

Over the last year IWYP has been assisting with the 2 new IWYP Hubs for the development of winter wheat germplasm to complement the IWYP Hub at CIMMYT in Mexico, which focuses on spring wheat germplasm. The winter wheat Hubs, operated as public-private partnerships, are geographically positioned to serve two major winter wheat germplasm pools, one in North America and the other in Europe. These 3 Hubs form an interconnected network that provides IWYP the opportunity to support wheat growing regions across the world, thus expanding IWYP's impact into more breeding programs globally and potentially in more farmers' fields.

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 is funded by a grant from USDA NIFA and supported by several IWYP Private Partners as well as 5 US State wheat commodity groups.

In the last year, several donor traits (see panel) have been selected from 7 IWYP Research Projects for introgression using marker assisted backcrossing into 11 targeted elite genetic backgrounds representing hard red winter, soft red winter and soft white winter wheat market classes. These recipient lines include germplasm from the states of Kansas, Nebraska, Oklahoma, Colorado, Texas, Idaho and Washington.

Gene-Trait Introductions at the IWYP North American Winter Wheat Breeding Hub

Two alleles associated with increased yield

Three alleles associated with increased grain size and weight

Two alleles associated with inflorescence architecture (increased number of spikelets or grains per spike)

Several alleles linked with changes in phenology / plant development

Several alleles linked with high biomass

Chromosomal segments from wheat wild relative *Aegilops mutica* that confer improved photosynthesis

Chromosomal segments from wild wheat relative *Triticum timopheevii* that enhance floral characters (pollen size and stigma receptivity)

European Winter Wheat Hub at NIAB (UK)

Also 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.

The European Winter Wheat Hub partners selected several key traits important for hybrid wheat seed production after consultations with IWYP Management and research project PIs. These traits are being introgressed into selected wheat lines by marker-assisted backcrossing.

Communicating / Promoting IWYP Outputs

Annual Reports

This Annual Report and all previous annual reports are available for download from https://iwyp.org/annual-report/. Each seeks to convey IWYP's strategy for boosting wheat yields, selected highlights of the scientific progress made in the IWYP Research Projects and the progress of the IWYP Hub at CIMMYT and the winter wheat Hubs in the USA and in Europe.

Science Briefs

Begun in early 2020, the 1-page IWYP Science Briefs were developed to succinctly summarize exciting discoveries from the IWYP Research Projects and progress being made by the IWYP Hubs in boosting the genetic yield potential of wheat. These briefs are published monthly and all are available for download from https://iwyp.org/iwyp-science-briefs/.

IWYP Publications

IWYP tracks and compiles publications in scientific journals made by IWYP associated researchers resulting from their IWYP research projects. Since 2016, over 130 scientific articles have been published. A full list of all publications citing IWYP since 2016 is available for download from https://iwyp.org/publications/.

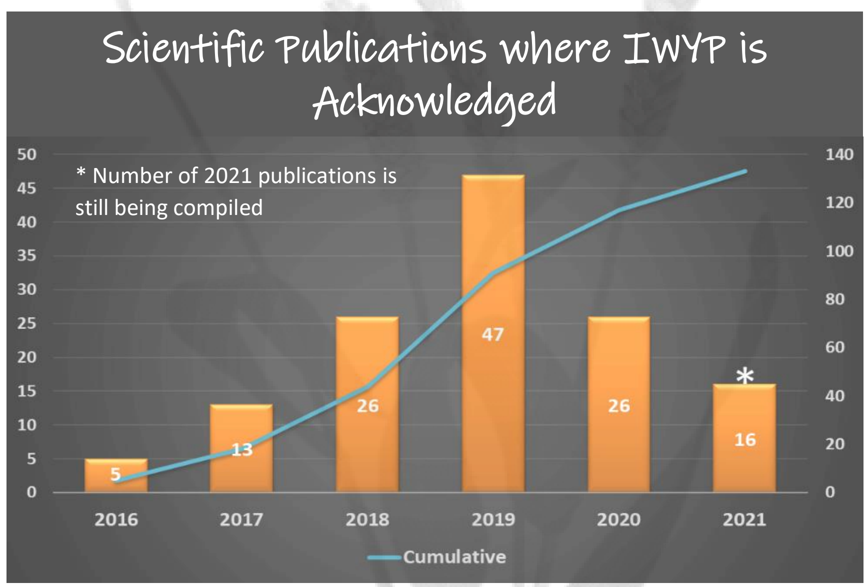
Some Notable IWYP Science Briefs 2020-21

