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Power Wheat: Genes for Improvement of Modern Wheat
Case Study 3

Research goal	Identify genes that increase grain protein content (GPC), micronutrients and stripe rust resistance in wild emmer wheat, and their transfer to commercial varieties.
Beneficiaries	Wheat breeders, growers, bread and pasta industries, consumers.
Activities conducted in order to achieve the objectives	Positional cloning of genes generating increased GPC and stripe rust resistance. Evaluation of the gene effects in field trials. Introgression of the genes into commercial varieties.
Funding	5 BARD awards: US-3224-01R, US-3573-04C, US-4024-07, US-4323-10C, IS-4628-13: $1.47 million between 2001 to 2016. Other academic funds: $0.5 million, California wheat growers: $0.25 million
Publications	20 journal publications, 2 book chapters and 1 book. 14 papers are in the top impact factor quartile (Q1) and 5 have been cited more than 100 times. Science (2006) > 1000 citations.
Students involved	20 post graduates. Currently: 10 in academia of which 3 in the US, 3 in Israel, 2 in China, 1 in UK and 1 in Argentina; 1 in the biotechnology industry.
Stakeholders' collaboration	Genetic maps, DNA markers and gene sequences were made publicly available. Germplasm has been shared with wheat researchers all over the world. International Wheat Genome Sequencing Consortium (IWGSC).
Environmental impact	Reduced application of fungicides for a similar grain protein content and yield.
Social impact	Potential reduction of malnutrition in Fe and Zn. Reduction in pesticide exposure.
Commercial engagement	Syngenta, Arizona Plant Breeders, Resource Seeds, Baglietto Seeds, Bay State Milling, and Limagrain.
Patents	2 patents joint to Haifa U and UC and 8 PVP for US cultivars
Practical agricultural applications	In US and Canada, between 2013 – 2018, commercial introgressed cultivars were grown on ~ 110,000 ha.
Economic impact	Net present value of the BARD's investment is $118 million, thereof $20 million already attained. The Internal rate of return is 32%. Benefit cost ratio is 50, thereof 9 already attained.

Green- Academic information; Yellow - Social and environmental information; Blue - Economic information

1 Objective: Developing Better Wheat to Feed the World

Wheat is a main worldwide protein supply and is an important source for micronutrients such as Zn and Fe. The research aimed to transfer increased protein and disease resistant traits from wild emmer wheat to modern wheat varieties, without yield penalty, through marker assisted breeding (MAB). This objective is important for increasing the nutritional value of wheat, increasing productivity (*via* decreased wheat loss) and reducing pesticide application.

2 Research Activities

The researcher's proposal for mapping of the GPC (Grain Protein Content) gene had been previously denied by several competitive grant programs. Between 2001 and 2013 five BARD awards were granted to Jorge Dubcovsky (UC Davis) Tzion Fahima (U Haifa), Ann Blechl (USDA, ARS) and Philip San Miguel (Purdue). See Appendix A for full details of the awards.

The first two studies focused on mapping of a previously determined QTL for the GPC gene in wild emmer wheat. The gene region was narrowed to a single Mendelian locus, named *GPC-B1*. Continued work identified a single gene (GenBank DQ871219) responsible for the increase in GPC, Zn and Fe concentration. Field trials were conducted in Israel and the US.

In the latter three studies, positional cloning was conducted for the stripe rust ("yellow rust") resistance genes, *Yr36*, and *Yr15*, derived from wild emmer wheat. *Yr36* is unique in that it provides a broad-spectrum partial resistance against numerous stripe rust races, and hence is more durable than race-specific genes. *Yr15* provides immunity to most currently known races of stripe rust. The researchers demonstrated that pyramiding these resistant genes with race specific partial resistant genes into a single wheat variety provides excellent protection to the new, more virulent and aggressive, races of stripe rust.

3 Academic Impact

3.1 Publications

Two book chapters and 20 peer-reviewed publications in top impact factor journals were published based on research from the 5 BARD awards. 14 papers are in the top impact factor quartile (Q1) and 5 have been cited more than 100 times. The Science (2006) paper reporting the cloning of the *GPC-B1* and *Yr36* genes has been cited more than 1,000 times[1].

