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Washington State University Wheat and Barley Research Progress Reports

Washington Grain Commission

2021-2022 Fiscal Year

2021-22 WSU Wheat & Barley Research Progress Reports to the Washington Grain Commission

Washington Grain Commission
Barley Research Report

Project #: 3019-3200

Progress Report Year: 1 of 3

Title: Improving Spring and Winter Barley Varieties for Malt, Feed and Food

Cooperators: Deven See, Xianming Chen, Max Wood

Executive Summary: During the first year of this grant and my second full season as the WSU barley breeder excellent progress was made towards improving WSU barley varieties for malt quality. The Washington Grains Commission (WGC) funds were integral in transitioning the WSU breeding program into a spring and winter malt barley breeding program. With the infrastructure now in place for malt quality analysis the bar is set to develop both spring and winter adjunct and all malt barley varieties with consistent quality and agronomics to make the American Malting Barley Association (AMBA) recommended list.

To quickly transition to a fully integrated malt barley breeding programs we established the state-of-the-art WSU Malt Quality Lab (WMQL) which was accomplished through funding provided by the WGC. The fully operational WMQL is producing excellent data as compared to samples provided by Hartwick College. The correlation between the labs is excellent ($R^2 = 0.988$) and is well within the tolerance for reproducibility. We are currently malting and analyzing elite 2021 field season yield trials material prioritized by high yielding experimental lines derived from elite-by-elite malt barley parental crosses. The quality data which we can now generate in house weeks from harvest provides great efficiency when selecting early and late generation materials for malt quality. To aid the rapid early generation selection we also developed a new association mapping panel of 364 elite malting lines from the 2021 WSU yield trials. The parents of these lines included eight adapted experimental lines with decent malt quality crossed with seven high quality varieties (Bentley, CDC Copeland, CDC Kindersley, CDC Meredith, AC Metcalfe, Merem, and Cerveza). All 364 lines are being genotyped utilizing the 50K SNP panel and malt quality analysis is currently being generated in the WMQL. The data will be utilized to develop a panel of ~150 DNA markers associated with malt quality traits initially focused on malt extract, alpha amylase, protein, and beta-glucan composition. We are currently developing a new marker system utilizing the Oxford Nanopore MinION DNA sequencing technology to genotype our early generation materials in house. Thus, the early generation spring head rows (~12,000/year), advanced single rep yield trials (~600/year) and multi rep yield trials (~60/year) will be enriched for malt quality so we can concentrate on selecting for farmer traits including yield, height, standability and disease resistance in the field utilizing traditional selection strategies. This will provide much more efficient use of the WGC funds and will allow for greater capacity to analyze later generation material that have already been screened for quality in the WMQL and via marker assisted selection.

Impact: In the first year of this WGC grant we have now transitioned the program to a fully integrated malt barley breeding program with the genetics, genotyping and phenotyping capabilities in place with the focus on the development of both spring and winter classes of malt barley varieties. We identified five promising advanced spring malt barley lines with excellent agronomics across diverse environments with preliminarily data suggesting that they have excellent malt quality. The current plan is to fast track these lines into the WSU variety testing program and collect one more year of malt quality data at two locations then enter them into the AMBA pilot program in 2023. If the data allows we would like to release the best performing line as an all malt craft variety then pursue AMBA recommendation if they make it through the AMBA testing program.

In our efforts to maintain the spring malt barley development pipeline we made over 100 new crosses focused on malt quality and targeted agronomic traits and disease resistance. Ten elite-by-elite crosses were selected and progeny advanced to plant an additional 12,000 F_{3-4} head rows in the field for evaluation in the 2022 field season. In the 2021 field season we screened approximately 12,000 single head plots from our 2020 crossing block and selected 623 candidate malt barley progeny lines for single rep yield trials for the 2022 field season. All lines have been harvested and processing to collect data for selection and advancement of elite material. In the 2021-2022 greenhouse the third spring malting barley crossing blocks were planted. The parental lines were selected based on quality and additional crosses are currently being made.

Winter malting and feed barley lines were also selected and planted to begin crossing for the WSU winter barley breeding program that was initiated in the Fall of 2020. In Fall 2020 we planted over 600 elite and advanced winter malting lines provided by Dr. Pat Hayes, the Oregon State University winter malt barley breeder. We identified 70 parental lines for the WSU breeding program that perform well at Spillman farm in terms of yield and will assess them for quality once the spring materials have been completed. Because of the adverse year we experienced in the 2021field season (heat and drought) many of these lines were planted again in Fall of 2021 to generate a second year of evaluation and malt quality data in 2022. We are also continuing to evaluate and advance IMI-tolerance in multiple classes of selected elite barley lines.

To better utilize molecular marker selection current parental lines and breeding material from the WSU breeding program were to be evaluated utilizing genotyping with the malt quality molecular markers developed in collaboration with the USDA-ARS cereal genotyping lab, Pullman, WA. However, the data was not sufficient for the analysis, thus we are forging a new path for early generation genotyping. To aid the rapid early generation selection we developed a new association mapping panel of 364 elite malting lines from the 2021 WSU yield trials. The parents of these lines include eight adapted experimental lines with decent malt quality crossed with seven quality varieties (Bentley, CDC Copeland, CDC Kindersley, CDC Meredith, AC Metcalfe, Merem, and Cerveza). All 364 lines are currently being genotyped utilizing the 50K SNP panel (USDA-ARS cereal genotyping lab, Fargo, ND) and malt quality analysis is being performed in the WMQL with nearly 100 of the lines already malted. We are developing a new DNA marker system utilizing the Oxford Nanopore MinION DNA sequencing technology. We have two MinION DNA sequencing instruments and experience utilizing the technology. However, now we will utilize this technology for an adapted amplicon sequencing strategy to generate genotyping data of over 2,000 experimental lines each year for early generation malt quality selection. Once this AM mapping data is generated, and a training set is validated on the MinION DNA sequencing technology we will select a training population from the WSU 2021 field lines genotyped with the 50K SNP panel and with the malting data generated in the WMQL we will test prediction accuracy. Once this research is completed we can begin utilizing the marker panel for marker assisted selection strategies early in our selection process with the markers associated with low grain protein, increasing malt extract, high alpha amylase and reduced wort ß-glucan.

