STRATEGIC RESEARCH AGENDA

WHEAT INITIATIVE

CONTENTS

A NOTE FROM THE WHEAT INITIATIVE SECRETARIAT

The Wheat Initiative wishes to thank the many people who have contributed to this document and in particular, those who responded to the stakeholder consultation as well as the members of the consolidation task-force who included representatives from the Scientific Board, the Research Committee and the Institutions' Coordination Committee of the Wheat Initiative. We also would like to thank the Expert Working Groups and the Research Committee who provided their input in the Strategic Research Agenda.

Finally, we thank all the Wheat Initiative Members who are contributing to the progress of the Wheat Initiative. Please note that this is the second version of the Wheat Initiative's Strategic Research Agenda (SRA), which was originally published in 2015. The SRA builds on the "International Vision for Wheat Improvement" document that was created in May 2013. The SRA is an evolving agenda that will be consistently updated to properly reflect the Wheat Initiative's challenges and demands.

I. EXECUTIVE SUMMARY

To meet the expected 60% increase in demand for wheat by 2050 in a sustainable and resilient way, more research is needed through significant investment and collaboration between public and private partners.

To address this challenge, the Wheat Initiative (WI) was established in 2011 under the aegis of the G20 Ministries of Agriculture. WI works to coordinate international research efforts regarding wheat and aims to provide opportunities for an increased and more efficient utilisation of resources through the alignment of national and regional activities and pooling of resources.

This is the second version of the Wheat Initiative Strategic Research Agenda (SRA), which derives from the2013 Wheat Initiative Vision Document. This SRA has been updated and designed to set out clear policy-relevant wheat research priorities for the short (1-5 years), medium (5-10 years) and long term (>10 years). Furthermore, this updated document lists the strategic actions needed to address these international priorities.

The key challenges and priorities for wheat research are organised around four thematic core themes:
(1) Increase wheat yield potential,
(2) Protect yield potential,
(3) Protect the environment and increase the sustainability of wheat production systems,
(4) Ensure the supply of high quality, safe wheat.

The following cross-cutting themes are also important for global wheat research:
(5) Enabling technologies and shared resources,
(6) Knowledge exchange and education.

The SRA identifies game-changers that allow the efficient delivery of improved wheat cultivars adapted to target environments, including:

- A fully assembled and aligned wheat genome sequence to access and understand the richness of wheat genetic diversity;
- The availability of all wheat data via an open information exchange framework, which supports the understanding of the interaction of genotype, environment, and crop management on the phenotype; ultimately allowing for prescriptive wheat breeding;
- The ability to build new combinations of alleles, which will increase the deployment of natural and engineered genetic variability in inbred or hybrid wheat cultivars.

In addition, the SRA recognises the importance of the following underlying priorities:

- Continuously supporting existing activities aimed at yield improvement through conventional breeding methods by using existing germplasm and molecular technologies;
- Understanding the genetic, molecular, and physiological basis of agronomic and nutritional, as well as the identification of gene networks involved in their expression;
- Integrating genetics and agronomy to allow the development of sustainable growing systems that will accommodate ever-improving cultivars with high yield potential;
- Supporting the development of a global public-private community of wheat researchers by sharing knowledge and information that self-perpetuates and expands by means of specialised training and education.

The Wheat Initiative Strategic Research Agenda provides a unique opportunity for policy makers, public research organisations, and industry to work together to address the aforementioned challenges and contribute to global food security through a sustainable increase of wheat production.

II. INTRODUCTION

A key factor in the stability of human societies is access to a reliable and affordable food supply. Food security, as defined during the 1996 World Food Summit, "[…] exists when all people at all times have physical and economic access to sufficient, safe and nutritious food to meet their dietary needs and food preferences for an active and healthy life."

Wheat is an integral part of the human diet in numerous cultures around the world. Farmers cultivating millions of hectares in more developed and less developed regions often have no alternative to wheat, as the crop is often the most economically efficient and nutritious cereal in those areas.

While our global population continues to rise, we see that diets are changing and further research efforts are drastically needed to efficiently increase wheat productivity per land area. Such activities are necessary in order to avoid production losses due to pathogens and a changing climate, as well as to increase the quality and safety of wheat products, while participating in global efforts to minimise the impact of modern-day agriculture on the environment.

The Wheat Initiative identifies priorities and coordinates the international wheat research efforts by providing opportunities for an increased and more efficient utilisation of resources than is currently achievable. WI implements these efforts through the alignment of national activities and pooling of resources to avoid duplication, fill gaps, and create critical mass.

THE CHALLENGE: IMPROVING WHEAT PRODUCTIVITY, QUALITY, AND SUSTAINABILITY

Wheat is the most widely grown crop in the world and provides 20% of the population's daily protein and food calories. After rice, wheat is the second most important food crop in less developed regions. In recent years, wheat production levels have not satisfied global demands, triggering price instability, hunger riots, and government instability.

With a predicted world population of over 9 billion by 2050 [Ref. UN Department of Economic and Social Affairs: https://www.un.org/development/desa/en/news/population/world-population-prospects-2017.html] , the demand for wheat will increase by 60% compared to 2010. To meet this demand, global annual yield increases must rise from the current level of 1% per year (2001-2010) to 1.6% per year (2011-2050).

All wheat producing countries share an urgent need to increase the rate of genetic gains for yield, tolerance to abiotic stresses, resistance to pathogens and pests, as well as to improve input use efficiency for sustainable wheat production, while ensuring high quality, safe and nutritious food products.

To take full advantage of wheat genetic potential, improved agronomic practises and the development of innovative cropping systems are paramount. These challenges can be met through an unprecedented effort from the wheat research community to increase and coordinate funding at the international level.

COORDINATING WHEAT RESEARCH AND CONTRIBUTING TO FOOD SECURITY

Created in 2011 following endorsement from the G20 Agriculture Ministries, the Wheat Initiative provides a framework to establish strategic research and organisation priorities for wheat research at the international level. The Wheat Initiative fosters communication among the research community, funders and global policy makers. WI also aims to secure efficient,long-term investments to meet global wheat research and development goals.

The success of the Wheat Initiative depends on the dedicated engagement of the global wheat community. All countries, companies, stakeholders, and NGOs interested in wheat improvement are welcome to participate and contribute to the development of this global research coordination platform. WI welcomes the active participation of every entity that aims to improve food security and resolve the urgent challenge of sustainably providing enough safe, nutritious, and affordable food for a growing population.

III. WHEAT INITIATIVE'S STRUCTURE

VISION AND MISSION

The Wheat Initiative aims to encourage and support the development of a vibrant global public-private research community by sharing resources, capabilities, data, game changing ideas, and technologies to improve wheat productivity, quality, and sustainable production around the world.

To respond to the challenges of wheat research internationally, the Wheat Initiative:

• Offers a dynamic global Strategic Research Agenda for wheat research through the identification of priorities and challenges beyond the capacity of single research groups and countries, which can be best addressed by international coordination and communication between researchers, research institutions, and funding organisations;

• Encourages efficient investment in wheat research based on the capabilities and synergies of national and international programmes;

• Stimulates the development of new collaborative programmes and coordinated actions across More developed and less developed regions;

• Develops, communicates, and coordinates knowledge sharing amongst the international wheat research community;

• Improves international access to knowledge, resources, services, and facilities;

• Supports the education of students and life-long learning of wheat researchers, and provides educational resources to stakeholders and consumers;

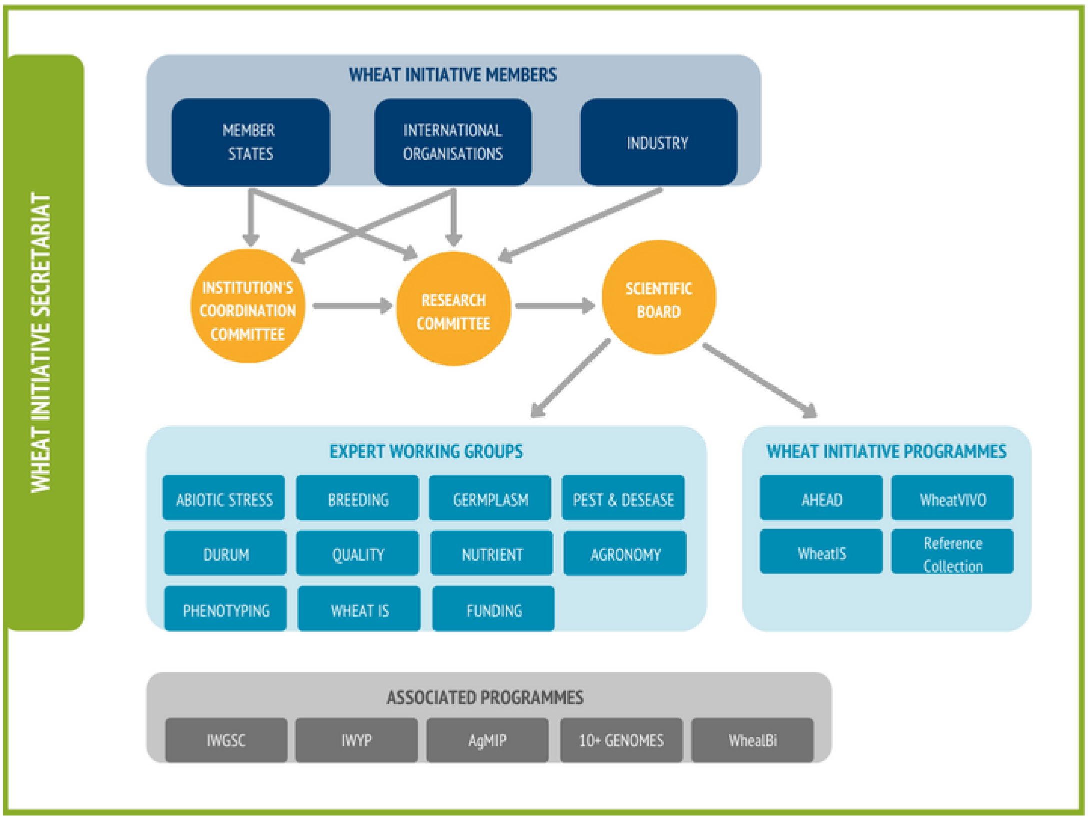
• Stimulates public-public, public-private, and private-private collaborations.