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[1] Uauy C., Distelfeld A., Fahima T., Blechl A. and Dubcovsky J. 2006. A NAC gene regulating senescence improves grain protein, zinc and iron content in wheat. **Science,** 314:1298-1301

3.2 Capacity Building

Two M.Sc. students, twelve Ph.D. students and six post-doctoral researchers were involved in these projects. Currently, ten of them are in academia: 3 in the US, 3 in Israel, 2 in China, 1 in Argentina and 1 in the UK; 1 is a molecular breeder in industry.

4 Stakeholder's Collaboration

The BAC library of tetraploid wheat[2] was made publicly available, and gene sequences for *GPC-B1*, *Yr36* and *Yr15* have been deposited in GenBank. The impacts of *GPC-B1* allelic have since been extensively analyzed in diverse field studies spanning forty environments and seven countries.[3] Germplasm carrying these genes have been shared with wheat researchers all over the world.

The research facilitated the incorporation of T. Fahima and colleagues into the International Wheat Genome Sequencing Consortium (IWGSC). J. Dubcovsky contributed a database of 10,000,000 mutations that was incorporated to the annotation of the Wheat genome. Cristobal Uauy, a PhD student in UC Davis and funded by BARD, continued to a position at the John Innes Centre in the UK and led the transcriptomic analysis of the wheat genome[4].

5 Commercial Engagement

The California Wheat Commission and the California Crop Improvement Association provided support to the wheat breeding program at UC Davis led by J. Dubcovsky, facilitating the introgression of the genes into commercial varieties. J. Dubcovsky has also established

collaborations with several companies to incorporate the genes into their varieties. These companies include Syngenta, Arizona Plant Breeders, Resource Seeds, Baglietto Seeds, Bay State Milling, and Limagrain. Commonly, the backcrossing of the genes was conducted at UC Davis with the financial support of the private industry.

Assaf Distelfed, a graduate student involved in the BARD research in both the Israeli and US labs, continued to a position at Tel Aviv University and collaborated with the industry partner NRGene who applied their newly developed cutting-edge sequencing technology

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[2] Cenci, A. (2003). Construction and characterization of a half million clone BAC library of durum wheat (Triticum turgidum ssp. durum). Theor Appl Genet, 107, 931–939. https://doi.org/10.1007/s00122-003-1331-z

[3] Tabbita, F., Pearce, S., & Barneix, A. J. (2017). Breeding for increased grain protein and micronutrient content in wheat: Ten years of the GPC-B1 gene. Journal of Cereal Science, 73, 183–191. https://doi.org/10.1016/j.jcs.2017.01.003

[4] The transcriptional landscape of polyploid wheat, R. H. Ramírez-González et.al, Science, 2018, http://dx.doi.org/10.1126/ science. aar6089

to map the genome of wild Emmer wheat[5]. This successful and unprecedented sequencing approach paved the way for collaboration between IWGSC and NRGene to assemble, within a few months, the first complete sequence of the bread wheat genome. Since the sequence was publicized as a community resource, research has accelerated and is driving disruptive innovation in wheat improvement worldwide.

C. Uauy collaborates actively with the industry partners Limagrain, RAGT, KWS and BASF on the development of molecular markers for MAS for a series of productivity traits.

5.1 Patents and Plant Variety Protection (PVP)

Two patents emerged from these projects:

1) *Kinase-start gene conferring resistance to plant disease and transgenic plants comprising it*, Dubcovsky, Fahima, Distelfeld, Uauy, Blechl, Fu, US946429B2, Granted: 2016-10-11 to Carmel-Haifa University Economic Corp Ltd, University of California and US Department of Agriculture
2) *NAC from wheat for increasing grain protein content*, Dubcovsky, Fahima, Uauy, Distelfeld, US7820882B2,Granted: 2010-10-26 to Carmel-Haifa University Economic Corp Ltd and University of California,

In the case that regulation will permit transgenic wheat, these genes can be used for genetic engineering of elite varieties utilizing the patented IP.

Eight PVP cultivars have been released from the wheat-breeding program led by J. Dubcovsky. See Appendix B for the full list.

6 Practical Agricultural Applications

Broad-spectrum resistance genes are sought after by breeders because such genes are expected to provide robust protection against stripe rust diseases. The BARD research enables introgression by using markers, rather than by phenotype, and this facilitates simultaneous selection for multiple stripe-rust resistant genes. This is expected to increase the durability of the resistance genes.