We collected a virulent population of *Puccinia graminis* f. sp *tritici* (*Pgt*) from three Washington barley fields and from the alternate hosts Mahonia and barberry from locations in Spokane, Colfax, and Pullman, WA and Moscow and Potlatch, ID . We generated nearly 200 hundred single pustule isolates and inoculated them onto lines containing the only two effective barley stem rust resistance genes, *Rpg1* and *rpg4/Rpg5.* We determined through the phenotyping of the entire population that ~10% of the isolates collected were highly virulent on both *Rpg1* and *rpg4/Rpg5.* This virulence had never been reported as the combination of the two genes has always provided resistance to all known isolates collected worldwide. These data show that this *Pgt* population contains the most virulence isolates in the world in regards to barley virulence and pose a potential issue to barley and wheat production in Washington and the region. We conducted phenotypic and genotypic screening of the World Barley Core Collection (WBCC) with the most virulent isolate Lsp21 and utilized association mapping to identify new sources of resistance on barley chromosomes 2H and 5H that are effective against the Washington State *Pgt* virulent isolates. In our 2020 field barley crossing block we hybridized lines containing these novel resistance sources with malt barley parental lines and are using a backcrossing scheme to introduce these resistances into our breeding materials. In 2021 we established an adult plant stem rust screening nursery in the field at Spillman farm and included the lines from the WBCC that had seedling resistance as well as barley lines form the WSU variety testing program and lines from the OSU barley breeding program that contained novel stem rust resistance genes. Alarmingly, the seedling resistance identified from the WBCC did not translate to adult plant resistance in the field and all WSU experimental materials and WSU variety testing lines were highly susceptible to the cocktail of six PNW isolates identified as representing the broadest virulence on both barley and wheat resistance genes. However, six lines from the OSU breeding program showed a high level of adult plant resistance. We are currently utilizing these lines in our 2022 crossing block to introduce these new sources of adult plant resistance into the WSU breeding program.

As we further optimize and streamline selection utilizing high throughput genotyping and phenotyping the infrastructure put into place early in the development of my program will have a measurable impact on optimizing the return on the WGC's investments. This investment in time and resources will expedite the development of AMBA recommended malt barley varieties in the future. As we move the breeding program forward these investments will have an impact on the ability to make more precise selections from intensive hybridization and screening of larger numbers of recombinant individuals. Our major focus will be on fixing malt quality in the program while increasing agronomic traits such as water use efficiency, heat tolerance, stature and lodging resistance, disease resistance and ultimately yield.

The most measurable impact(s) this project has had in this funding cycle was that we can now fully utilize the infrastructure and instrumentation investment by the WGC to transform the WSU barley breeding program into a self-sustained spring and winter malt barley breeding program. It became apparent where the bottlenecks were in the program, specifically genotyping, and we are alleviating these hindrances so we can move malt barley variety development forward in an expedited fashion. Although, it may take a few years before I can report on the release of

AMBA varieties, with the tools in hand it is only a matter of hard work to achieve this goal. We will focus on the goal of transforming the program into a top malt barley breeding program that will help increase barley acreage to feed the domestic supply of quality malting barley as well as international markets.

Outputs and Outcomes:

Objective	Deliverable	Progress	Timeline	Communication
1	Release of a craft malting barley cultivar suited to brewing with enhanced flavor profile	Several of the advanced malting barley breeding lines have performed well in malting end use quality tests and agronomically in Variety Testing. A second WSU malting line should be released in the coming year	2022-2023	Talks and presentations at field days; distribution of informative variety rack cards; Wheat Life articles; Pod Casts
2	Release of a WSU winter malting barley variety suited to adjunct and or all malt craft brewing	We are selecting parental lines and making crosses from material selected from the OSU breeding program that performs well in eastern Washington	2027-2029	Talks and presentations at field days; distribution of informative variety rack cards; Wheat Life articles; Pod Casts
3	Release of a second IMI-tolerant barley variety with high yield and excellent disease resistance to complement Survivor. This could also be in the food or malt market class	We have thousands of known IMI-tolerant barley lines in our breeding pipeline. These have and will continue to undergo greenhouse and field trials as well as multi-location yield trials to identify the superior breeding lines available.	2024	Talks and presentations at field days; distribution of informative variety rack cards; Wheat Life articles

4	Hulless, waxy food barley variety release to support non-waxy high beta glucan varieties Havener and Meg's Song	Our hulless, high Beta-glucan breeding lines are performing well in the advanced breeder trials and will be included in variety testing trials	2023-2024	Talks and presentations at field days; distribution of informative variety rack cards; Wheat Life articles; Pod Casts

Communications continued

Publications are listed here as the block above was too small.

Peer-Reviewed Publications (12 total) and Book Chapters (1 total):

Published, Accepted or Submitted from January 1, 2021 – December 31, 2021

Peer-Reviewed Publications:

1. Ameen, G., Solanki, S., Sager-Bittara, L., Richards, J., Tamang, P., Friesen, T.L., and **Brueggeman, R.** (**2021**) Mutations in a barley cytochrome P450 gene enhances pathogen induced programmed cell death and cutin layer instability. *PLOS Genetics* (Accepted).

2. Clare, S.J., Duellman, K.M., Richards, J.K., Sharma Poudel, R., Friesen, T.L. and **Brueggeman, R.S.** (**2021**) Association mapping reveals A reciprocal virulence/avirulence locus within diverse US *Pyrenophora teres* f. *maculata* isolates. *BMC Genomics* (Accepted).

3. Upadhaya, A., Upadhaya, S., and **Brueggeman, R.S.** (**2021**) The wheat stem rust (*Puccinia graminis* f. sp. *tritici*) population from Washington State contains the most virulent isolates reported on barley. *Plant Disease* DOI: 10.1094/PDIS-06-21-1195-RE.

4. Alhashel, A., Sharma Poudel, R., Fiedler, J., Carlson, C., Rasmussen, J., Baldwin, T., Friesen, T., **Brueggeman, R.**, and Yang, S. (**2021**) Genetic mapping of host resistance to the *Pyrenophora teres* f. *maculate* isolate 13IM8.3. *Genes Genomes Genetics/G3* DOI: 1093/g3journal/jkab341.

5. Clare, S.J., Celik Oguz, A., Effertz, K., Sharma Poudel, R., See, D., Karakaya, A., and **Brueggeman, R.S.** (**2021**) Genome wide association mapping of *Pyrenophora teres* f. *maculata* and *Pyrenophora teres* f. *teres* resistance loci utilizing natural Turkish wild and landrace barley populations. *Genes Genomes Genetics/G3* DOI: 10.1093/g3journal/jkab280.

6. Capo-chichi, L.J.A., Eldridge, S., Elakhdar, A., Kubo, T., **Brueggeman, R.**, and Anyia, A.O. (**2021)** QTL Mapping and Phenotypic Variation for Seedling Vigour Traits in Barley (*Hordeum vulgare* L.). *Plants*, DOI: 10.3390/plants10061149.

7. Tamang, P., Richards, J. K., Solanki, S., Ameen, G., Sharma Poudel, R., Deka, P., Effertz, K., Clare, S., Hegstad, J., Bezbaruah, A., Li, X., Horsley, R. D., Friesen, T. L., **Brueggeman, R. S. (2021)**. The barley HvWRKY6 transcription factor is required for resistance against *Pyrenophora teres* f. *teres*. *Frontiers in Genetics* DOI: 10.3389/fgene.2020.601500

8. Zhang, Z., Running, K.L.D., Seneviratne, S., Peters Haugrud, A.R., Szabo-Hever, A., Shi, G., **Brueggeman, R.**, Xu, S.S., Friesen, T.L., Faris, J.D. (**2021**) A protein kinase-major sperm protein gene hijacked by a necrotrophic fungal pathogen triggers disease susceptibility in wheat. *The Plant Journal* DOI: 10.1111/tpj.15194

9. Jin, Z., Solanki, S., Ameen, G., Gross, T., Sharma Poudel, S., Borowicz, P., **Brueggeman, R.S.**, and Schwarz, P. (**2021**) Expansion of internal hyphal growth in Fusarium Head Blight infected grains contribute to the elevated mycotoxin production during the malting process. *Molecular Plant-Microbe Interactions* DOI: 10.1094/MPMI-01-21-0024-R.