DEVELOPMENT OF THE WHEAT INITIATIVE STRATEGIC RESEARCH AGENDA (SRA)

The Wheat Initiative SRA builds on the Wheat Initiative International Vision for Wheat Improvement. WI provides a framework for public and private research organisations, funding agencies, and policy makers to coordinate efforts through shared implementation plans.

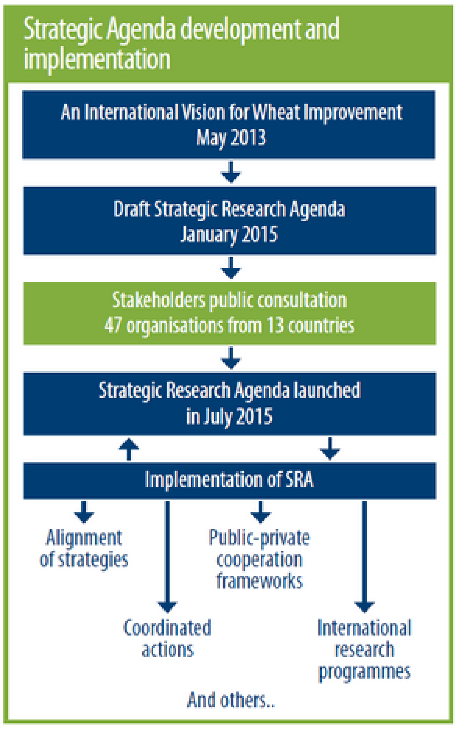
The Wheat Initiative SRA was developed through an iterative process involving the Wheat Initiative Scientific Board (SB) and Research Committee (RC), both of which contributed to the definition of WI's core themes and organizational content. Expert Working Groups (EWGs) of the Wheat Initiative, which are also open to non-members of the Wheat Initiative, were consulted on the research priorities.

Given this broad consultation, this SRA reflects the priorities of the global public and private wheat research community.



The Wheat Initiative fosters communication between the international wheat research community, funders and global policy makers through interactions between its Research Committee, Institutions' Coordination Committee and Scientific Board, in which sit representatives from its members. The Expert Working Groups of the Wheat Initiative provide members with expert knowledge and strategic advice on specific research areas.

The Wheat Initiative Institutions' Coordination Committee (ICC) provided great input for the 2015 SRA and organised an open consultation of Stakeholders. The 47 responding organisations broadly endorsed the draft SRA and their views were valuable in shaping the final document and, in some cases, defining the research priorities in a more precise manner.



The SRA seeks to represent the current views of the wheat community and stakeholders regarding the key challenges that face wheat research globally, as well as the actions that are needed to address these challenges.

Technology is changing rapidly as new techniques and resources are developed to promote the study of biological systems. Similarly, the issues facing wheat producers and end users are in continuous flux. The role of the Wheat Initiative will continue to change over time as new partners come on board and new international research programs are developed.

The Strategic Research Agenda will adapt in order to reflect these changes.Therefore, reviewing and updating the SRA on a regular basis is a process that will be undertaken by the EWGs, Associated Programmes, and the different committees of the Wheat Initiative.

DELIVERY OF THE STRATEGIC RESEARCH AGENDA PRIORITIES

The Wheat Initiative SRA identifies research priorities that can best be tackled at the international level through integrated or coordinated action. Countries and companies wishing to contribute to the SRA implementation should develop mechanisms that enable them to work together and answer the challenges identified. The Wheat Initiative aims to create a dialogue among its members to define the initial global priorities. Individual members have the opportunity to identify their strengths and networks to underpin areas identified in the SRA.

For each priority area of the Strategic Research Agenda, implementation plans are developed, largely through the EWGs or the Associated Programmes. These groups also monitor the progress of the implementation plans and provide regular updates. The Institutions' Coordination Committee works to develop a portfolio of mechanisms that facilitate the efficient delivery of the SRA. This includes the encouragement of active research collaborations, alignment of strategies with the Wheat Initiative research priorities at the national, regional or company level, joint-funding mechanisms such as the EU Horizon2020 ERA-NETs, public-private cooperation frameworks, as well as international calls for coordinated research programs.

Associated programmes will also be developed where countries participate voluntarily on the basis of their respective socio-political and financial commitments and strategies. A global database for wheat research is in the process of being developed to provide researchers and policy-makers with information regarding who is researching what, where, and with whom. Such measures will facilitate international collaboration and coordination of research. The Wheat Initiative's overall implementation and updating progress of the SRA will be monitored to ensure that it fulfills its objective of coordinating international research efforts on wheat. Furthermore, such revisions will provide opportunities for efficient utilisation of the available capabilities and resources through the alignment of national activities to international priorities.

IV. WHEAT RESEARCH KEY CHALLENGES AND PRIORITIES

The strong rise in wheat yields has been associated with genetic improvements in yield potential, resistance to diseases and pests, adaptation to abiotic stresses, and advances in agronomic practises from the Green Revolution in the 1960's to the early 1990's.

However, the rate of increase in wheat productivity has slowed down, which has resulted in large variations of yield from country to country. Genetic yield increases of up to 1% per year have been achieved historically, but global 'on-farm' wheat yields are beginning to plateau in many wheat producing areas.

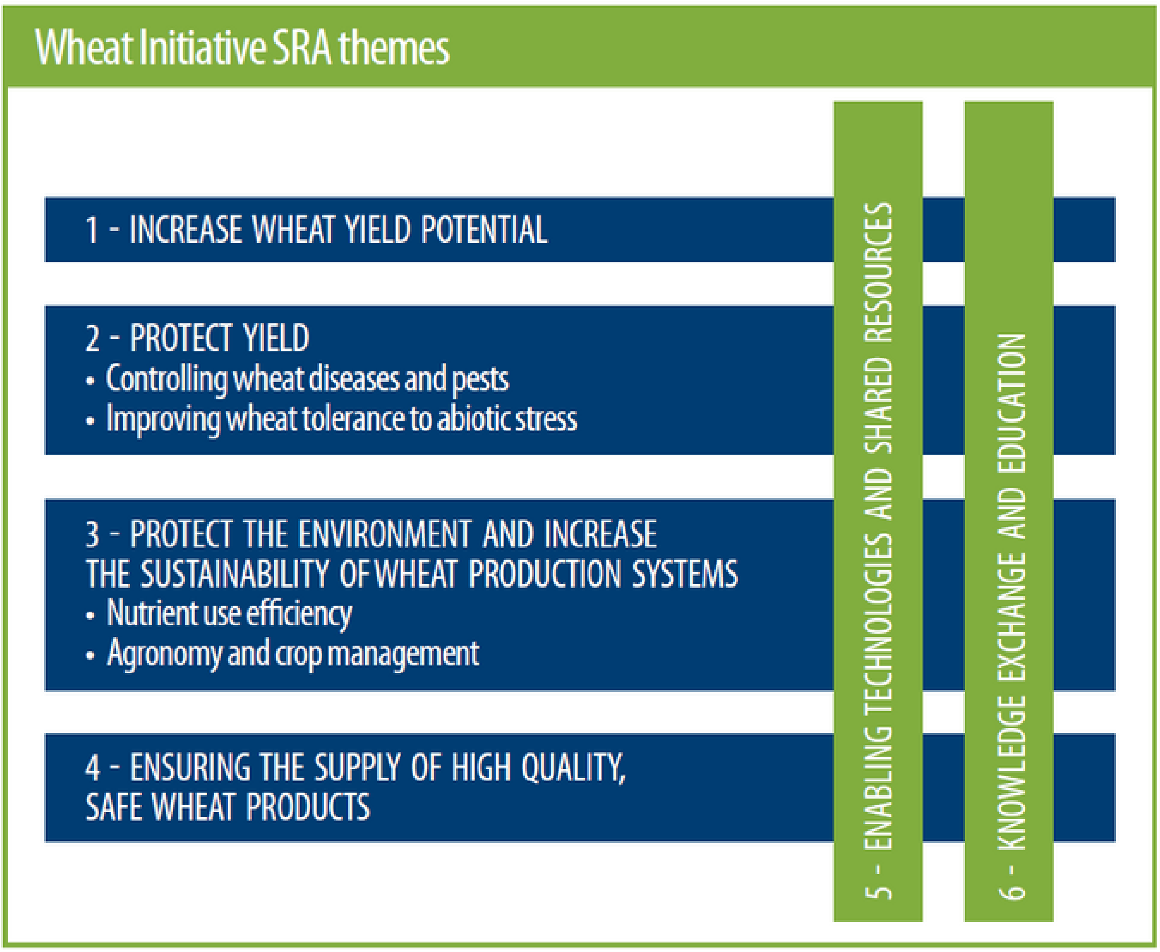
In order to increase wheat production by at least 60% by 2050, several targets were identified in the Wheat Initiative's Vision Paper:

- Increase the yield potential of wheat cultivars;
- Close the yield gap on under-performing land and increase the sustainability of cropping systems;
- Monitor wheat diseases and develop wheat cultivars with durable resistance;
- Increase resource use efficiency and tolerance to abiotic stress;
- Improve the nutritional,processing quality and safety of wheat cultivars;
- Tailor wheat cultivars and types to diverse agro-ecosystems and production systems;
- Support the implementation of modern breeding methods by all breeders;
- Ensure inclusive access to shared platforms and standards;
- Benefit from a Wheat Information System to provide easy access to data and information.

STRATEGIC RESEARCH AGENDA THEMES

The Wheat Initiative SRA was developed with the aim of achieving the aforementioned targets in 2030 and beyond through partnerships between private and public organisations. The SRA is organised into four thematic core themes and two cross-cutting themes.