"Waste Not, Want Not – Higher Yields with More Energy Efficient Wheat". B. Pogson, Australian National University with other colleagues in Australia and CIMMYT

"Boosting Wheat Yield with Genes from the Wild". E. Murchie, University of Nottingham with other colleagues in the UK

"Tailoring Crop Models to Identify Yield Increasing Traits for Different Environments". S. Asseng, Technology University Munich, Germany with colleagues in Germany, the USA, France, New Zealand, and CIMMYT

"Tuning Plant Development to environments Boosts Yield". S. Griffiths, John Innes Centre with other colleagues in the UK, Australia, Argentina, Spain and CIMMYT



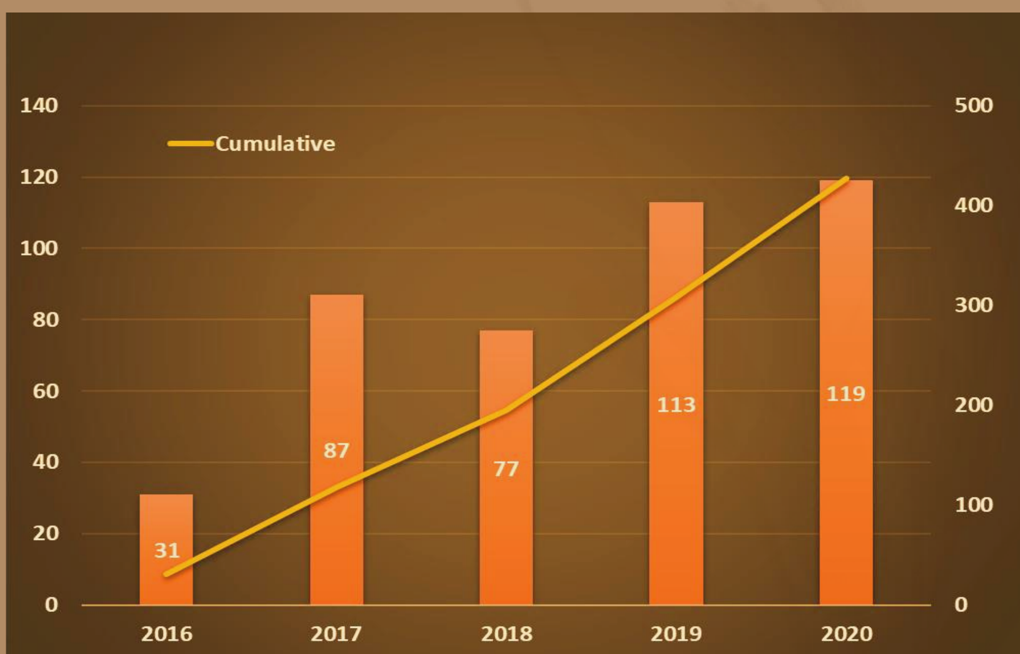
IWYP Trait and Seed List

Starting in 2020, IWYP developed a "Trait List" which provides information on available outputs from the IWYP associated research projects. The primary objective for this list is to inform the decision-making of the IWYP Hub management committees on new options for trait development and stacking. The list is available to all IWYP Members and is revised annually.

The IWYP "Seed List" is a list of germplasm available from the IWYP Hubs and research projects, primarily from the IWYP Hub at CIMMYT for now. The list is updated biannually and contains lines in early development and lines that may later be included in the germplasm sets sent out via the International Wheat Information Network (IWIN) labeled as the Wheat Yield Consortium Yield Trial (WYCYT). Phenotypic information and genotypic data for major trait genes of interest are also provided. IWYP Members have early access to the most up-to-date list. Following a 6-month embargo period, the list is then moved to the public side of the IWYP website from which anyone may order germplasm or find information on markers or protocols. Instructions for ordering are provided along with the list.

Training and Capacity Building

The number of scientists engaged in the IWYP Research Projects and receiving training has increased year on year with numbers very similar to last year. The total number receiving training reported over the years likely includes some level of duplication.