10. Deka, P., , **Brueggeman, R.**, and Bezbaruah, A. (**2021**) Sequestration of Zinc Nanoclusters in Root Vacuoles of Spinacia oleracea exposed to Nanoscale Zinc. *Nanotechnology for Environmental Engineering* (Accepted).

11. Clare, S.J., Duellman, K.M., Richards, J.K., Sharma Poudel, R., Friesen, T.L. and **Brueggeman, R.S.** (**2021**) Association mapping reveals A reciprocal virulence/avirulence locus within diverse US *Pyrenophora teres* f. *maculata* isolates. *BMC Genomics* (Accepted).

12. Amezrou, R., Rehman, S., Pal Singh Verma, R., **Brueggeman, R.S.**, Belquadi, L., Arbaoui, M., and Gyawali, S. (**2021**) Identification of SNP markers associated with *Pyrenophora teres* f. *maculata* resistance/susceptibility loci in barley (*Hordeum vulgare L*.). *Euphytica* (Submitted).

Book Chapters:

1. Effertz, K.M., Clare, S.J., Harkins, S.M., and **Brueggeman, R.S.** (**2021**) Understanding plant-pathogen interactions in net blotch infection of cereals. In Oliver, R. (ed) Achieving durable resistance in cereals. Burleigh Dodds Science Publishing, UK (In Press)

Washington Grain Commission
Wheat and Barley Research Annual Progress Reports and Final Reports

Project #: **3019-3155**

Progress Report Year: 3 of 3

Title: **Weed Management in Wheat**

Researcher(s): Ian C. Burke and Drew J. Lyon

Executive summary: Weed control is one of the major challenges facing wheat growers in the PNW. To address this problem, the Weed Science Program conducts a multi-disciplinary field, greenhouse, and laboratory research project to address the critical issues that Washington wheat growers face. One aspect of this work is the evaluation of herbicides, both registered and nonregistered, for crop tolerance and weed control in wheat production systems. This work is often, but not always, conducted in partnership with agricultural chemical companies. These field studies allow us to make better recommendations to growers, and they provides us the opportunity to work with the various companies to better refine their labels for the benefit of Washington wheat growers. The results from these studies are summarized in the WSU Weed Control Report, which is shared with the Washington Grain Commission and posted on the WSU Extension Small Grains website annually. The Weed Science Program continues to look at the biology and ecology of troublesome weeds including downy brome, Russian-thistle, and mayweed chamomile.

Impact: The WSU Weed Science Program impacts wheat and barley production in Washington and the Pacific Northwest by producing timely, accurate, non-biased weed control and weed biology information. That information is most commonly extended to stakeholders in the form of presentations, extension publications, news releases, and the Internet (wsu.smallgrains.edu). In terms of value, herbicide inputs are typically among costliest a grower faces, and using the most economical and effective treatment will improve the net income and long term sustainability of any operation

- The project continues to generate data and local insights for various agrichemical companies to assist them in labeling their new herbicide products for weed control in wheat. We have been working with bicylopyrone, a new broadleaf herbicide from Syngenta, as well as new herbicides from Corteva, Bayer, FMC, and old herbicides from Albaugh and Gowan.
- A number of grower driven projects were continued in the new cycle, including management of rush skeletonweed and other troublesome weeds in fallow, management of scouringrushes in wheat, use of weed sensing sprayers in fallow, spring wheat preemergence herbicides for Italian ryegrass control, harvest weed seed control, and management of brome species with preemergence herbicides.
- Extending the outputs of the project was a challenge during the pandemic. Dr. Lyon continued to publish extension output in the form of webcasts and extension bulletins based on our research, and several presentations were created in active field trials. We look forward to resuming our active extension grower engagement in 2022.

WGC project number: 3019-3155
WGC project title: Weed Management in Wheat
Project PI(s): Ian C. Burke and Drew J. Lyon
Project initiation date: July 1, 2019
Project year: 3 of 3

Objective	Deliverable	Progress	Timeline	Communication
Evaluate herbicides	Efficacy and crop injury data to support use recommendations, new labels, and label changes to benefit WA small grain growers.	The WSU Weed Control Report was published annually and distributed to the Washington Grain Commission, County Extension Educators in eastern Washington, and sponsoring chemical companies. The published studies are posted on the WSU Extension smallgrains website and discussed at winter Extension meetings.	Annually, in time for winter meetings.	Annual weed control report; articles in Wheat Life, trade magazines and/or posted to WSU smallgrains website; field days; winter Extension meetings; decision support system tools. The Small Grains website now hosts an outlet for our efficacy results see https://herbicideefficacy.cahnrs.wsu.edu/
		A 5-year field study near Omak to look at how frequently Finesse and Amber herbicides must be used to maintain control of smooth scouringrush in winter wheat-fallow production systems was completed in 2021. Two 6-year field studies were initiated in 2019 in the intermediate rainfall zone (Edwall and Steptoe) to determine the same thing in winter wheat-spring wheat-fallow production systems. Studies were also initiated in 2019 and 2020 to look at the impact of various surfactants on the efficacy of glyphosate for smooth scouringrush control in fallow.	Results from the Omak study will be reported in Wheat Life and at various winter Extension meetings. Publication of the results in a scientific journal will have to wait until the completion in 2025 of the two 6-year studies from the intermediate rainfall zone. We will continue the glyphosate plus surfactant studies in 2022 with the expectation of submitting a manuscript for publication in 2023.	Annual weed control report, Wheat Life magazine, extension publications, extension meetings and field days, and refereed journal articles.
		Field studies were completed in 2020 near Lacrosse and Hay addressing control of rush skeletonweed in fallow. A manuscript describing this work has been accepted in Weed Technology and will be published in 2022. Field studies comparing various rates of picloram (Tordon 22K) applied broadcast or with a weed-sensing sprayer for the control of rush skeletonweed in fallow were initiated in 2019 and 2020 near Lacrosse and Hay. The subsequent winter wheat crop planted in the fall of 2021 will be harvested in 2022 to complete the study.	The picloram study should be completed after the 2022 wheat harvest. A manuscript will be submitted to a scientific journal in 2022 or 2023.	Annual weed control report, extension publications, extension meetings and field days, and refereed journal articles