The SRA was originally designed to set out clear policy-relevant research priorities for the short (1-5 years), medium (5-10 years) and long term (>10 years), and to list the strategic actions needed to address these priorities.



OUTSTANDING GAME-CHANGERS

Wheat production will be revolutionised in the future by a few game-changing breakthroughs, which will allow for more efficient delivery of improved wheat cultivars adapted to their environment, along with achievements in several areas of research as described in the SRA. For example:

• The richness of wheat genetic diversity will be accessible and understood with a fully assembled wheat reference genome sequence; full annotation of the wheat genome will provide access to its functionalities.
• Wheat data and analysis tools will be available globally via an open information exchange framework, which supports the understanding of the interaction of genotype, environment, and crop management regarding the phenotype; this enables prescriptive wheat breeding.
• New combinations of desirable alleles in inbred or hybrid wheat cultivars will be created through increased deployment of natural and engineered genetic variability via the characterisation of the existing wheat and related species germplasm, as well as by the generation of new genetic resources by all available and emerging methods; including genome editing, control of meiotic recombination, use of wheat relatives, and transgenesis.

UNDERLYING KEY PRIORITIES

In addition, it is of utmost importance to maintain continued support for existing activities aimed at yield improvement through conventional breeding methods, using existing germplasm and molecular technologies.

Major improvements will be achieved for traits of agronomic, processing and nutritional importance, which includes yield potential, interaction with pathogens and pests,beneficial microorganisms, tolerance to abiotic stress, nutrient use efficiency, technological and nutritional quality. Such trait improvements will be carried out through the understanding of their genetic, molecular and ecophysiological basis as well as the identification of the gene networks involved in their expression and their interaction with the environment.

The integration of genetics and agronomy will allow the development of sustainable growing systems that will use appropriate germplasm and be dynamic enough to accommodate ever-improving cultivars with higher yield potential. The deployment of new breeding technologies and improved crop management will make it possible to increase wheat yield potential and close the on-farm yield gap in different wheat growing areas, while minimising the impact of agriculture on the environment and addressing challenges related to global change.

Game-changers

Fully assembled and annotated wheat genome reference sequence

Wheat scientific data and analysis tools available to all via a dedicated global information system

Increased deployment of natural and engineered genetic variability allowing new combinations of desirable alleles in wheat varieties

Outstanding partnerships between private and public organisations must be established in order to deliver an increase in yield of greater than 1% per annum. New ways of broadly sharing knowledge and germplasm, that are free from the limitations and hindrances of restricted intellectual property (IP) use, while allowing value capture mechanisms to support private investment are essential Coordinated public and private investments, as well as the development of global partnerships within the key priority areas identified in the Wheat Initiative SRA ensures the stable and sustainable delivery of research outputs. Innovations resulting from the latest research achievements produced by a new generation of breeders throughout the world and their adoption by farmers and consumers will allow a 60% increase in wheat production in 2050, thereby contributing to global food security and safety.

V. CORE THEME 1: INCREASE WHEAT YIELD POTENTIAL

CHALLENGE: INCREASING YIELD POTENTIAL

Yield increases of up to 1% per year have historically been achieved in some regions of the world.This global increase was obtained by a combination of increased genetic yield potentials and improved crop management practices.

Yield potential is defined as the yield of a cultivar when grown in environments to which it is adapted, with non-limiting nutrients and water, and with pests, diseases, weeds, lodging, and other stresses effectively controlled. Wheat yield potential differs according to the environment in which it is grown.

The challenge will be to further increase the yield potential in wheat cultivars adapted to diverse environments and cropping systems by improving the efficiency of light interception and conversion into biomass by photosynthesis and of partitioning into grain.

ASPIRATION: Wheat cultivars with yield potential enhanced 50% in 2040

AIMS AND OBJECTIVES

The current ceiling of genetic yield potential is likely to be the result of constraints in many processes in the scheme of carbon capture, biomass accumulation, and redistribution into grain. The biology of yield is very complex and needs to be tackled by numerous approaches including:

- Increasing our understanding of the genetic and physiological basis of yield potential;
- Modelling yield potential in different regional areas and conditions while defining adapted ideotypes;
- Improving light interception in the canopy by modifying plant and ear architecture;
- Enhancing solar energy conversion efficiency in wheat by optimisation of photosynthesis;
- Optimising plant phenology, development, and partitioning to maximise grain yield;
- Transferring discoveries and technology breakthroughs obtained in other species into wheat.

Most of these aims are in the scope of the International Wheat Yield Partnership (IWYP). In addition, increasing the resilience of yield to climate change through improvements in yield stability should allow consistently high yields in numerous regions during the next decades.

RESPONDING TO RESEARCH NEEDS

Breeders can deliver new cultivars with higher yield potential if provided with the germplasm, resources and the tools to do it, as shown by the success that has been achieved to date by private and public breeders. However, the current rate of gain is insufficient and significant investments to develop more robust programmes, as well as large international and public-private partnerships, are needed. Fundamental and applied research will contribute to enhancing genetic gain for yield potential and is required to translate it into final products (cultivars) and information on how to grow them.

These requirements are conveyed in the following four key research activity areas:

• Increasing the knowledge base for improving yield potential, including the genetic control of yield components, physiological and biochemical processes that can increase biomass and harvest index, the optimisation of phenology and plant architecture, and the identification or generation of variation in the efficiency of photosynthesis in wheat germplasm;

• Utilising game-changing breeding methods and the latest technologies to improve the effectiveness of breeding for yield potential, such as the use of hybrids, application of 'omics', bioinformatics, and genomic selection;

• Developing new genetic resources for breeders with tools such as interspecific crosses, targeted mutation, and genetic engineering.

• Exploiting research results from other genera to improve yield in wheat.

PRIORITY ACTIONS

RESEARCH OBJECTIVES:

Short-term (1-5 years)	• Coordination of yield testing protocols and networks and germplasm exchange
Medium-term (5-10 years)	• Develop new germplasm adapted to different environments and cropping systems with enhanced yield potential for distribution to breeders • Increase knowledge of the underlying physiology, biochemistry and genetics of yield and yield components together with Genotype x Environment x Management (G x E x M) interactions • Apply new breeding and selection strategies to yield and yield stability, such as hybrids and genomic selection
Long-term (>10 years)	• Novel germplasm generated through new technologies, such as genome editing and genetic engineering

ON-GOING INTERNATIONAL ACTIONS

• International Wheat Yield Partnership (IWYP)

• CGIAR Research Program on Wheat (WHEAT CRP), Flagship Projects (FP) 2 and 3

WHEAT INITIATIVE ACTIONS

• Support IWYP through the promotion and provision of support

• Monitor global activities and identify any unfulfilled research needs

• Promote and support new international actions

VI. CORE THEME 2: PROTECT YIELD POTENTIAL

Subtopic 2.1 Controlling wheat diseases and pests

CHALLENGE: PROTECTING WHEAT FROM YIELD LOSSES DUE TO PESTS AND DISEASES

It is estimated that almost 20% of the global wheat production will be lost each year due to diseases and pests. This amounts to 140 million tonnes ($35 billion dollars at $250/ton) of estimated wheat crop loss in 2012 [Ref: FAOSTAT 2014 http://www.fao.org/3/a-i3590e.pdf]. Globally, current wheat yields would not be achievable without the application of chemical protectants, especially in less developed regions.

However, concerns regarding health and environment call for the drastic reduction of chemicals, and for their replacement by cultivars resistant to diseases and pests, which are the prerequisite for environmentally and consumer friendly wheat production. Many farmers in less developed regions depend on resistant cultivars. However, most resistance genes and chemical strategies can be overcome by rapidly evolving pathogens.

For example, the occurrence of the new stem rust race Ug99, which was virulent on 90% of all cultivars grown world-wide when it was initially detected. Yellow rust races were adapted to higher temperatures and potential emerging diseases, such as wheat blast and the Fusarium species , call for more investments in developing wheat cultivars with durable resistance and managing available resistances. Major wheat pathogens include rusts (yellow, brown, and stem rust), powdery mildew, Fusarium species producing mycotoxins in the grain leading to its unsuitability for human or animal consumption, and necrotrophic pathogens that appear on dead tissues such as some Septoria and Pyrenophora species.

ASPIRATION: Wheat cultivars with durable resistance to most major pests and diseases

AIMS AND OBJECTIVES

While sustained increases in wheat yields are needed to meet future demands, the remarkable ability of pests and pathogens to mutate, produce novel toxins, and adapt to overcome environmental adversities makes breeding for durable resistance a considerable challenge. Many diseases and pests drastically impact international wheat growing zones, while others cause local or regional epidemics.

The deployment of host resistance to diseases and pests is the most effective and environmentally sound way of plant protection, as has been demonstrated by the Borlaug Global Rust Initiative (BGRI) in the case of resistance against the stem rust race Ug99, which is threatening wheat production in Africa and Asia. Indeed collaborative global efforts are needed to develop management and gene stewardship deployment strategies with the ultimate aim of achieving broad spectrum and durable disease resistance in wheat crops.

The implementation of such efforts will involve:

• Continued identification of novel sources of disease and pest resistance, including the newest technologies of phenotyping, to broaden the genetic base of resistance against primary wheat pathogens and pests;

• Development of diagnostic genetic markers to assist breeding programmes in the development of disease resistant cultivars;

• Deep knowledge on wheat-pathogen interactions, in relation to environment and management systems, to further develop new and existing resistance strategies;

• Monitoring of pathogen populations for their ability to overcome resistance genes;

• Understanding the impact of climate change on pathogens in order to assess potential new epidemics;

• Deployment of cis/transgenes to augment strategies toward durable disease resistance;

• Coordinated efforts in pre-breeding and breeding programmes to optimise strategies for the efficient use of resistance genes in wheat and to ensure their sustainable deployment by developing resistance management systems.