North American commercial varieties carrying *GPC-B1, Yr36* and *Yr15* are listed in Appendix C. Worldwide, breeding programs are working on marker assisted introgression of *GPC-B1*, *Yr36* and *Yr15* into local varieties and we anticipate that within the next 5 years many more varieties will be released, See Appendix D.

[5] Cenci, A. (2003). Construction and characterization of a half million clone BAC library of durum wheat (Triticum turgidum ssp. durum). Theor Appl Genet, 107, 931–939. https://doi.org/10.1007/s00122-003-1331-z

7 Social Impact

The NGO 2Blade and the Mexico-based International Maize and Wheat Improvement Center (CIMMYT) are developing pre-breeding wheat lines that offer multiple resistance against wheat rust. An exclusive license has been signed for the incorporation of *Yr-36* into the resistance cassette. CIMMYT will distribute these varieties free of charge to third world countries.

Pasta and bread wheat lines carrying *GPC-B1*, have been sent to CIMMYT for incorporation in their wheat-breeding program and shared with researchers in countries whose population suffer from malnutrition (resulting from iron and zinc deficiencies) such as India and Ethiopia. Though CIMMYT has released cultivars with increased zinc content which are used by over a million growers (small stakeholders with an average of 1ha each) in East India, Pakistan, Nepal and Bangladesh, these cultivars that include the GPC-gene as well as additional zinc enhancing genes were developed through traditional breeding methods. To date, CIMMYT mostly utilizes the marker introgression of the BARD cloned genes for small scale research and proof of concept studies. There is no anticipation of advancing the marker assisted breeding in the next 3-4 years

In India, in 2015-16, a variety including GpcB1 and Yr36 was evaluated in National trials as part of a special Biofortification trial, but could not be promoted for release.

8 Environmental Impact

To date, in California, the resistance conferred by *Yr15* and *Yr36* to stripe rust means that no fungicides are applied. *Gpc-B1* contributes to better use efficiency of nitrogen. Therefore, growers can reduce the amount of N applied and reach the same protein level.

9 Economic Impact

9.1 Investment Cost

BARD contributed $1.47 million in research funds between 2001 to 2016, which is $2.4 million in 2018 dollar-terms. Supplementary funds to the core BARD research support came from USDA-NIFA and Howard Hughes Medical Institute who contributed around $0.5 million. The breeding activities were supported with $0.25 million from the California Wheat Commission. In 2018 dollar-terms, the other funds contributed $1.1 million.

9.2 The Benefits

The economic benefit is estimated based on premiums given to wheat with increased protein content and the savings in fungicide due to the stripe-rust resistance of the *Yr15* and *Yr36* genes, using acreage estimates of the varieties containing these genes provided by breeders worldwide.

Grain Protein Content

The presence of the *GPC-B1* gene results in an 8-11% increase in grain protein, Fe and Zn. In some cultivars, it also results in an average yield reduction of 3-4%. We assume net increase of 5%-10% in grain protein content, as discussed with the researchers.[6]

This increase results in protein premiums and discounts that ranges for winter wheat between $5-$22/ton and for spring wheat between $0.5-$3/ton[7]. In the US, at least 60% of the grown acreage are winter varieties, while in Canada most are spring varieties. We calculated an average premium for winter varieties carrying *GPC-B1* at $10/ton, and for spring varieties, $1.5/ton. We added to this premium 40%, which is the retail + wholesale share in the end-consumer prices of cereal based products in the US. Thus, the benefit is calculated for winter varieties $16/ton (=10/0.6), and for spring varieties $2.5/ton (=1.5/0.6).

The economic impact of iron and Zn content increase is prominent where either the deficiency is widespread, or the adverse effects are very costly, even though only a small group is affected. No current economic benefit was assessed.