		Multiple field studies were conducted in association with agrichemical companies to investigate efficacy and crop tolerance to a range of grass and broadleaf weed control products. These studies allow us to evaluate new chemistries or new uses of old chemistries and also help us modify company labels to better suit our region.	Field studies will be conducted every year during this project.	Annual weed control report, extension publications, extension meetings and field days, and refereed journal articles
		A WEED-It sensor sprayer system was acquired in the spring of 2018 using Camp Endowment funds, and multiple experiments were initiated to evaluate efficacy of various fallow herbicides using the sensor system.	Additional trials were installed in the spring of 2020. New trials will be designed based on the trial experiments to evaluate the sensor sprayer when used season long in fallow as well as in crop, and emphasize economics and use of alternate herbicide modes of action.	Annual weed control report, extension publications, extension meetings and field days, and refereed journal articles
		A field study was completed in 2021 to assess the efficacy of gibberelic acid on Italian Ryegrass germination and control in combination with Zidua, Fierce, and Fierce MTZ. Results indicated that gibberelic acid had no effect on Italian ryegrass control.	This project will be completed in the year of 2022.	Annual weed control report, extension publications, extension meetings and field days, and refereed journal articles
		A field study assessed Anthem Flex and Talinor alone and in combination for tumble mustard and mayweed chamomile control in winter wheat.	Field studies are completeThis project will be completed in the year of 2022.	Annual weed control report, extension publications, extension meetings and field days, and refereed journal articles
		Indaziflam was tested for preemergence control of Italian ryegrass in wheat cropping systems in 2020 and 2021. Results indicated that no additional control of IR was achieved via applications of Indaziflam in 2021. This was likely due to abnormal drought conditions for the region, which negatively impacted weed germination and establishment.	This project will be completed in the year of 2022.	Annual weed control report, extension publications, extension meetings and field days, and refereed journal articles

Evaluate weed biology & ecology	Weed biology and ecology to aid in the design of effective and economic control strategies for troublesome weeds in WA small grain crops; decision support system database development.	Common garden and greenhouse experiments using the downy brome PNW core collection have started to identify variation in flowering time. Flowering time genes strongly coordinate with vernalization genes to regulate when flowering occurs in downy brome. In previous work, vernalization regulated if flowering occured, but it was evident that, when place in different environments, flowering time was plastic.	A large downy brome panel was phenotyped for flowering time. Initial analyses indicate that flowering time is highly heritible, unlike growth or tillering. Highly heritable traits may facilitate ecological approaches to management of downy brome by field, and indicates that movement between fields should be minimized.	Annual weed control report, extension publications, extension meetings and field days, and refereed journal articles.
		We have identified a new and potentially troublesome pest in the inland Pacific Northwest. Discovered while conducting field trials near Asotin and Ewan, sterile brome does not appear to respond to postemergence herbicides. The weed has a very similar appearance to downy brome except while flowering, and thus is usually identified as downy brome.	We are preparing an identification guide for Bromus species and will produce an extension bulletin in spring 2021 - the pandemic derailed plans to produce a document in 2022.	Annual weed control report, extension publications, extension meetings and field days, and refereed journal articles.
Evaluate cultural & mechanical management	Data to support recommendations for integrated weed management systems to control troublesome weeds in WA small grains.	As part of our work to understand seed dormancy in downy brome, we have discovered that gibberillic acid can be used to stimulate germination in the field. Current work has focused on identification of the duration of the effect as well as on additional weed species that may respond to such an input. Recent greenhouse work indicates that soil temperature may play a role in the effect we have observed.	Field studies will be conducted every year during this project.	Annual weed control report, extension publications, extension meetings and field days, and refereed journal articles.
		A current greenhouse project is underway to assess the effects of temperature and GA applications on germination rates in annual grass weeds. The current studies are investigating how environmental conditions during and shortly after application of GA could impact germination rates of dormant annual grass seeds. Previous greenhouse studies have indicated that appliactions of GA have an effect on germination rates of annual grass weeds that were several years old. Environmental conditions such as light and temperature may play a role in the efficacy of GA on newly produced annual grass weed seed.	Field studies are complete, and greenhouse trials are in the final stage. This project will be completed in the year of 2022.	Annual weed control report, extension publications, extension meetings and field days, and refereed journal articles.

		We conducted field studies to ascertain seed shattering in Italian ryegrass by harvest time in winter and spring wheat. In 2020, we initiated a field study to evaluate chaff lining for the management of Italian ryegrass in winter wheat.	Italian ryegrass samples were collected in 2017 and 2018 in winter wheat and from spring wheat in 2019 and 2020. The samples have been evaluated for seed shatter and seed germination. A manuscript will be prepared for journal submission in 2022. Chaff lining experiments will be repeated in 2022.	Annual weed control report, extension publications, extension meetings and field days, and refereed journal articles.

Washington Grain Commission
Wheat and Barley Research Annual Progress Reports and Final Reports

Project #: 3193

Progress Report Year: *3 of* 3

Title: Field Breeding Hard White and Red Winter Wheat

Investigator/Cooperators**:** **AH Carter,** KG Campbell, XM Chen, TD Murray

Executive summary: Due to the price of hard red winter wheat being below that of soft white winter wheat, hard red production in the state has been decreasing. Because of this, we have not proposed for release any new hard red cultivars, but instead have let Scorpio begin to gain traction in the state. Scorpio was released in 2019 and commercial seed is available of this line. Scorpio is broadly adapted to many intermediate and high rainfall growing areas of the state, and have very good end-use quality, very good stripe rust resistance, is resistant to Hessian fly, and tolerant of low pH soils. Scorpio was also one of the best performing lines in 2021, indicating the ability to perform even under drought stress conditions. This combination of traits makes it a desirable cultivar for many production areas. We continue to work with seed dealers to make this cultivar available to growers. We will continue to watch the hard red market and in discussion with seed dealers and growers, determine when new cultivars need to be released to enter the market. We have several lines which have been performing well in trials and will continue to evaluate these for release potential. Continued emphasis is placed on selecting breeding lines with superior quality and disease resistance. We also have a strong interest in developing hard lines with excellent emergence capabilities, and continually screen material to this end. Efforts have been initiated and are ongoing to develop hard cultivars with herbicide tolerance (Clearfield and CoAXium systems are our main targets), snow mold tolerance, and aluminum tolerance. We maintain about 10% of the hard material as hard white and apply heavy selection pressure to ensure adapted material is advanced. Some of these hard white lines have been tested under irrigation in Southern Idaho and have performed very well. There is interest to release these lines for production under irrigation in Idaho.

Impact: Sequoia replaced many of the Farnum acres in the state due to its excellent emergence capability and high yield potential under low rainfall and deep planting conditions. Although grown on limited acres, we continue to develop lines with excellent emergence for those regions which need this trait to reduce risk to planting failures under deep planting conditions when moisture is limited. Scorpio is a recent WSU hard red cultivar targeted to high rainfall conditions and will provide growers with a high yielding line with good disease resistance, aluminum tolerance, and Hessian fly tolerance, adapted to PNW growing conditions. Current and future hard red and white lines will continue to lead to a sustainable production of hard wheat in the PNW.