RESEARCH NEEDS

To improve resistance of wheat to pests and diseases an efficient collaboration between phytopathologists, geneticists, molecular biologists, and breeders is needed to cover the whole chain from the identification of new races of pathogens and the development of new resistant cultivars, to integrated pest management.

There are two key factors to consider for improving resistance of wheat to diseases and pests: pathogen surveillance and the identification of new sources of resistances in the wheat gene pool. When these factors are focused on simultaneously it will be possible to develop novel wheat management regimes that resist the most economically important wheat pathogens and pests.

Identified resistance sources will be analysed in terms of the genetics of the respective resistances followed by the development of molecular markers and the development of efficient (pre-breeding) strategies for marker-based introgression ideally as multiple gene combinations into adapted cultivars. Genomic tools currently available in wheat, along with future developments, will pave the way for resistance breeding at the allele level. To achieve this, special emphasis must be given to the isolation of resistance genes from wheat and wild relatives on a large scale, especially for those proven to confer durable resistance.

Knowledge of the sequence of resistance genes will facilitate the detection of the natural allelic diversity and the estimation of the effectiveness of different alleles, while providing an opportunity for the creation of new, functional alleles by site directed mutagenesis. With the development of genome editing techniques it will also be possible to perform targeted editing of genes conferring susceptibility with the goal of generating novel resistant phenotypes.

Furthermore, isolated genes will facilitate a better understanding of genetic networks working to improve durable resistances. Though research regarding the host's natural resistance is of utmost importance, a deeper understanding of the biology of wheat pathogens and their evolution, in relation to wheat-pathogen interactions, is needed to fully comprehend issues regarding diversity and the epidemiology of diseases. This also holds true for expanding knowledge concerning the effects of the wheat microbiome on resistance.

PRIORITY ACTIONS

RESEARCH OBJECTIVES:

Short-term (1-5 years)	• Identification and characterisation of novel sources of resistance to the main wheat diseases • Exchange germplasm and markers associated with resistance loci
Medium-term (5-10 years)	• Genomics-based surveillance of pathogen populations and epidemiology in routine use • Novel resistance mechanisms identified • Durable resistance to several diseases present in many cultivars
Long-term (>10 years)	• Comprehensive understanding of genetic networks of resistance against primary pathogens • Deployment of durable resistance to multiple pests and diseases

ON-GOING INTERNATIONAL ACTIONS

• Borlaug Global Rust Initiative – Wheat Rusts
• WHEAT CRP, FP 3
• National public and private programs that target regionally important diseases and pests
• ENDURE EU network (Fusarium)
• International Fusarium and Fusarium Genomics Workshops

WHEAT INITIATIVE ACTIONS

- Coordinate research in the area by:

+Developing the Control of Wheat Pathogens and Pests EWG - Collaborating with the Wheat +Germplasm Conservation and Use Community EWG

- Facilitating access to technologies
- Supporting the BGRI
- Encouraging the development of an international program on necrotrophic pathogens

WHEAT INITIATIVE ACTIONS

- Coordinate research in the area by:
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B. SUBTOPIC 2.2 IMPROVING TOLERANCE OF WHEAT TO ABIOTIC STRESS

CHALLENGE: MAINTAINING YIELD UNDER HIGHLY VARIABLE ENVIRONMENTAL CONDITIONS

Environmental stresses such as heat and drought, salinity and soil acidity, as well as frost and many other factors, severely limit global wheat production. Wheat yield models indicate that a 1°C temperature increase has the potential to restrict wheat yields by 10% in some regions of the world and that the wheat producers in South Asia and North Africa will be hit the hardest by climate change. In 2050, wheat yields in some regions could decline by 27%, compared to yields in 2000, due to issues pertaining to climate change.

ASPIRATION: Wheat cultivars better adapted to diverse environmental conditions in terms of yield and yield stability under stress

AIMS AND OBJECTIVES

In most production environments, multiple abiotic stresses challenge wheat plants simultaneously. While tolerance to some stresses is under simple genetic control, others are regulated by multiple interacting genetic mechanisms. Managing tolerance to abiotic stresses will require:

- Characterisation of the environmental and abiotic stresses that limits wheat production around the world,assessing the impact of climate change, and developing conceptual models of adaptation to different mega-environments;
- Development of techniques for assessing stress adaptive characteristics of germplasm under field conditions, as well as under controlled conditions where appropriate;
- Identification of sources of tolerance to individual stresses and combinations of stress from a broad base of genetic resources;
- Genetic, physiological, and biochemical analysis of stress response pathways and processes in wheat;
- Refinement of genetic and physiological models for enhanced stress tolerance;

- Building resilience into cultivars, so they can cope with variable environmental conditions;
- Isolation of genes and alleles underlying stress tolerance loci.

RESEARCH NEEDS

Research must address the complexity of stresses faced by wheat producers across highly diverse production environments. Higher plants have evolved multiple, interconnected strategies that enable them to survive unpredictable environmental fluctuations. However, these strategies are not always well developed in the cultivars grown by wheat producers and most of the strategies used in model non-crop species are focused on plant survival at the expense of yield.

The Intergovernmental Panel on Climate Change (IPCC) has predicted that rising temperatures, drought, floods, desertification, and weather extremes will severely affect agriculture. For wheat, the genetic control of traits determining yield in water-limited and low yielding environments are generally expected to be of low heritability and polygenic.

Furthermore, many of the key loci will show epistatic rather than additive effects. Breeding and genetic techniques need to detect and select for these types of loci while also accounting for factors such as maturity, height, resistance, or tolerance to soil borne diseases. Tolerance to related stresses such as boron, acidity, salinity, and nutrient deficiencies must also be taken into account.

While breeders have been successful in improving performance through direct selection for lines under a broad range of environmental conditions, the opportunity to integrate other approaches now exists. Areas where greater research activity will offer significant advances include:

- Climate modelling and monitoring, including the characterisation of the stresses and probability of stress in different wheat production environments;
- Statistical tools for the analysis of field and controlled environment trials;
- Comprehensive models of physiological and biochemical responses to stresses and stress combinations;
- Field phenotyping methods and well-characterised field sites that have been validated in breeding and gene discovery work;
- A wide range of genomics technologies;
- Studies of the impact of abiotic stress on grain quality;
- Information from crop and non-crop plant systems;
- Impact of cropping systems on managing stressful environments.

WHEAT INITIATIVE

PRIORITY ACTIONS

RESEARCH OBJECTIVES:

Short-term (1-5 years)	• Standardisation of abiotic stress phenotyping techniques • Sharing well characterised germplasm with phenotypic and genotypic data to add value to existing studies
Medium-term (5-10 years)	• Genetic analysis of response to multiple abiotic stresses • Isolation of genes and alleles controlling performance under a range of abiotic stresses • Rapid introgression of stress resilient germplasm into breeding programs • Comprehensive databases of genetic, physiological and biochemical responses of wheat lines to abiotic stresses
Long-term (>10 years)	• Isolation of genes associated with yield stability – high yield under diverse environmental conditions • Maintaining yield in a 2 to 3°C warmer environment and improved adaptation to dry conditions

ON-GOING INTERNATIONAL ACTIONS

- WHEAT CRP, FP 2 and 3
- HeDWIC (Heat and Drought Wheat Improvement Consortium)
- DROPS, EURoot, WHEALBI – EU 7th Framework Program for Research

WHEAT INITIATIVE ACTIONS

- Support the development of HeDWIC
- Coordinate research in the area through the development of the Adaptation of Wheat to Abiotic Stress EWG
- Collaborate with the Wheat Phenotyping to Support Wheat Improvement EWG and the Wheat Germplasm Conservation and Use Community EWG
- Facilitate access to technologies
- Facilitate the development of a network of well-characterised sites for germplasm evaluation

VII. CORE THEME 3: PROTECT THE ENVIRONMENT AND INCREASE THE SUSTAINABILITY OF WHEAT PRODUCTION SYSTEM

A. SUBTOPIC 3.1: NUTRIENT USE EFFICIENCY

CHALLENGE: IMPROVING NUTRIENT USE EFFICIENCY, DEFINED AS THE QUANTITY OF GRAIN THAT CAN BE PRODUCED FROM A GIVEN AMOUNT OF NUTRIENT AVAILABLE IN SOIL OR APPLIED AS FERTILISER

Adequate nutrition and nitrogen availability is essential for optimal yield and quality of wheat crops. However, given the economic and environmental costs, efficient use is essential. More than 25 Mt fertilisers are used annually on wheat with a global nitrogen (N) use efficiency as low as 30% and high discrepancies occur across regions. For instance, it is estimated that N use efficiency is twice as high in Western Europe when compared to India and China, and it is 50% more efficient than in the United States.

Micronutrients, particularly iron (Fe) and zinc (Zn), are important for both plant health and the nutritional value of the grain for humans. Rising CO2 levels is expected to decrease levels of these nutrients in grain and higher yields are frequently associated with decreases in nutrient density.

ASPIRATION: Increase the efficiency of nutrient use to ensure the applied fertiliser is used by the crop. For example, increase N use of over 60% of the applied amount

AIMS AND OBJECTIVES

There is a major opportunity for improvement in both the genetic and the agronomic components of wheat nutrient use efficiency, including:

- Enhancing use efficiency for all the macro- and micro-nutrients that are important for optimal crop production. Special focus should be given to nutrients that are either costly to produce and supplied in excess of plant requirements in some agro-ecosystems (e.g. N), derived from finite rock mineral resources (e.g. phosphorus), have negative environmental impacts if inappropriately used (e.g. N), and/or are essential elements of human and animal diets (e.g. Zn and Fe);
- Combining cultivars adapted to optimal agricultural practices (Subtopic 3.2) and optimising nutrient uptake by the roots, nutrient utilisation to produce biomass, and nutrient translocation to the grain to ensure quality;
- Integration of genetics, ecophysiology, rhizosphere microbiology, and symbiotic interactions to identify traits and chromosomal regions relevant for nutrient use efficiency improvement;
- Taking into account global change impacts on nutrient use for production and quality.