2021 IWYP Program Conference

Due to the ongoing Covid-19 pandemic, the 2020 IWYP Program Conference was postponed. This year, the Conference was organized as a virtual event since restrictions on travel due to the pandemic remain in place. It was held over three half days on 21st, 22nd and 28th September. A "by-invitation only" event, the Conference was structured as a mix of selected scientific presentations and breakout sessions. Over 90 IWYP Members participated with more than 60 participants attending each day.

Topics covered in the Conference included a review of IWYP Scientific Strategy, presentation of the Wiring Diagrams using IWYP research to demonstrate application, how IWYP outputs are promoted through the IWYP Stage Gate system (germplasm, molecular genetic markers, tools and protocols), reviewing the outputs and tools available from the USDA National Institute of Food and Agriculture (NIFA) Wheat CAP Project, the role of crop modelling, an update on the progress from the 3 IWYP wheat translational Hubs and how all these relate to IWYP outputs, progress and needs.

What did we learn?

The IWYP "brand" is still highly respected by the wheat scientific community

There is value in what IWYP is doing (integrating the science, operating internationally, building a community)

The IWYP Hub platforms and Network have great value and should continue

More funding opportunities needed for IWYP projects

Support for more use of genome editing to address both research questions and creation of new genetic variation

Opportunity to focus on a subset of outputs for rapid delivery to communicate success, generate more enthusiasm, attract new partners and attract more financial support

Partners and Funders

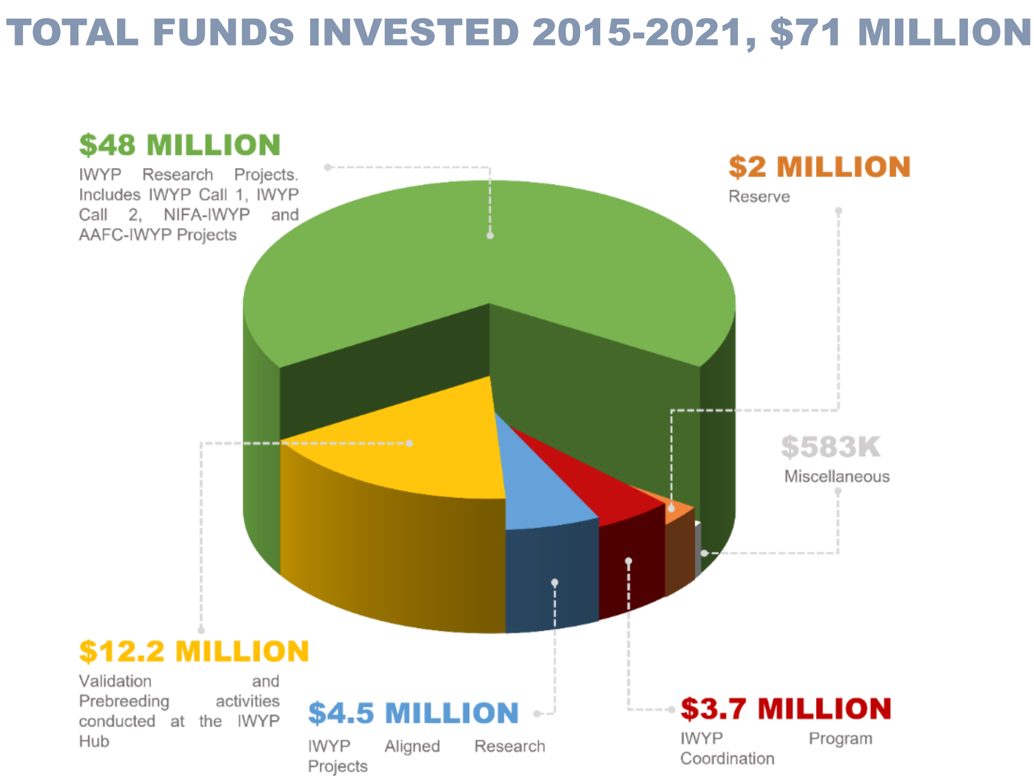
IWYP operates as a public-private partnership with members from many countries. The Partners provide strategic direction and advice on the means of translating crop-based research discoveries into new wheat varieties for farmers. As of today, financial support and advice is provided by 14 public funding and research organizations and 10 private industry partners.