Resistance to Stripe Rust

In recent decades, stripe rust has spread rapidly to areas previously unaffected. Global stripe rust annual losses are estimated at 4.74 million tons. In the US, stripe rust epidemics caused average annual yield losses of 0.54% in the period of 1961 – 1984. Then came a period of successful use of resistant cultivars and fungicides that reduced the losses to 0.15%. At the beginning of the 2000's, new stripe rust pathotypes emerged and resulted in average annual yield losses of 1.5%.[8]

The introgression of *Yr15* eliminated the need for fungicides since it confers complete immunity to all the new races of stripe rust.[12] Gosal (2000)[9] found that yields of wheat line incorporating gene *Yr15* were 3.8 ton/ha compared to 0.91 ton/ha for a highly susceptible parent cultivar.[10]

Yr36 reduces, but does not confer complete immunity. However, when used in combination with other partial resistance genes it confers good levels of resistance. Wheat varieties were

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[6] http://fsp.ucdavis.edu/Seed_Catalog/Wheat/Patwin-515HP/
http://fsp.ucdavis.edu/Seed_Catalog/Wheat/Desert_King-High_Protein/
http://fsp.ucdavis.edu/Seed_Catalog/Wheat/Lassik/

[7] https://chssunprairie.com/grain/premiums-and-discounts/#WinterWheat

[8] https://www.globalrust.org/sites/default/files/2014%20BGRI%20Pardey.pdf

[9] Gosal K.S., 2000. Aspects of resistance to wheat stripe rust in Australia. Ph.D. Thesis. University of Sydney, Australia

[10] https://www.plantwise.org/KnowledgeBank/Datasheet.aspx?dsid=45876

evaluated for resistance to stripe rust in Canadian nurseries during 2009 and 2010. The researchers found that the combination of genes *Yr18* and *Yr36* (cultivars: Lillian and Burnside) resulted in a mean disease severity of 0.45% - 1.4%, while cultivars carrying only *Yr36* (cultivar: Somerset) resulted in a mean disease severity of 8.1%.[11]

Today, roughly, 40,000 ha of wheat in CA and 110,000 ha in Punjab State, India - integrate *Yr36* or *Yr15*, and practically no fungicides are currently applied.[12] We know that in India the potential acreage is much larger and that new *Yr15* varieties are now in trails, but this is not included in the economic calculation since data is still not available.

In order to avoid the stripe rust, farmers can use resistant cultivars or systemic triazole fungicides that cost $10-$25/ha[13], or $10-$40/ha[12], depending on the product and application rate. Indian experts reported to us a cost of $30/ha. Sometimes, multiple applications (2-3) are needed for susceptible varieties. In 2003, farmers in California lost 25% of the crop even with fungicide applications.[12] This value reflects only the fungicide savings. In addition, there is the reduction of the risk of significant crop losses, despite fungicide application but we cannot assess how frequently these would be expected to occur. Hence, we estimate the economic value of cultivars carrying Yr15 as $30/ha, and for cultivars carrying Yr36, we attribute only half of the benefit: $15/ha.

We added 40%, which is the retail + wholesale share in the end-consumer prices of cereal based products, in the US. Therefore, the benefit for cultivars carrying Yr15 is calculated as $50/ha (=30/0.6), and for cultivars carrying Yr36 $21/ha (=25/0.6).

<u>Cultivated Area and Related Benefits</u>

The current economic benefit is calculated for N. America and Punjab state, India.

In North America and Punjab, commercial cultivars introgressed with the *Yr15* gene were grown in 2018 on an average of 144,000 ha. Cultivars incorporating *GPC-B1/Yr36* were grown on an average of 77,000 ha. Total production of the *GPC-B1/Yr36* cultivars is estimated at 246,000 tons, based on 3.2 ton/ha, the average wheat yield in the US. Calculating for the specific growing area, the 2018 annual economic benefit was $6 million. See Appendices C and E for details on the cultivation area and wheat productivity.

Currently in the US, the area carrying these genes is less than 2% of the total wheat area. New releases of cultivars carrying these genes are anticipated to be used worldwide, and in the US. For the purpose of conservative calculations, we assume the rate of future annual acreage growth to be 10% compared to previous year between the years 2019-2028.

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[11] https://www.researchgate.net/publication/230846104_Stripe_rust_resistance_among_western_Canadian_spring_wheat_and_triticale_varieties
[12] Personal communication, J. Dubcovsky and with Prof. Parveen Chhuneja, Punjab Agricultural University
[13] https://aces.nmsu.edu/pubs/_a/A415/welcome.html

The Desert King-HP has the potential to expand the durum growing area in the San Joaquin Valley region where previous varieties were unable to reach the high grain protein content levels required for high-quality pasta varieties. We did not attribute any benefit for expanded growing areas as we do not have information about new acreage cultivated.