RESEARCH NEEDS

Research is needed to maximise capture, partitioning, and remobilisation of nutrients in the canopy to the grain through genetic improvement. Research will be primarily focused on:

- Improving the capacity to phenotype nutrient use efficiency in a standardised way in terms of definitions and practical aspects, such as controlling the environment to create defined nutrient availability and measurement technologies to evaluate the responses of the plant/crop at different physiological levels;
- Develop pre-breeding programmes to facilitate the use of genetic resources (e.g. landraces, synthetics, and wild relatives) for traits that will enhance nutrient use efficiency. This may include further research regarding increasing leaf/canopy photosynthesis per unit of N using the existing genetic variability;
- Favour beneficial interactions with soil microorganisms and enhance the capability to capture N and other nutrients (e.g. root architecture, mycorrhizal/diazotroph associations, chemical and biological nitrification inhibitors, and root exudation of organic acids);
- Identify loci and alleles involved in enhanced nutrient use efficiency. This approach may be combined with the development of crop simulation modelling and sensitivity analysis for nutrient use efficiency traits, as well as the identification of chromosomal regions associated with model parameters.

PRIORITY ACTIONS

RESEARCH OBJECTIVES:

Short-term (1-5 years)	• Standardise definitions and phenotyping • Identify key traits and ideotypes
Medium-term (5-10 years)	• Identify natural variation for relevant traits • Quantify potential impacts in different environments and cropping systems • Identify favourable alleles for target genes • Develop molecular tools to breed cultivars which interact favourably with beneficial soil micro-organisms
Long-term (>10 years)	• Deploy germplasm with enhanced nutrient use efficiency • Develop wheats with high nutrient density in grain • Introduce the capacity to biologically fix atmospheric nitrogen

ON-GOING INTERNATIONAL ACTIONS

- WHEAT CRP, FP 2, 3 and 4
- CGIAR Research Program on Agriculture for Nutrition & Health: HarvestPlus
- International Geosphere Biosphere Program (IGBP) project "The International Nitrogen Initiative"
- COST action on Endophytes in Biotechnology and Agriculture (EU)
- B&MGF programmes on N-fixing cereals

WHEAT INITIATIVE ACTIONS

- Coordinate research through the development of the Nutrient Use Efficiency in Wheat EWG
- Support the identification of favourable alleles for target genes linking with research in rice, barley, and maize
- Collaborate with projects that aim to introduce the capacity to fix atmospheric N2

B. SUBTOPIC 3.2: AGRONOMY AND CROP MANAGEMENT

CHALLENGE: CLOSE ON FARM YIELD GAP AND ADAPT TO NEW PRODUCTION SYSTEMS AND REGULATIONS

The yield gap, as defined by the difference between the yield potential and the average farmers' yield in a given environment and time span, varies enormously due to different climate and cropping systems. Crop management plays an important part in the expression of the genetic potential and in the sustainability of crop production systems.

- Roughly one-half of the yield potential is realised through agronomic factors. Attainable wheat yield and improved system stability can only be achieved or possibly exceeded when genetics are coupled with innovative integrated crop management strategies, including those based on principles of conservation agriculture;
- If wheat used more of the annual rainfall,and not only that of the growing season, grain yield could be increased. Enhanced water efficiency combined with emerging water use technologies and precision tools provide opportunities to reduce the gap;
- In addition to water, Nitrogen is the major limiting factor in wheat. Management strategies, which include placement and foliar feeding, should aim to enhance use efficiency and/or limit losses to groundwater or the atmosphere;
- Agronomics must include components which minimise losses from diseases, weeds, or insect pests.
- The best combinations of agronomic practices and genotypes will improve the soil characteristics (e.g. pH, organic matter, water infiltration rate, and water holding capacity), irrigation efficiency, drought tolerance, and reduce the chemical load that occurs due to fertilisers, pesticides and herbicides.

ASPIRATION: Develop highly stable wheat production systems that integrate novel genetic traits, deliver attainable yield goals and quality targets, enhance environmental sustainability, and mitigate production threats

AIMS AND OBJECTIVES

Bringing together experts from a broad range of disciplines will contribute to the refinement of wheat production systems to meet the global challenges facing wheat growers and end-users through:

• Site-specific technologies that are tailored to the needs of different production systems. An understanding of the trade-offs as agronomics are manipulated is needed, so the proposition of solutions is meaningful;
• Integration of new cultivars adapted to innovative and diversified management systems;
• Advancements in farming equipment, such as seeding equipment, and precision agriculture tools as key components of agronomic solutions and decision support systems.

These knowledge-based tools and next generation precision agriculture approaches will be key to enabling farmers to reach optimal wheat yield and quality with minimum resources irrespective of agro-ecological production areas.

RESEARCH NEEDS

Research is needed to develop highly productive and stable cropping systems with enhanced environmental sustainability. This will include:

- Development of holistic and integrated agronomic strategies to mitigate the negative impacts of climate change and to enhance environmental sustainability;
- Optimal crop residue management, as well as no-till and cover crops;
- Development of site-specific resource optimisation, integrated nutrient management and wheat rotational strategies for the long-term sustainability, and the stability of production systems;
- Integration of novel genetic traits and agriculture tools into innovative cropping systems;
- Intensified manipulation of agronomic factors to fully exploit wheat yield potential and technological quality to meet end-use requirements;
- Development of decision support systems to mitigate insect, weed and disease related threats to wheat production;
- Agronomics to improve crop water use and efficiencies in rain-fed and irrigated moisture regimes;
- A knowledge transfer strategy to ensure uptake of new knowledge and innovations at the farm gate and to update scientists on changing field realities.

PRIORITY ACTIONS

RESEARCH OBJECTIVES:

Short-term (1-5 years)	• Build agronomic capability (highly qualified personnel and modernised equipment) in developing countries
Medium-term (5-10 years)	• Develop integrated crop management systems that provide agronomic solutions to close on farm yield gap • Develop location-specific resource optimisation (water, soil) technologies for the long-term sustainability of crop production • Further develop knowledge-based decision-making tools (incl. simulation models) and new generation of precision-agriculture approaches • Development of decision support systems
Long-term (>10 years)	• Further development of innovative wheat cropping systems • Develop new plant and crop ideotypes to take advantage of agronomic solutions and vice versa

ON-GOING INTERNATIONAL ACTIONS

- Global Yield Gap Atlas (http://www.yieldgap.org)
- WHEAT CRP FP 4
- Cereal Systems Initiative for South Asia (CSISA)

WHEAT INITIATIVE ACTIONS

- Establish an EWG that brings experts together to transfer knowledge, from large national and international programmes with global outreach
- Facilitate discussions with complementary EWGs to develop future research goals and activities
- Support programs that build agronomic human capability in lesser developed regions
- Promote interactions between experts to develop integrated pest management systems

VIII. CORE THEME 4: ENSURING THE SUPPLY OF HIGH QUALITY, SAFE WHEAT

CHALLENGE: PRODUCING SAFE AND NUTRITIOUS WHEAT WITH ADEQUATE END-USE QUALITY IN AN UNSTABLE CLIMATE

Wheat produces 20% of our daily protein and food calories, which is why wheat grain proteins are an important determinant of the quality of end-products, such as bread and pasta. However, these grain proteins might also cause allergic reactions in some populations. Furthermore, grain carbohydrates affect food processing conditions, as well as the texture, shelf life, and digestibility of end products. Non-starch carbohydrates are of interest in reducing obesity and the incidence of cardiovascular diseases, type 2 diabetes, and some cancers.

Wheat is also an important source of dietary fibre, minerals, and vitamins (notably B vitamins) in the human diet. The crop also contains a wide range of bioactive phytochemicals, many of which have health benefits when consumed as part of a balanced diet. Understanding the variation in grain content and composition is necessary to enhance beneficial health effects and reduce negative effects. In addition, grain processing plays an important role in determining the availability, functionality, and physiological effects of the grain components.

ASPIRATION: Production of nutritious and healthy wheat grains with adequate end-use quality to meet the demand from subsistence users to industry and produce the great variety of food products made from wheat

AIMS AND OBJECTIVES

Improvement of quality and safety necessitates the integration of knowledge from multiple disciplines such as cereal chemistry, microbiology, human nutrition, toxicology, agronomy, and genetics. This complex task will involve studies that consider:

- Gluten and starch composition, as well as grain hardness;
- Human nutrition and biofortification;
- Food safety, food technology, and chemistry;
- Local breeding and environmental stability, combined with the extremely diverse end-uses of bread and durum wheat;
- Developing genomic resources for breeding for end-use quality;
- Tuning protein composition to maintain end-use properties while reducing the protein content, resulting in improved nitrogen use efficiency;
- Specific traits for specific end-uses, including engagement with processors and nutritionists.

RESEARCH NEEDS

Future research on wheat quality and safety should aim to:

- Standardise methods involving the examination of gluten proteins and improving the understanding of the role of gluten proteins regarding different dough processing conditions and end-product properties, which includes unifying the nomenclature of gluten alleles;
- Promote germplasm screening for the identification of sources of variation for various quality component traits;
- Further develop a deep understanding of the inheritance of grain bioactive compounds, as well as the genetics of the bioavailability of micronutrients and high dietary fibre, to improve the nutritional value of wheat and increase healthy cereal-based food consumption;
- Work to increase understanding of the nature and content of wheat proteins that show allergen and toxic reactions, while developing low-allergen wheat that is suitable for patients suffering with wheat related food disorders;
- Continue developing research that examines the effects of food manufacturing processes regarding the digestibility of wheat proteins, bioavailability of nutrients, and the interaction with gut microorganisms;
- Fine tune gluten, starch properties, and grain hardness according to specific and diverse end-uses by understanding Genotype x Environment x Management interaction;
- Reduce mycotoxins (please refer to core theme 2, subtopic 2.1) and toxic minerals in wheat;
- Continue developing low cost biomarkers for determinants of wheat quality and safety.