Funding Organizations and Research

Private Industry

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.

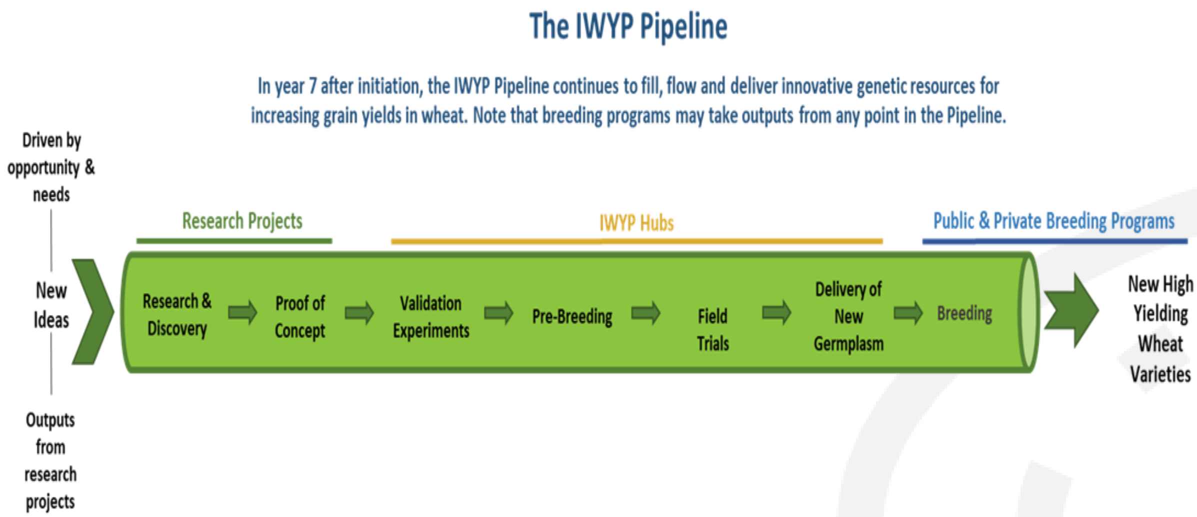


The IWYP Science Program is funded by a group of IWYP Partners (BBSRC, USAID, GRDC, USDA-NIFA, SFSA and AAFC). The total investments made by the Partners, directly or indirectly since the inception of IWYP amount to $71 million. This is divided up as indicated in the figure presented above. During this 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 and the necessary associated coordination, scientific management and communication needs. About $2 million remains in reserve. 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.

Looking Ahead

As IWYP assesses the progress and changing needs of its Science Program there are several important Program components to consider. Firstly, continuing to feed the IWYP pipelines with new discoveries that fill gaps or enhance discoveries already in-hand is essential. We would be naïve to expect that we already have all the genetic variation tools necessary to drive yields to the levels we seek. Next, validating and developing the more than two dozen outputs already delivered into pre-breeding from existing research projects remains the largest and most complex task, especially when considering the need to make and identify the optimal trait combinations for driving yields even higher and across different environments. We will continue to refine our international field trialing system and scale it as necessary to evaluate the newly created elite germplasm possessing novel traits and trait combinations. This is critical for understanding the effects of IWYP discoveries on yield improvement as well as generating the necessary information to drive uptake by varietal breeding programs.

Management, coordination and international integration of the overall IWYP Program is essential to generate maximum value and push delivery through to impact. It requires constant monitoring of the various steps within our technical systems, using effective communication tools and active engagement with the wheat scientific community. Lastly, securing the required funds and resources to support these needs remains an urgent task.



In the coming year, we will continue to apply what we have learned about the specific traits, trait sets, tools and protocols that should have the largest effect on yield gains and facilitate breeding systems. The Wiring Diagrams will be a very important tool. 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 modelling, linked to the Wiring Diagrams, should become a valuable tool in the IWYP Program for predicting trait performance in different environments. Understanding the genetic basis of trait improvements and markers and scalable precision phenotyping protocols, for both new and existing traits, will continue to receive high emphasis to facilitate breeding. Overall, a larger proportion of the Program is shifting more toward delivery, implementation of newly developed tools, uptake of proven outputs and thus brings us closer to impact.

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Research to Deliver Wheat for the Future