9.3 Economic Results

The project was initiated by BARD's investment and continued to receive support throughout all the years of research and development. However, as additional funding was provided during this same period, we attribute 67% of the benefit to BARD, according to its share in the total investment.

- Net present value of BARD's investment is $118 million, thereof $20 million already attained
- The Internal rate of return is 32%.
- Benefit cost ratio is 50, thereof 9 already attained.

The US economy benefit is calculated according to the production in the US.

Benefits attributed to the project that were not included in the calculation:

- Environmental impact and social impact, as detailed above, were not included in the benefit calculation

Table 1: Main Results, 2018 Million Dollar-Terms

	The Project	BARD	BARD Attained	Thereof to the US	Thereof to Israel	Other Countries
BARD's Share in the Cost	67%					
Share in the Benefit		67%				
Cost	4	2	2	1.2	1.2	
Benefit	180	120	22			
Net Present Value	176	118	20	37	-1	82
Internal Rate of Return	33%	32%	27%	33%		
Benefit Cost Ratio	50	50	9	31	-1	

9.4 Sensitivity Analysis

The low and high alternative assumptions used in the sensitivity analysis were brought together to estimate results under pessimistic and optimistic scenarios. Table 3 displays the net present value sensitivity results, between the low result: $23 million, to the high result: $187 million.

Table 2: NPV - Sensitivity Analysis, 2018 Million Dollar-Terms

			BARD's Share in the Benefit		
			Low	Central	High
			57%	67%	77%
Change in Benefit	Low	50%	49	58	67
	Central	100%	100	118	136
	High	150%	151	178	205

10 Appendix A: BARD Awards

Table 4: List of 5 BARD awards granted between 2001-2013

Project No	Full Title				
	Investigators	Institutes	Budget	Duration	Start Year
US-3224-**01R**	Positional cloning of a gene responsible for high grain protein content in tetraploid wheat				
	Dubcovsky, J. Fahima, T. Blechl, A.E.	UC, Davis U Haifa USDA, ARS	$335,000	3 years	2001
US-3573-**04C**	Validation of a candidate gene for increased grain protein content in wheat				
	Dubcovsky, J. Fahima, T. Blechl, A.E. San Miguel, P.	UC, Davis U Haifa USDA, ARS Purdue	$313,458	3 years	2004
US-4024-**07**	Map-based cloning of high-temperature adult plant stripe rust resistance gene Yr36 from wheat				
	Dubcovsky, J. Fahima, T. Blechl, A.E. San Miguel, P.	UC, Davis U Haifa USDA, ARS Purdue	$267,000	3 years	2007
US-4323-**10C**	Molecular characterization and deployment of the high-temperature adult plant stripe rust resistance gene Yr36 from wheat				
	Dubcovsky, J. Fahima, T. Blechl, A.E.	UC, Davis U Haifa USDA, ARS	$251,596	3 years	2010
IS-4628-**13**	Map-based cloning of the novel stripe rust resistance gene YrG303 and its use to engineer 1B chromosome with multiple beneficial traits				
	Fahima, T. Dubcovsky, J.	U Haifa UC, Davis	$303,996	3 years	2013

11 Appendix B: Plant Variety Protection (PVP)

Dubcovsky, J., O. Chicaiza, L. Jackson:

- HRS wheat variety “Lassik”. PVP 200800176.

Dubcovsky J., O. Chicaiza, X. Zhang:

- Durum variety Desert King-High Protein. PVP 20100585.
- HWS wheat variety “Patwin-515”. PVP 201200476.
- HRS wheat variety Yurok. PVP 201500492.
- HWS wheat variety Patwin-515HP. PVP 201600390.
- High resistant starch wheat UC-Patwin-RS. PVP 201800058.
- HRS wheat with high resistant starch UC-Lassik-RS PVP 201800070.
- HRS wheat UC-Central Red. PVP 201900011