PRIORITY ACTIONS

RESEARCH PRIORITIES:

Short-term (1-5 years)	• Standards for gluten protein alleles and methods • Germplasm with low content in mycotoxins and toxic minerals • Low-cost molecular (and non-molecular) markers for quality, safety and nutritional determinants
Medium-term (5-10 years)	• Low-allergen wheats suitable for patients suffering from wheat related food disorders
Long-term (>10 years)	• Deployment of healthy wheat considering unstable climate and diverse end-uses

ON-GOING INTERNATIONAL ACTIONS

- Gluten group and workshop
- International Cereal Chemistry (ICC)

WHEAT INITIATIVE ACTIONS

- Coordinate research in the area through the development of the Improving Wheat Quality for Processing and Health EWG
- Coordination with the Durum Wheat Genomics and Breeding EWG and the Wheat Germplasm Conservation and Use Community EWG
- Coordinating activities
- Facilitating access to technologies

VIIII. CROSS-CUTTING THEME 5: ENABLING TECHNOLOGIES AND SHARED RESOURCES

CHALLENGE: BUILDING RESOURCES AND CAPABILITIES THAT SUPPORT CUTTING-EDGE WHEAT RESEARCH, BREEDING, AND AGRONOMY

Wheat has a large and complex genome, it is grown in diverse production environments, and it has broad germplasm resources. The very best tool-kit of cross-cutting technologies and methodologies, together with increased characterisation, use, and sharing of available genetic diversity of wheat, is needed to support the challenges faced by wheat researchers and breeders.

ASPIRATION: Wheat as a preferred research target for scientists as a result of freely available technology, germplasm, and resource base

AIMS AND OBJECTIVES

There has been rapid advances concerning techniques which support biological research, many of which have been developed due to recent medical research and studies in model crops. Supporting the rapid transfer of these technologies to wheat and developing new methods and resources based on wheat is a key aim of the Wheat Initiative.

The main aims of this core theme are the:

• Development of cross-cutting enabling technologies in support of core themes 1-4 to address shared platforms and methodologies for breeding, genotyping, and phenotyping;

• Completion of a high quality reference sequence and full annotation of the wheat genome to serve as a resource for marker development and gene discovery in wheat;

Completion of a “Wheat Information System” (WheatIS) to provide the international wheat community a single, comprehensive access point for wheat data and informatics tools;

Development, characterisation, and deployment of genetic resources and technologies to enhance the rate of genetic gain in wheat breeding programs.

SUBTOPIC 5.1: ENABLING TECHNOLOGIES AND METHODS

RESEARCH NEEDS: A REFERENCE SEQUENCE OF THE WHEAT GENOME

The availability of a reference sequence of the wheat genome will build a foundation which enables gene isolation, functional analyses, new allele discovery for pre-breeding, polymorphism discovery for marker-assisted selection, an increased understanding of the impact of epigenetic modifications, and transposable elements on gene regulation. Generation of a reference sequence anchored to genetic and phenotypic maps is the focus of the International Wheat Genome Sequencing Consortium (IWGSC). IWGSC is coordinating research to complete the bread wheat genome sequence by focussing on the:

- Completion of genetically anchored physical maps for all 21 wheat chromosomes;
- Sequencing of the minimum tiling-path of BAC clones derived from the physical maps;
- Assembly and annotation of pseudo-molecules for each of the 21 wheat chromosomes;
- Integration of the sequence data into the WheatIS.

Parallel research activities to integrate whole genome shotgun sequencing and improve the definition of the wheat gene space, as well as support for the annotation of the reference genome sequence, are also priorities of the IWGSC. Sequencing of the durum wheat genome and using the hexaploid wheat genome reference sequence as a foundation are also main priorities for the durum wheat genetics and breeding community. In addition to the genome sequence, large RNAseq data sets, as well as proteomic and metabolomics data, are being produced for wheat. These datasets will be related to the genome sequence and phenotypic traits, and integrated into the WheatIS.

Involving additional genomic resources is necessary to respond to post-genomic challenges such as diversity, population genetics, regulation and epigenetics. These resources must also be integrated into the WheatIS.

REVOLUTIONISED BREEDING SYSTEMS

Turning research into novel methods, tools, and technologies will facilitate the development of widely-adapted elite genotypes and accelerate selection cycles to reduce time from discovery to the target market.

Predictive science has the potential to improve the efficiency and sophistication of breeding by phenotyping only those genotypes with the greatest potential for cultivar release. Research to develop new algorithms and predictive models for genome wide-association mapping studies and implementation of genomic selection in applied breeding programmes is needed.

Recombination underpins the generation of new genetic combinations through crossing and provides the raw material for selective breeding. Recombination is mostly limited to distal regions of wheat chromosomes and restricts new combinations of alleles to these regions in breeding populations. Modulation of recombination along the chromosomes should allow new genotypes to emerge and facilitate the introgression of useful genes from wheat related species.

Deployment of hybrid wheat will likely contribute to wheat productivity and yield stability in the future. Research focusing on defining heterotic pools to maximise hybrid vigour and yield, and to develop effective pollination control systems for cost-effective hybrid seed production systems, are needed. Genetic engineering through mutation, genome editing, and transformation is a critical tool for the identification and characterisation of wheat genes. Deployment of hybrid wheat will likely contribute to wheat productivity and yield stability in the future. Research focusing on defining heterotic pools to maximise hybrid vigour and yield, and to develop effective pollination control systems for cost-effective hybrid seed production systems, are needed. Genetic engineering through mutation, genome editing, and transformation is a critical tool for the identification and characterisation of wheat genes. Furthermore genetic engineering has the potential to generate new genetic variation that will be valuable in breeding new cultivars. International coordination of well-characterised Targeted Induced Local Lesions In Genomes (TILLING) (populations and research programs to allow full implementation of gene and genome editing technologies is needed.

Although the techniques for producing and evaluating transgenic wheat lines are now well established, the technology is closely regulated and the regulations vary across jurisdictions. In many regions, field evaluation of transgenic wheat is not permitted or the process is complex and expensive. Currently, no transgenic wheat is under commercial production. Other technologies such as genome editing are now being applied to wheat, but it is still unclear how this technology will be viewed by different regulatory agencies.

The Wheat Initiative supports the use of genetic engineering to advance wheat research and looks forward to its responsible application to wheat improvement. Given the importance of genetic engineering to wheat research and the variation in regulatory requirements, the Wheat Initiative encourages partnerships and collaborations that assist in the development and evaluation of genetically engineered wheat breeding lines and genotypes, while respecting jurisdictional requirements and sensitivities. The Wheat Initiative will act as a source of credible, unbiased information regarding current activities and opportunities for wheat transgenic research and cultivar development.

CROP AND PLANT MODELLING – SYSTEMS BIOLOGY

As the global climate is changing, the interactive effects of plant traits, environment, and management must be understood in relation to region-specific climate change scenarios. The ability of process-based crop models to simulate the interactive effects of plant traits, environment, and management makes such models attractive tools for plant breeding.

However, more research is needed to improve model responses to disease and pests, and climate and soil factors, including high temperature, elevated atmospheric CO2, variable water and nutrient supply,their interaction with specific crop traits, and to develop a framework to handle crop model uncertainties and enable model applications to:

- Characterise and define target environments including climate change “hotspots”;
- Test the potential impact of specific morpho-physiological traits on yield, quality, and resource use for key environments and climate change hotspots;
- Explore possible ecophysiological mechanisms affecting traits;
- Assist in understanding interactions of traits, environment, and management;
- Improve the characterisation of traits in genetic studies and breeding nurseries.

In recent years, several international projects have led to an explosion of phenotypic data and detailed characterisation of wheat molecular variation, differential transcriptome profiles, metabolite profiling, and proteomic characterisation. Research focusing on a systems biology approach is a high priority, where integrating multiple -omics platforms and sophisticated bioinformatics systems can be used to unravel the underlying mechanisms of plant growth and development, adaptation to harsh environments, and resistance to biotic stresses. This is a growing area in model plant research and it is important that it is also captured for addressing the needs of wheat improvement. Incorporation of major adaptation gene information into wheat models is a first step in this process.

PRIORITY ACTIONS

RESEARCH OBJECTIVES:

Short-term (1-5 years)	• A high quality, ordered, annotated reference sequence of bread wheat • Reshape breeding schemes to optimally integrate genomic prediction to enhance genetic progress
Medium-term (5-10 years)	• A reference sequence of the durum wheat genome • Routine high-throughput gene and QTL cloning in wheat • Robust systems-based models for wheat responses to the environment • Hybrid wheat cultivars
Long-term (>10 years)	• Game-changing breeding technologies to accelerate the rate of genetic gain

ON-GOING INTERNATIONAL ACTIONS

- IWGSC
- WHEAT CRP
- CGIAR Research Program on Climate Change, Agriculture and Food Security
- AgMIP Wheat
- Integrated Breeding Platform
- International Triticeae Mapping Initiative (ITMI)
-

WHEAT INITIATIVE ACTIONS

- Support the activities and funding of the IWGSC
- Coordinate research in the area through the development of EWGs:
  +WheatIS
  +Wheat Breeding Methods and Strategies
  +Wheat Plant and Crop Modeling
  +Durum Wheat Genomics and Breeding
- Facilitate access to game-changing technologies
- Develop a credible information resource on transgenic wheat research and opportunities

B. SUBTOPIC 5.2: SHARED PLATFORMS

RESEARCH NEEDS: WHEAT INFORMATION SYSTEM (WHEATIS)

Integrated research approaches require combining data and information from all areas of wheat research. We need to develop an integrated information system that provides access to information that can then be applied to wheat research, practical breeding, crop modelling, and wheat management strategies. Currently, wheat data is independently dispersed among several databases around the world, which limits access of information to the wheat research and breeding community.