WGC project number: 3193
WGC project title: Development of hard red and white winter wheat
Project PI(s): AH Carter
Project initiation date: July 1, 2009
Project year: 3 of 3

Objective	Deliverable	Progress	Timeline	Communication
Develop hard red and white winter wheat cultivars	New cultivars released for production in WA	In 2019 we released Scorpio, which combines high yield, good protein content, stripe rust resistance, low pH soil tolerance, and Hessian fly tolerance in one line. Seed of Scorpio is being increased by the seed industry and was available in 2021. The line Balance was released in 2020 for production in Montana, as this line shows high yield and very good protein content, and has low pH soil tolerance. Balance is also available to growers in Washington, but testing suggests Scorpio would be the better selection for Washington. No new hard red lines were released in 2021 given the decreased interest in hard red lines due to declining price. We had over 2,000 plots and 8,000 rows of hard material under evaluation at various stages of the breeding process for 2021. Some hard white winter lines have been submitted for testing in Southern Idaho and have had very good performance under irrigated conditions. These continue to be evaluated for release potential. Focus has also been on developing lines with herbicide tolerance.	Each year we evaluate germplasm at each stage of the breeding process. Each year lines are entered into statewide testing for final release consideration. A cultivar is released, on average, every two years.	Progress is reported through field days, grower meetings, commission reports, popular press, and peer-reviewed manuscripts, and through the annual progress reports
	Agronomic traits	Field trials and agronomic data was conducted and collected at 15 locations in 2021. This includes emergence, winter survivability, heading date, test weight, plant height, and grain yield. Our Kahlotus and Ritzville trials gave a very good screen for emergence potential in 2021. Our snow mold locations gave a good rating of snow mold tolerance. All other locations had very good stand establishment and we are looking forward to a good year of screening the germplasm.	Evaluation is done annually at multiple locations across the state.	In 2021 we communicated results of this project through the following venues: 21 peer-reviewed publications; 1 virtual field day recordings; 4 field day abstracts; various field days and grower interactions; 8 poster presentations; 1 popular press interviews; 1 podcasts; 2 grower meeting presentations; and 4 seed dealer presentations;
	Biotic and Abiotic stress resistance	Lines were screened for snow mold, stripe rust, eyespot foot rot, nematodes, Cephalosporium stripe, SBWMV, Hessian fly, and aluminum tolerance.	Evaluation is done annually at multiple locations across the state.	

	End-use quality	All breeding lines with acceptable agronomic performance in plots were submitted to the quality lab. Those with acceptable or better milling characteristics were advanced to baking trials. Data should be back in early-2022. Lines with inferior performance will be discarded from advancement. We screened nearly 500 early generation lines for end-use quality in 2021.	Each year, all head rows are evaluated for end-use quality and lines predicted to have superior quality advanced. Each yield trial is submitted for quality evaluations and those with high performance are advanced in the breeding process.	
	Herbicide resistance	Trials were conducted in Lind, Walla Walla, Prescott, and Pullman for herbicide resistance. The hard red material had a lower priority for development when we started compared to the soft white germplasm, but we now have multiple populations and advanced lines being tested. Crossing has been initiated to incorporate novel herbicide resistance into hard red lines.	Evaluation is done annually at multiple locations across the state	Advanced hard red lines with herbicide tolerance are in final stages of testing for release consideration.
Field test adapted germplasm with novel genes introgressed for essential traits	Incorporation of novel genes into adapter germplasm for evaluation under WA environments			Progress is reported through field days, grower meetings, commission reports, popular press, and peer-reviewed manuscripts, and through the annual progress reports
	Rht genes	Populations have been developed and are under field evaluation for Rht1, 2, and 8.	Crosses made through the project #5195 will be evaluated under field conditions upon MAS.	
	Stripe rust genes	Multiple different stripe rust resistance genes have been introgressed into our germplasm which are under evaluation in Mount Vernon, Central Ferry, and Pullman. We have also started mapping populations to find markers linked to these genes.	Crosses made through the project #5195 will be evaluated under field conditions upon MAS.	
	Foot rot genes	Pch1 has been selected for and is under evaluation in field trials in Pullman.	Crosses made through the project #5195 will be evaluated under field conditions upon MAS.	
	SBWMV	Crosses are initiated and being evaluated for resistance to SBWMV, mainly first through marker analysis and then under field trials in Walla Walla.	Crosses made through the project #5195 will be evaluated under field conditions upon MAS.	
	Herbicide tolerance	Hard red lines with herbicide tolerance are being developed in both the Clearfield and CoAXium systems. Populations are first screened in the greenhouse, then transitioned to field testing.	Crosses made through the project #5195 will be evaluated under field conditions upon MAS.	

	Hessian fly tolerance	With the identification that Scorpio was tolerant to Hessian fly, we have been able to go into our crossing block and find crosses and populations with Scorpio as a parent to begin making selection. These lines will be screened at the University of Idaho as part of the Hessian fly proposal. One additional line, WA8368, has been identified as having Hessian Fly tolerance.	Crosses made through the project #5195 will be evaluated under field conditions upon MAS. Screening will be done through project #3674	
	GPC-B1 and Bx7oe	These two genes have been incorporated into many hard breeding lines. These are being tested for agronomic performance in the field. Some lines have already been returned to the breeding program as parents for additional crosses.	Crosses made through the project #5195 will be evaluated under field conditions upon MAS.	

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Project #: 5195

Progress Report Year: *1 of 3*

Title: Use of biotechnology for wheat improvement

Investigator/Cooperators: **AH Carter,** KG Campbell, M Pumphrey, D See

Executive summary: In 2021 we continued our effort to advance breeding lines as quickly and efficiently as possibly by employing both molecular marker analysis and doubled-haploid technology. The traits of focus for marker-assisted selection are foot rot resistance, stripe rust resistance, herbicide tolerance, and end-use quality. All these traits are already in established breeding lines and have very good markers to track them. Additional traits include aluminum tolerance, SBWMV, dwarfing genes, low PPO, Fusarium head blight, Hessian fly, and nematode resistance. While we have established some breeding lines with these traits, we are working to increase the number of lines carrying these traits, using markers to track their presence. Thousands of data points were collected on multiple populations to confirm presence of traits of interest. All lines which go through marker testing are then transferred to field testing to confirm the expected phenotype is expressing. Markers were also used to screen all advanced breeding lines to identify presence of known genes. This information, along with field data, was used for selection and advancement purposes as well as for selecting lines which should be cross-hybridized to create future populations. Our genomic selection efforts are proceeding and we have completed our sixth year of phenotypic evaluations in the field and genotyping. Data is being used to validate selection models for multiple traits through the efforts of graduate students funded on various other competitive grant funding. Results have identified the best models to use for specific traits, as well as how to build multi-trait models. In the greenhouse, we made approximately 650 crosses consisting mainly of soft white and hard red germplasm. In 2020 we started a large crossing block to incorporate new traits of interest, mainly herbicide resistance and pest resistance traits. These lines have been advanced in the breeding program, with some of them returning to the crossing block for back-crossing. We planted ~2,000 DH plants in the field in 2021 for evaluation. Our screening process continues to be adjusted to improve efficiency as new techniques and traits come into the program for screening.