12 Appendix C: Cultivation Area and Benefits of the New Cultivars (ha)

GPCB1+Yr36 Cultivars	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**Average (2013-2018)**
Lassik,					0	200	
Patwin-515HP					0	240	
Desert King-HP			3,000		1,200	3,266	
Westmore						13,400	
Tiburon					1,400	1,400	
C-Lassik-RS							
Yurok							
Sprinter			5,376				
Egan,							
Farnum		19,878	11,474	7,152	12,178	2,127	
Lillian							
Burnside							
Glencross	142						
Somerset		264	701	1,256	195		
AAC Connery			50	1,090	14,221	52,219	
Conquer	13,765	33,595	32,352	33,106	6,461	4,054	
Sub-total	**13,908**	**53,737**	**52,954**	**42,604**	**35,655**	**76,907**	**45,961**
Yr15 Cultivars	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**Average**
Blanca Grande 515,	15,000	5,920	5,600		3,200	3,200	
Summit 515	19,200	36,000	32,400		20,660	26,780	
Patwin 515			1,360		5,200	3,800	
New Dirkwin	2,800	4,000	4,280		4,000	600	
UC-Patwin-RS							
UC-Central Red							
Unnat PBW550						110,000	
Sub-total	**37,000**	**45,920**	**43,640**	**Incomplete Data**	**33,060**	**144,380**	**38,800**
Total	**50,908**	**99,657**	**96,594**		**68,715**	**121,287**	**85,432**
Benefits	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**Average**
Yr15 Benefit, $42/ha	1,554,000	1,928,640	1,832,880		1,388,520	6,063,960	2,553,600
Yr36 Benefit, $21/ha	292,060	1,128,481	1,112,026	894,692	748,751	1,615,043	979,272
Protein GPCB1 Benefit	93,802	1,122,169	795,686	560,699	705,903	600,010	663,514
Total	726,308	1,893,379	1,620,099	Incomplete Data	1,267,527	3,171,080	1,735,679

Sources: California[14] Arizona[15], Washington[16], Canada[17], India[18]

13 Appendix D: Some Relevant Global Breeding Programs

13.1 North America

In addition to the PVP cultivars from UC listed in Appendix B, the following cultivars have been released

- Farnum (developed at Washington State University, Pullman, USA)
- Westmore (developed by Arizona Plant Breeders, Inc. ABP)
- Tiburon (Arizona Plant Breeders)
- Blanca Grande 515 (Resource Seeds, Inc and UC Davis)
- Summit 515 (Syngenta Cereals (formerly Resource Seeds, Inc.) and UC Davis)
- Sprinter (Washington State University)
- Somerset (developed by CRC and AAFC, Winnipeg, Canada)
- AAC Connery (Canada, Cuthbert 2014)
- Conquer (Canada, Brown et al. 2017)

The Canadian Varieties Lillian and Somerset (both developed by CRC and AAFC, Winnipeg) include the GPC-B1 gene that was introgressed based on DNA markers that preceded the positional cloning by the BARD researchers, and hence were not included in the economic analysis.

13.2 Europe:

In Europe the *Yr36* allele has been introduced into UK advanced breeding lines for a private breeding company and it is expected that the first cultivars with *Yr36* will be released in 2021. For *GPC-B1*, there was no explicit selection in the UK given that shorter grain filling is an undesirable trait in the long growing seasons encountered in UK. However, in France the functional GPC-B1 allele has been introduced into breeding programs and is currently in advanced breeding lines since short growing cycles are preferred in the southern France, Mediterranean conditions. *Yr15* has also started to be introduced into European breeding programs since the *Yr5+Yr15* combinations were made public by Jorge Dubcovsky. The Uauy lab recently cloned *Yr5* which allows breeders to select *Yr5+Yr15* with perfect markers.

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[14] http://www.californiawheat.org/uploads/resources/898/vs-2018-report.pdf
http://californiawheat.org/uploads/resources/850/vs-2017-report--revised.pdf
http://californiawheat.org/uploads/resources/674/varsurvey-2014.pdf
[15] Personal communication, J. Dubcovsky.
[16] http://wagrains.org/wp-content/uploads/2015/04/2017_WAWheatVarietySurvey.pdf
http://wagrains.org/wp-content/uploads/2018/10/2018_WAWheatVarietySurvey.pdf
[17] https://www.grainscanada.gc.ca/statistics-statistiques/variety-variete/varieties-en.htm
[18] Personal communication, Parveen Chhuneja.