The development of a single-access web-based WheatIS (www.wheatis.org) linking existing and new databases will allow sharing and integration of data resources as well as provide a common platform housing available bioinformatics tools. To achieve the full potential of the Wheat Information System, efforts are needed to:

• Define standards, protocols and processes for sharing and integrating wheat data in keeping with other international initiatives;
• Develop a web platform allowing the exchange of standardised data files and associated metadata between different repositories;
• Develop a distributed index search engine which allows the dynamic search of different databases through a single entry point;
• Develop a robust and fast distributed infrastructure;
• Provide user-friendly bioinformatics tools to use the data efficiently;
• Establish links with the wheat users' community through outreach, training, and dissemination activities.

PHENOTYPING PLATFORMS

Novel high throughput phenotyping platforms for the field and controlled environment enables the precise measurement of wheat traits, either for phenotypic selection or for genetic studies designed to dissect complex traits. To reduce the gap between genomics and phenotyping for wheat improvement, it is necessary to characterise existing infrastructure and to strengthen international initiatives aimed at developing new technologies for wheat phenotyping, including protocols for simulating target environments and for trait phenotyping and/or identification.

Priorities include:

- Improving the precision of current phenotyping techniques;
- Establishing common protocols and reference germplasm to facilitate data comparison and exchange;
- Developing low cost, high throughput tools for field-level screening and for specific traits;
- Assessing new technologies to study currently inaccessible characteristics, such as the non-invasive detection of root architecture and function.

High-throughput phenotyping facilities and the use of modern sensor technologies is expected to result in the generation of large volumes of data. Therefore, a concerted effort is needed to develop efficient tools for the analysis, storage and publication of high-resolution phenotyping data.

There is also a critical need for research to evaluate and improve the prediction of trait effects measured in controlled conditions relative to performance in the field. Defining global sets of reference cultivars and defining standards for phenotypic and environmental data collection are priorities which will assist with the comparison and statistical integration of phenotypic datasets.

GENOTYPING PLATFORMS

High throughput genotyping methods provide an unprecedented supply of molecular markers for anchoring genomic sequences that will allow the genetic dissection of complex wheat traits for use in wheat breeding programs. The number of Single Nucleotide Polymorphism (SNP) markers in wheat is no longer a limitation for application into breeding and several SNP detection platforms based on different technologies that are already available to the community.

However, such technologies are not always accessible to breeders with limited resources and it is important that training and access to resources are supported within the wheat community. Further research concerning common high throughput Genotyping by Sequencing (GbS) and other genotyping/sequencing strategies, as well as the association of genetic variation with plant phenotypes, is needed to further facilitate wheat genetic improvement.

PRIORITY ACTIONS

RESEARCH OBJECTIVES:

Short-term (1-5 years)	• A web-based data access portal for wheat • Standardised genotyping and phenotyping methods and selection of reference germplasm sets
Medium-term (5-10 years)	• Global network of accurate high-throughput field phenotyping
Long-term (>10 years)	• Accelerating the rate of genetic gain through utilisation of global phenotyping networks

ON-GOING INTERNATIONAL ACTIONS

• WHEAT CRP
• International Plant Phenotyping Network (IPPN)
• European Plant Phenotyping Network (EPPN)

WHEAT INITIATIVE ACTIONS

- Coordinate research in the area through the development of the WheatIS and the Wheat Phenotyping to support Wheat Improvement EWG:
  +WheatIS
  +Wheat Phenotyping to support wheat improvement
- Act as a source of standardised data management and link to international phenotyping networks
- Facilitate access to technologies

C. SUBTOPIC 5.3: GENETIC RESOURCES

RESEARCH NEEDS

Utilisation of genetic resources is the basis of wheat breeding and is therefore fundamental to sustaining global wheat production. However, part of the genetic diversity present in landraces of wheat and in ancestral species was not captured or was lost during wheat domestication and subsequent selective breeding. Introgression of novel functional variation found in wheat landraces, old cultivars and related species into adapted backgrounds will be critical to enhancing yield potential of wheat and to provide new sources of resistance and tolerance to biotic and abiotic stresses. Diversity also plays a central role in a hybrid wheat approach.

However, the use of genetic resources in breeding is currently limited, largely because there has not been a global assessment and characterisation of the hundred thousands of accessions conserved in genebanks, leading to scarce genotypic and phenotypic information. Additionally, gene transfer from related species has been hindered due to linkage of deleterious traits and by certain biological aspects such as differences in ploidy levels or specific genomes. In addition, information is dispersed among genebanks, which makes systematic access from the wheat research community difficult.

Ex-situ collections of wheat and related species held in genebanks must be managed securely in a cost effective manner and accessed easily and freely by a broad range of users. While great advances have been made in recent years, further support is needed to help genebank managers collaborate and operate individually held collections within a global system that aims to support the wheat global ex-situ conservation and utilisation strategy through efficient coordination, capacity building, integrated information systems, and by rectifying key gaps in existing collections including genomic and phenotypic data. Specifically, efforts to update and implement the global wheat conservation strategy should be supported with an emphasis on the use of wheat and related species germplasm in breeding.

Current work pertaining to the development of a single-access web-based system enabling cross-searching of multiple gene banks must be supported to facilitate sharing of genetic material. This will be further enhanced by the inclusion of bioinformatics tools, such as the WheastIS, that will link them with systematic genomic and phenotypic data.

To facilitate the utilisation of genetic resources, new methods for their effective incorporation and uptake into breeding programs are required. This involves developing reliable phenotypic and genotypic data concerning accessions in gene bank collections, as well as pre-breeding efforts. The wheat genetic resources community needs to operate as a global partnership to ensure the cohesion, security, functionality, and use of germplasm collections that follow the recommendations of the International Treaty on Plant Genetic Resources.

PRIORITY ACTIONS

RESEARCH OBJECTIVES:

Short-term (1-5 years)	• Define collaboration and sharing responsibilities for management of key collections • Assess and facilitate availability of collections and associated information • Evaluate the germplasm base for wheat and related species and broaden it if needed • Define guidelines for regeneration, multiplication, distribution, evaluation and utilisation of genetic resources
Medium-term (5-10 years)	• Upgrade key collections • Explore new sites for collection of new wheat germplasm • Enhance capacity to maintain and distribute genetic resources effectively • Expand allelic diversity deployed in breeding programs via a more efficient and broader use of wheat and related species' genetic variability
Long-term (>10 years)	• Generate sequence and detailed phenotypic information for all genebank accessions

ON-GOING INTERNATIONAL ACTIONS

- National Genebanks and Genebanks CRP
- WHEAT CRP
- Global Crop Diversity Trust
- DivSeek

WHEAT INITIATIVE ACTIONS

- Support coordination in the area through the development of the Global Wheat Germplasm Conservation and Use Community EWG
- Facilitate stronger interactions between the gene banks and breeding communities
- Facilitate collaborative efforts among the WheatIS and Wheat Phenotyping to Support Wheat Improvement EWGs
- Support the International Treaty on Plant Genetic Resources to promote the international circulation of germplasm and their use in breeding

X. CROSS-CUTTING THEME 6: KNOWLEDGE EXCHANGE AND EDUCATION

CHALLENGE: EXCHANGING KNOWLEDGE BETWEEN GLOBAL WHEAT RESEARCHERS AND BUILDING CAPACITY

The need to exchange knowledge to strengthen wheat research globally and to enhance public-private partnership has appeared in all of the SRA's scientific core themes. Furthermore, education in wheat research was pointed out as a necessity by scientists and policy makers. For example, industry has difficulties recruiting wheat breeders because there are not enough being trained.

In addition, capacity building in agriculture in developing regions was identified as a means to more efficiently address the needs faced in regions of the world with lower GDPs. Finally, a major limitation to the use of modern technology is variable community support and understanding the full potential of these technologies to solve pressing issues regarding food security and sustainable development

While mentoring and networking are critical components for success in all disciplines of science, they are even more important within smaller scientific communities, such as wheat improvement, where resources are limited but the need for impact is great. Mentoring is of vital importance for the development of scientists, which is why the U.S. National Science Foundation required its grantees to provide information concerning how they will mentor postdoctoral fellows.

It is important to acknowledge that the working world of scientists is changing. For the same reasons that the Wheat Initiative must work to strengthen public-private partnerships in research and product development, we also must acknowledge and incorporate all of the roles (such as manager, mentor, administrator, and scientist)that researchers must play in order to be successful in their careers; as these roles vastly contribute to the successful delivery of the Wheat Initiative's strategic objectives.

Education, training, networking, and mentorship are especially important for engaging and retaining early career researchers, particularly from developing regions, as well as scientists who identify as female. The Wheat Initiative's strategic goals will only be achieved if a vibrant, inclusive community of scientists is fostered and supported well into the future.

They must be fully supported so they can establish and maintain quality standards for research, data collection, and knowledge sharing. The global support of wheat researchers will also lead to the development of a collective voice that will advocate for needed funds, policy support, and public attention. Such a community will likely further contribute to the Wheat Initiative's strategic goals by engaging with the public for the purposes of dialogue building and learning.

ASPIRATIONS: A well-connected public-private community of wheat researchers sharing knowledge and information throughout the world, self-perpetuating and expanding by means of training, education, networking and mentorship. A broad understanding of wheat, wheat science and of the role of research and technology in addressing the challenges of facing global wheat production

AIMS AND OBJECTIVES

Addressing the challenges of communication, training and education will be the responsibility of people involved or connected to wheat research and industry. The Wheat Initiative will aim to support these activities, help develop generic tools and programmes, and facilitate the development of training and communication partnerships. This will be achieved through:

- Developing networking activities to build communities around common research objectives;
- Encouraging and facilitating the mobility of researchers globally and at all levels to foster transfer of knowledge;
- Organising seminars and conferences to foster creative thinking and cross-disciplinary exchanges;
- Organising training workshops around specific areas of research and technology for the scientific community, wheat growers and end-users;
- Fostering education and training of early career scientists in wheat science, in developed and developing countries;
- Advertising training opportunities and fostering social networks of scientists, both virtually and face-to-face;
- Supporting scientists' efforts to engage with public audiences and the media to contribute to dialogue and learning.