Impact: This project covers all market classes and rainfall zones in the state of Washington, with about 70% of the effort on soft white crosses. This work will improve end-use quality, genetic resistance to abiotic and biotic stress, and agronomic adaptability and stability of released cultivars. All cultivars released (Otto, Puma, Jasper, Sequoia, Devote, Stingray CL+, Scorpio, Purl, Piranha CL+, Sockeye CL+) have benefited through this project by incorporation of disease, herbicide resistance, and end-use quality genes. Released lines have gained popularity and are growing in demand due to the gene combinations they were selected for. The breeding program has become more efficient in the selection process, and more focus is placed on field evaluations since known genes are already confirmed to be present in the breeding lines. Continued success will be measured by increases in acreage of these lines as well as enhanced cultivar release through DH production, marker-assisted, and genomic selection.

WGC project number: 5195
WGC project title: Use of biotechnology for wheat improvement
Project PI(s): AH Carter
Project initiation date: July 1, 2009
Project year: 1 of 3

Objective	Deliverable	Progress	Timeline	Communication
Marker-assisted selection				Results are presented through annual progress reports, the research review, field tours, and grower meetings
	Foot rot resistant lines	In 2021, all lines under field testing were screened for both Pch1 and Pch2 markers. This information was used to assist selection of lines for further testing under the field program. As more lines are selected for advancement and recycled in the breeding program for new cross-hybridizations, fewer populations will be segregating for this trait.	Each year new crosses are made to Pch1 and Pch2 containing lines. These are subsequently developed, screened, and advanced to state-wide yield trials. At any given time, lines are in every stage of development	In 2021 we communicated results of this project through the following venues: 21 peer-reviewed publications; 1 virtual field day recordings; 4 field day abstracts; various field days and grower interactions; 8 poster presentations; 1 popular press interviews; 1 podcasts; 2 grower meeting presentations; and 4 seed dealer presentations;
	Stripe rust resistant lines	In 2021, all lines under field testing were screened for six stripe rust resistance markers to identify presence of genes useful in the PNW. New populations segregating for resistance to Yr5 and Yr15 were screened and selected for advancement.	Each year new crosses are made to stripe rust resistant lines. These are subsequently developed, screened, and advanced to state-wide yield trials. At any given time, lines are in every stage of development	
	End-use quality lines	In 2021, populations that were selected for combinations of the GBSS genes (waxy) and the glutenin genes were selected in field testing. All breeding lines are screened for the presence of low PPO genes, and populations were advanced of lines containing none of the PPO genes to field testing.	Each year new crosses are made to lines containing unique end-use quality genes. These are subsequently developed, screened, and advanced to state-wide yield trials. At any given time, lines are in every stage of development	
	Reduced height lines	In 2021, all breeding lines in field trials were screened to identify which dwarfing gene they carry in order to aid in selection and crossing decisions. Selection is then made on which genes are present rather than incorporating new genes as they already exist in our breeding program. All lines are field tested for emergence potential.	Each year, we verify presence of dwarfing genes in all material to assist with selection of lines with enhanced emergence potential.	

	Genomic selection	With the assistance of graduate students, we continue to build genomic prediction models for traits of interest. Lines from the 2015-2021 breeding program have been genotyped and used for model building. We have begun incorporating high-throughput phenotyping measurements in these selection models, which has improved selection accuracy and efficiency.	Each year we will continue to phenotype the training panel, add more lines to the training panel (and genotype them), and refine the prediction model. Validation of results is proceeding.	Results are presented through annual progress reports, the research review, field tours, and grower meetings. Eight manuscripts have been published on this research.
Genotyping advanced breeding lines	Provide useful information regarding genetic diversity and gene profiles to better estimate crossing potential	In 2021, the advanced germplasm was screened with DNA markers for about 25 markers of interest. This information was used to enhance selection of field tested material, as well as assist in parent cross-combinations to develop populations with desired traits of interest.	This is done annually	Results are presented through annual progress reports, with the outcomes of this research being realized in new cultivars
Greenhouse				Results are presented through annual progress reports, with the outcomes of this research being realized in new cultivars
	Hybridization and propagation	In 2021 we made approximately 750 crosses which were targeted for herbicide resistance, low rainfall and high rainfall production. About 80% of these are in soft white backgrounds, and the remaining in hard red backgrounds. Crosses were advanced to the F2 stage. We also made about 100 crosses for trait introgression to continue to build germplasm for traits which are important to PNW growers.	This is done annually, with the number of crosses/populations varying	
	Single-seed descent	In 2020 we began developing more SSD populations to better standardize the production of lines from our crossing program. We are fine-tuning the protocols to maximize the number of lines which can be tested, and are looking forward to seeing how this new process assists the breeding program.	This is done annually, with the number of crosses/populations varying	
	Doubled haploid	In 2021 our DH production focused on increasing seed quantities of 2020 produced lines. The goal is to have all lines produced go into 4-row observation trials at both Pullman and Lind.	This is done annually, with the number of crosses/populations varying	

	Trait Introgression	We made crosses to germplasm containing resistance/tolerance to snow mold, stripe rust, end use quality, foot rot resistance, preharvest sprouting, Al tolerance, Ceph Stripe, SBWMV, vernalization duration, low PPO, Fusarium head blight, imazamox, the CoAxium system, and other herbicides (in coordination with Dr. Burke). Herbicide tolerant lines are screened in the greenhouse for tolerance, as well as with markers, before going into field trials. We now have markers for many of these traits, and can efficiently screen for their presence. After advancement, all populations are transferred to the field program to undergo further testing.	This is done annually, with the number of crosses/populations varying	
Trait assessment				Results are presented through annual progress reports, with the outcomes of this research being realized in new cultivars
	Coleoptile length	Lines are screened and selected for coleoptile length.	Screening and selection will continue in 2022. Superior lines were planted in the field and crossed back into the breeding program.	
	Herbicide Tolerance	We now have a strong pipeline of germplasm tolerant to imazamox, and continue to develop and screen populations. We have many soft white lines using the CoAXium system under field evaluation, and continue to make crosses for this trait. We have expanded to select for both hard and soft germplasm, and work with all three tolerance genes. In collaboration with Dr. Burke, we have new sources of herbicide tolerance which are being tested under both greenhouse and field conditions for tolerance.	Screening and selection will continue in 2022. Superior lines were planted in the field and crossed back into the breeding program.	
	Cold Tolerance	All advanced breeding lines are screened for cold tolerance through the USDA funded WGC grant.	Screening and selection will continue in 2022. Superior lines were planted in the field and crossed back into the breeding program.	

	Stripe rust	Because many sources of resistance in our germplasm are uncharacterized, we have begun developing genomic selection models to use for selection in our breeding populations. We have started the development of more populations to identify more of the genes which are contributing to resistance in our germplasm. These are being advanced in the greenhouse to create recombinant inbred lines.	Screening and selection will continue in 2022 after limited 2021 screening due to limited disease pressure. Superior lines were planted in the field and crossed back into the breeding program.	