13.3 India:

The Indian government has been funding a network project in 5 Indian institutes for introgression of *GpcB1* into elite wheat backgrounds for almost 10 years. The introgression lines are in various stages of evaluation and some advanced breeding lines are being evaluated at national level trials. Specific to the Punjab Agricultural University (PAU) *Yr36* did not give enough protection against stripe rust under very high incidence and current efforts are underway to pyramid *GpcB1* with additional major rust resistance genes. Lines in advanced stages of evaluation at PAU are:

- PBW821 (PBW550+*GpcB1*+*Yr36*+*Yr15*) is presently being tested in Advanced Varietal Trials-Year 1 on Marker Assisted Backcross Breeding (2018-19)
- BWL6964 (PBW550+*GpcB1*+*Yr36*+*Yr15*): is being evaluated in State trials 2018-19 for release in Punjab State

PAU use *Yr15* extensively and have released two varieties with stripe rust resistance gene *Yr15* from Punjab Agricultural University, Ludhiana, India

- Unnat PBW550 (PBW550+Yr15): Released for cultivation in Punjab State in 2017
- PBW757 (PBW550+Yr15): Released for cultivation in NWPZ under very late sown conditions

13.4 Australia:

Germplasm carrying marker assisted introgression of *GpcB1* was developed in a collaborative effort of Australian university and private parties[19] led by the South Australian Research and Development Institute[20]. The germplasm has been distributed to all the leading breeding companies in Australia (AGT, InterGrain and Longreach), but as yet no varieties have been released.

Australian Grain Technologies (AGT), Australia's largest plant breeding company, report that the *GpcB1* donor lines are used extensively in their breeding programs and they have advanced material in their breeding pipelines. However, no lines are currently advanced enough in the breeding programs to be released as commercial varieties in the near future.

AGT also use *Yr15*, but this has only become a serious breeding target in the past twelve months since the gene was cloned and the gene function characterised.

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[19] Involved parties were: Australian Grain Technologies, InterGrain Pty Ltd, LongReach Plant Breeders, GNSW Department of Primary Industries, School of Agriculture Food and Wine at Adelaide and Department of Environment and Primary Industries, Victoria.

[20] Eagles et al., (2014) *Crop & Pasture Science*, (**65**) http://dx.doi.org/10.1071/CP14106

14 Appendix E: US Wheat Production 2010 - 2018 in Million ha

Total US Wheat Production 2010 - 2018 in Million ha.

Year	HRW	HRS	SRW	WW	DUR	All Wheat	Yield T/ha	$/Ton
2010/11	9.6	5.0	1.6	1.6	1.0	18.8	3.1	211.1
2011/12	8.6	4.5	2.9	1.7	0.5	18.3	2.9	268.1
2012/13	9.8	4.6	2.7	1.5	0.8	19.5	3.1	287.8
2013/14	8.2	4.3	3.6	1.6	0.5	18.1	3.2	254.4
2014/15	8.8	4.8	2.9	1.6	0.5	18.6	2.9	221.9
2015/16	9.3	4.9	2.4	1.6	0.8	18.9	2.9	181.1
2016/17	8.7	4.2	2.0	1.6	0.9	17.5	3.6	144.1
2017/18	7.1	3.9	1.7	1.5	0.8	15.0	3.1	174.8
2018/19 (est.)	6.8	5.0	1.8	1.5	0.8	15.8	3.2	190.7

Sources: Calculation is based on: https://www.ers.usda.gov/data-products/wheat-data/

15 Appendix F: Information providers: Personal communication

- Jorge Dubcovsky – PI and Co-PI for BARD grants, UC Davis, College of Agricultural and Environmental Sciences, Wheat Genetics & Breeding
- Tzion Fahima – PI and Co-PI for BARD grants, Haifa University, Department of Evolutionary and Environmental Biology
- Velu Govindan - Senior wheat breeder at International Maize and Wheat Improvement Center (CIMMYT)
- Cristobal Uauy – Ph. D student on BARD grants in the Dubcovsky Lab, currently Professor in the Department of Crop Genetics, John Innes Centre, UK
- Parveen Chhuneja, School of Agricultural Biotechnology, Punjab Agricultural University, India.
- Ron DePauw – Consultant for SeCan, formally principle wheat breeder at Agriculture and Agri-Food Canada
- James Edwards - wheat breeder at Australian Grain Technologies
- Hugh Wallwork - Cereal Pathologist, South Australian Research and Development Institute – SARDI
- Russell Eastwood - wheat breeder with Australian Grain Technologies (former President of the Wheat Breeding Society of Australia).