PRIORITY ACTIONS

OBJECTIVES

Medium-term (5-10 years)	• Develop a global public-private community of highly trained and educated researchers in wheat research

ON-GOING INTERNATIONAL ACTIONS

- Different International Consortia, Projects and Programs: IWGSC, BGRI, WHEAT CRP SI-5,
- International Plant Phenotyping Network, European Plant Phenotyping Network, AgMIP, MACSUR, HarvestChoice, YieldGap, etc.
- International Wheat Conference
- International Wheat Genetics Symposium
- WHEAT CRP Strategic Initiative 5

WHEAT INITIATIVE ACTIONS

- Facilitate networking activities through the development of a WheatVIVO directory
- Support the organisation of training workshops for all EWGs
- Facilitate the organisation of an International Wheat Congress (IWC) every two years
- Develop a PhD scholarship programme dedicated to wheat
- Support coordination of e-learning in wheat education
- Advertise education opportunities, fellowships and job offers on the Wheat Initiative website
- Develop mentoring opportunities including drawing on a pool of retired scientists
- Facilitate public/private training opportunities

XI. 4 RESEARCH PRIORITIES

During the first week in July 2018, the members of the Wheat Initiative, the EWGs, and the Associated Programmes met to determine major challenges and top priorities for wheat research that would be best addressed through international collaborative programmes. They were asked to answer the questions that are highlighted in the infographic to the right.
These questions were presented and discussed in an open forum. Each EWG identified specific issues related to their area of expertise where there are currently significant challenges that limit major advances.

It was also noted that changing practices and the increasing frequency and severity of climate shocks have exposed our ignorance of the wheat plants' responses to combinations of stress, such as the simultaneous exposure to heat and drought stress, as well as responses to nutrient availability. The SB members also discussed issues on the importance of social sciences influencing topics such as technology adoption, communication, research support, diversity and equity, as well as access and sharing of data and resources. For example, they addressed concerns regarding the decline in aid support for agricultural research in least developed regions and the impact on technology delivery. Several members agreed that it would be helpful to form an EWG that would focus on the interaction of societal issues and global wheat research.

The discussions resulted in the identification of four common themes that are outlined as future research priorities in the text below.

1. THE ROLE OF AGRONOMY AND A CONSIDERATION OF WHEAT PRODUCTION WITHIN A BROAD FARMING AND SOCIETAL CONTEXT

The Wheat Agronomy EWG (Agronomy EWG) was a recent addition to the portfolio of Wheat Initiative EWGs, but has gained rapidly in importance with the realisation that many of the major challenges in wheat production relate to global factors; for example, nutrient use, minimising the environmental impact of agriculture, and addressing societal concerns around agricultural production and technology adoption. It is also important to remember that few wheat producers are able to realise the yield potential of their varieties and, in many regions, the greatest yield gains are likely to come from improved agronomic practices. A shift towards a consideration of the full production system is seen as critical to address production concerns.

The breadth of expertise in Wheat Initiative means that we are well placed to develop strategies that integrate agronomic considerations with other approaches. For example, there is interest in exploring breeding and selection strategies that evaluate performance based on cropping history. Similarly, the control of pests and pathogens, and management of abiotic stresses, rely on both breeding and management. The Crop Modelling Group started this process through a discussion paper proposing the use of crop models to integrate work from different areas of expertise. They use work targeted to enhancing radiation energy efficiency as an example of this approach.

2. DATA STANDARDS

Central to sharing information and collaboration is the ability to compare results and understand how data, materials, or germplasm were generated. The issue of accepted standards permeates many aspects of science and many groups have recognised its importance. Consequently, there are several initiatives underway to develop common standards for biological data. The Wheat IS EWG prepared a document on this issue and has been actively working with other EWGs, such as the Quality EWG and various organisations, to help develop common standards.

The structure of Wheat Initiative with its specialist EWGs, is ideally suited to help drive the development, adoption and implementation of standards across different areas of crop research. Some areas are already quite advanced, including genomics data, but other areas are lagging, such as the design and management of field trials.

The issues around field trial data offer a particularly important opportunity since most wheat growing countries run extensive field evaluation of germplasm on a regular basis and international organisations, such as CIMMYT and ICARDA, conduct extensive international trials.

The amount of information on accessions is vast but inconsistencies in trials make the data difficult to use outside the specific programmes.
The Control of Pests and Pathogens EWG (PandD EWG) also raised a related issue where the access to reliable disease diagnosis remains a significant problem for many researchers.

3. WHEAT SPECIFIC ISSUES

Although several species are members of the "wheat" group of plants, the group is unique. A wheat plant follows a specific developmental path and produces grain that has unique properties. Many aspects of development can be studied in model species, but there are also many features of wheat that can only be studied in wheat. The end-use and processing quality of wheat is a clear example. The wheat research community must study these unique features since no one else will take on this task.

The development of a reference quality genome sequence for hexaploid and tetraploid wheats provides a clear example of research that has been carried out by the wheat community. The sequence has provided a powerful resource that has already greatly enhanced the research capabilities of groups around the world. Resource development for wheat research has focussed on genomics resources where there is a well-organised community and good systems in place to ensure consistent data standards and access.

There are well advanced plans to add to the existing resources; exemplified in the 10+ Wheat Genomes Project and associated RNAseq work. The Quality EWG has also been developing reference germplasm for assessing processing quality.
Additional work is needed to define, as closely as possible, the unique features of wheat that will require input from the wheat community.

4. UTILISATION OF GERMPLASM AND GENETIC RESOURCES

There is general recognition that the germplasm base in modern breeding programs has become too narrow to allow significant and rapid genetic gain. Despite the current lack of diversity in elite lines, there are clear examples where exotic germplasm has led to major improvements in yield and performance. Although extensive germplasm collections are available, these have been poorly utilised since the effort involved in characterising and using even a small number of the hundreds of thousands of available accessions, is huge. International programmes have attempted to address this problem by characterising collections at the genotypic and phenotypic levels. These have included efforts to establish core or reference collections. While these have played an important role, so far they have had little impact on utilisation.

The Durum EWG has developed a reference collection of over 1000 tetraploid wheat lines to represent key germplasm for durum breeding and research. Both researchers and breeders were involved in selecting the lines. The plan is to develop extensive genotypic and phenotypic data sets on the lines so that these can serve as a general resource for the wheat research community.

An additional important attraction of developing and distributing reference collections, is that it helps tie the research community together and the more a collection is used, the more information generated and shared, the greater its value.

However, wheat is grown in many different regions and for different end uses. In order to develop an internationally valuable core collection, many different germplasm pools would be needed, and the collection may be too large to manage.

CONCLUSION

The Wheat Initiative is unique. The concept of a global coordination organisation to facilitate science exchange and stimulate collaborative research came out of the desire of the G20 group of countries to make a concrete contribution to addressing world food security. Because it is unique, the concept was also experimental. Over the seven years of its operation, the Wheat Initiative has established many collaborative groups and programmes.

The Durum EWG has been a success story. This group has developed into a highly collaborative and well organised group that has made significant advances in durum research. Importantly, they have developed strong links to groups that have previously focussed on bread wheat and this has resulted in important training opportunities.

Wheat Initiative is a community organisation with limited funding. We are dependent on the active participation of governments, industry and researchers. Our future progress and objectives will be built on the outcomes of the different working groups. The strong role played by the Durum EWG means that durum has been elevated in planning and, hopefully, investment and has profited from the improved ties to the global wheat research scene.

XII. FUNDING

THE CREATION OF THE FUNDING EXPERT WORKING GROUP (FEWG)

A key objective of the Wheat Initiative is to better coordinate wheat research to avoid duplication of effort and funding, and take advantage of synergies that can be derived from collaboration among wheat researchers throughout the world.

The various scientific and technical EWGss and Associated Programmes of Wheat Initiative are responsible for exchanging information regarding their members' ongoing work, while identifying gaps and opportunities for strategic science cooperation that will accelerate progress toward common goals.

Cooperative initiatives to fill gaps and accelerate cooperation can take many forms and scales. These include workshops, database development, data standardisation within and across EWGs, personnel exchanges, collaborative projects, platforms, and joint or linked calls. In some cases, it is relatively straightforward to identify funding sources from either national or multinational sources, such as EU and U.S. calls, or both.

However, in many cases the potential mechanisms for funding international science cooperation initiatives are not readily apparent. Lack of access to funding has been raised frequently by EWGs as an impediment to progress. Therefore, Wheat Initiative's ICC established an EWG to address funding issues.

ROLE OF THE FEWG

The proposed role of the FEWG is to:

- Identify and, where necessary, develop mechanisms for funding initiatives identified as priorities by the EWGs, RC, ICC, and SB;
- Identify mechanisms to promote bilateral and multilateral international alignment of national programmes and options for limited initial funding to develop an international research programme;
- Work with individual EWGs to develop the most appropriate options for funding specific initiatives and provide feedback to EWG or others from within Wheat Initiative on proposals or plans for international research collaborations;
- Explore options for providing "seed" funding to EWGs or other groups to develop large international funding proposals; and,
- Provide letters of support for international research funding applications.

ABBREVIATIONS

BGRI Borlaug Global Rust Initiative
CSISA Cereal Systems Initiative for South Asia
EPPN European Plant Phenotyping Network
EWG Expert Working Group
GbS Genotyping by Sequencing
ICC Institutions' Coordination Committee
IGBP International Geosphere Biosphere Program
IPCC Intergovernmental Panel on Climate Change
IPPN International Plant Phenotyping Network
ITMI International Triticeae Mapping Initiative
IWC International Wheat Congress
IWYP International Wheat Yield Partnership
RC Research Committee
SB Scientific Board
SNP Single Nucleotide Polymorphism
SRA Strategic Research Agenda
TILLING Targeted Induced Local Lesions In Genomes
WheatIS Wheat Information System
WI Wheat Initiative

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