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Washington Grain Commission
Wheat and Barley Research Annual Progress Reports and Final Reports

Project #: 6195

Progress Report Year: *1 of* 3

Title: Field Breeding Soft White Winter Wheat

Investigator/Cooperators**:** **AH Carter,** KG Campbell, XM Chen, TD Murray

Executive summary: The year 2021 provided many opportunities in the program to evaluate materials under both severe drought and high temperature conditions. Coming off 2020 which had some of the best growing conditions, it was quite the extreme shift. The advantage of these contrasting years allowed us to view material under very different climatic conditions and identify varieties that could perform well under both conditions. There were many lines in the program that were able to perform well even under the drought conditions and were advanced in the breeding program. Several of these lines were also prepared for Breeder seed production in Othello. Lines with the Axigen trait used in the CoAXium system were further evaluated in 2021 and lines with release potential were advanced to seed production. These will undergo their last year of qualification testing in 2022 and will be proposed for approval to be used in the CoAXium system. We hope to be able to release a number of these lines, that have fit in all the production regions in Washington. We also continue to work with novel herbicide resistance traits to bring new options for weed management into production. The breeding programs continues to maintain a high number of lines within testing at all levels of the program. Double haploid lines are continuing to be produced, along with lines produced under single-seed descent, which is less technically intensive. We continue to have multiple locations where yield testing occurs, along with numerous sites dedicated to testing stress resistance such as snow mold, stripe rust, and low pH soils. Planting into dry conditions in 2021 allowed for extreme pressure on emergence, and screening continues to identify lines with excellent emergence potential. In 2021, no new lines were proposed for release. Many of the lines released in 2019 and 2020 continue to have strong demand for commercial planting, and we continue to work with seed dealers to get these cultivars into the hands of growers. These recent releases all have high grain yield, good disease resistance, and good end-use quality. We anticipate additional releases in 2022 of lines which continue to fit into multiple cropping systems in Washington.

Impact: Traditionally, over 85% of the wheat crop in Washington is soft white wheat. Even very small reductions of required grower input and/or increases in productivity can mean millions of dollars to the growers, grain trade, and allied industries. By providing genetic resistance to diseases and increasing agronomic adaptability, input costs will be reduced and grain yield increased. WSU soft white cultivars are grown on approximately 40% of the acres. These include Bruehl, Eltan, Xerpha, Otto, Puma, Jasper, Purl, Curiosity CL+, Mela CL+, and Resilience CL+. Measured impact is demonstrated with performance of past cultivars, upcoming production of recent cultivars (Pritchett, ARS-Castella, Stingray CL+, Devote) and strong interest in new cultivars (Piranha CL+ and Sockeye CL+).

WGC project number: 6195
WGC project title: Field Breeding Soft White Winter Wheat
Project PI(s): AH Carter
Project initiation date: July 1, 2009
Project year: 1 of 3

Objective	Deliverable	Progress	Timeline	Communication
Develop soft white winter wheat cultivars	New cultivars released for production in WA	We released the soft white lines Otto, Jasper, Puma, Purl, Stingray CL+, Devote, Piranha CL+, and Sockeye CL+. Collaborative releases include Curiosity CL+, Mela CL+, Resilience CL+, Pritchett, ARS-Castella, and ARS-Cameo. All lines are being commercially produced or are in seed increase for commercial production. We have multiple breeding lines in statewide testing for consideration of release, many of which had excellent performance in 2020 and 2021. We have over 18,000 plots and 15,000 rows of soft white material under evaluation at various stages of the breeding process.	Each year we evaluate germplasm at each stage of the breeding process. Each year lines are entered into statewide testing for final release consideration. A cultivar is released, on average, every two years.	Progress will be reported through field days, grower meetings, commission reports, annual progress reports, and peer-reviewed manuscripts
	Agronomic traits	We have 18 locations across the state representing diverse climatic zones in which advanced breeding lines are evaluated for agronomic characteristics. Early generation material is selected for in Lind and Pullman. This year we moved all DH production to initial 4-row selections due to the ability to screen for important traits such as emergence and stripe rust, along with our snow mold screening in Waterville.	Evaluation is done annually at multiple locations across the state.	In 2021 we communicated results of this project through the following venues: 21 peer-reviewed publications; 1 virtual field day recordings; 4 field day abstracts; various field days and grower interactions; 8 poster presentations; 1 popular press interviews; 1 podcasts; 2 grower meeting presentations; and 4 seed dealer presentations;
	Disease resistance	Disease resistance is recorded on our 18 breeding locations as disease is present, with certain locations being selected specifically for disease pressure (Waterville for snow mold, Pullman for stripe rust, etc.). Additional locations are planted in cooperation with plant pathologists to screen other diseases of importance in WA.	Evaluation is done annually at multiple locations across the state.	

	End-use quality	All F4/DH and greater material is subjected to end-use quality screens to evaluate performance. Lines with poor quality are discarded from the breeding program and from selection in 2021.	Each year, all head rows are evaluated for end-use quality and lines predicted to have superior quality advanced. Each yield trial is submitted for quality evaluations and those with high performance are advanced in the breeding process.	
	Herbicide resistance	Multiple soft white lines have been developed for herbicide resistance and are being evaluated under replicated trials across the state. We have multiple Clearfield lines, advanced lines in testing for the CoAXium system, and novel traits are being incorporated into germplasm and field tested through collaboration with Dr. Ian Burke.	Evaluation is done annually at multiple locations across the state.	
Introgress novel genes for essential traits	Incorporation of novel genes into adapted germplasm for evaluation under WA environments			Progress will be reported through field days, grower meetings, commission reports, annual progress reports, and peer-reviewed manuscripts
	Rht and photoperiod genes	Crosses have been made to include non-traditional Rht and photoperiod genes into our soft white winter wheat germplasm for testing under PNW conditions.	Crosses made through the project #5195 will be evaluated under field conditions upon MAS.	
	Stripe rust genes	We constantly have material coming out of the MAS program for stripe rust. In 2021 we evaluated multiple populations in both early and preliminary yield trials, but there was limited disease pressure. Material includes new genes identified from Eltan, Coda, and novel genes from GWAS analysis.	Crosses made through the project #5195 will be evaluated under field conditions upon MAS.	
	Foot rot genes	We have many populations being screened for foot rot resistance. Both Phc1 and Pch2 are being evaluated. Field evaluations of these selections are done in collaboration with Dr. Campbell.	Crosses made through the project #5195 will be evaluated under field conditions upon MAS.	
	Cephalosporium	No markers are currently being used for this introgression. All selection is being done under field conditions. We recently made many crosses to resistant material and are now field screening them for selection of resistant material.	Evaluation were done in field locations in WA in 2021	
	Aluminum tolerance	Field screening of breeding lines for aluminum tolerance is being conducted under field conditions. We recently made many crosses with material that was aluminum tolerant. Screening of this material will be completed in 2021.	Evaluation were done in field locations in WA in 2021	

	Hessian Fly	In collaboration with Dr. Arash Rashed we screened 12 F2 populations with new sources of resistance to Hessian Fly. Resistant plants were returned to the breeding program for further crossing and segregating populations are currently being screened again for resistance. Selected lines were planted for field evaluations in 2021. Many lines were selected for good agronomic performance and are being further evaluated.	Additional populations were developed in 2021. Current populations were be field evaluated in 2021.	
	Nematodes	Nematode screening has been done in collaboration with Dr. Paulitz and Dr. Campbell.	Lines with resistance continue to be advanced in the breeding program.	
	End-use quality	Lines are continually screened for end-use quality. We submitted an additional 10 lines for statewide testing to begin generating quality scores prior to release decisions.	Validated genomic prediction models were available for selection in 2021.	

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Washington Grain Commission
Wheat and Barley Research Annual Progress Report

Project #: 3144

Progress Report Year: 3 of 3 (2021)

Title: Improving Control of Rusts of Wheat and Barley

Cooperators: K. Garland Campbell, A. Carter, M. Pumphrey, & D. See

Executive summary: During 2021, studies were conducted according to the objectives of the project proposal, and all objectives specified for the third year were completed on time. In addition to the major accomplishments and their impacts listed below, this project results in genetic resources and techniques for further studying the biology and genetics of the pathogens, stripe rust resistance, and mechanisms of interactions between the pathogens and plants.

Impact: 1) Stripe rust was forecasted and monitored throughout the 2021 crop season, and rust updates and advises were provided on time to growers. In March, stripe rust was forecast at a low level and the disease occurred at the lowest level in the past 30 years. The recommendations prevented unnecessary use of fungicides, saving growers multimillion dollars. 2) We identified 18 races of the wheat stripe rust pathogen and 9 (including 1 new) races of the barley stripe rust pathogen from 301 samples throughout the U.S., of which 14 (78%) races of the wheat stripe rust pathogen and 6 (67%) races of the barley stripe rust pathogen were identified from 159 (53%) samples collected in Washington. The race information is useful in screening breeding lines and germplasm for developing stripe rust resistant varieties. 3) We completed the study of molecular characterization of the U.S. stripe rust collections from 2010 to 2017 using 14 SSR markers. From 2,414 isolates, we identified 1,599 multi-locus genotypes (MLGs) and studied the genetic diversity and population differentiation. The results improve the understanding of stripe rust epidemiology and spore movement among different regions in the U.S. 4) We evaluated more than 20,000 wheat and barley entries for resistance to stripe rust. From the tests, we identified new sources of resistance and resistant breeding lines for breeding programs to release new varieties for growers to grow. In 2021, we collaborated with public breeders in releasing, pre-releasing, or registered 14 wheat varieties. The germplasm evaluation data were also used to update the Seed-Buying Guide for growers to choose resistant varieties to grow. 5) We completed a study of identifying a gene for durable high-temperature adult-plant (HTAP) resistance in a wheat near-isogenic line (NIL) for all-stage resistance gene *Yr17* originally from wild grass *Aegilops ventricosa* through ethyl methanesulfonate (EMS) mutagenesis, which separated the HTAP resistance from the *Yr17* resistance. Through phenotyping and genotyping a mapping population, we identified a gene for HTAP resistance and mapped it to the translocated part of chromosome from *Ae. ventricosa*, with the location similar to *Yr17*. This sources of both all-stage resistance gene *Yr17* and the HTAP resistance gene has been widely used in the Pacific Northwest and other regions of the U.S. This study shows the usefulness of the wheat varieties carrying the *Ae. ventricosa* translocation and the importance of combining all-stage resistance with HTAP resistance in developing wheat varieties with durable resistance. 6) In 2021, we published 29 journal articles and 5 meeting abstracts.

Outputs and Outcomes:

WGC project number: 3144				
WGC project title: Improving Control of Rusts of Wheat and Barley				
Project PI(s): Xianming Chen				
Project initiation date: 7/1/2019				
Project year: 3 of 3 (2021)				
Objective	**Deliverable**	**Progress**	**Timeline**	**Communication**
1. Improve the understanding of rust disease epidemiology and the pathogen populations.	**1) New races. 2) Information on distribution, frequency, and changes of all races, and possible fungicide tolerant strains. 3) New tools such as molecular markers and population structures.** The information will be used by breeding programs to choose effective resistance genes for developing new varieties with adequate and durable resistance. We will use the information to select a set of races for screening wheat and barley germplasm and breeding lines. The information is also used for disease management based on races in different regions.	All planned studies for the project in 2021 have been completed on time. There is not any delay, failure, or problem in studies to this objective. The race identification for the 2020 collection was completed and summarized. The data and summary were sent to growers, collaborators and related scientists in March 2021. In the 2021 crop season, we collected and received 301 stripe rust samples throughout the country, of which 159 samples (53%) were collected by ourselves from Washington. We have completed the race ID work for the 2020 samples and detected 18 races of the wheat stripe rust pathogen and 9 races of the barley stripe rust pathogen (including 1 new race), of which all 14 (78%) wheat and 6 (67%, including the new race) barley stripe rust races were detected in Washington. The distribution and frequency of each race and virulence factors in WA and the whole country have been determined. Predominant races have been identified. The information on races and virulence factors is used to guide breeding programs for using effective resistance genes in developing resistant varieties and selected predominant races with different virulence patterns are used in screening for breeding lines of wheat and barley with stripe rust resistance. We have completed the study on molecular charcaterization of the US stripe rust collections from 2010 to 2017 using 14 SSR markers. From 2,414 isolates, we identified 1,599 multi-locus genotypes (MLGs) and studied the genetic diversity and population differentiation. The results improve the understanding of stripe rust epidemiology and spore movement among different regions in the U.S. Using the same set of markers, we have been genotyping the 2018 - 2021 collections. Using the polymorphic simple sequence polymorphisms (SNPs) in the sequences of secreted protein genes associated to virulence genes, we are developing virulence-specific KASP markers for monitoring race changes in the pathogen population. The virulence and molecular studies have improved the understanding the epidemiology, biology and genetics of the pathogen, and provided information and resources for more efficiently monitoring and managing stripe rusts on wheat and barley.	The race identification work for the 2020 stripe rust samples was completed, summarized, and distributed. The race identification work for the 2021 samples has been completed, and the data are being analyzed and summarized. Molecular work for the population genetic studies has been completed and published up to the 2017 collection, completed for the 2018 collection, and is being conducted for the 2019-2021 collections. Preliminary results have been obtained for the development of Kompetitive (KASP) markers for monitoring virulence genes in the rust populations.	The rust race data were communicated to growers and researchers through e-mails, websites, project reports, meeting presentations and publications in scientific journals (for detailed information, see the lists in the main report file).

2. Improve rust resistance in wheat and barley varieties.	**1) Stripe rust reaction data of wheat and barley germplasm and breeding lines. 2) Reactions to other diseases when occur. 3) New resistance genes with their genetic information and molecular markers. 4) New germplasm with improved traits. 5) New varieties for production.** The genetic resources and techniques will be used by breeding programs for developing varieties with diverse genes for stripe rust resistance, which will make the stripe rust control more effective, efficient, and sustainable.	In 2021, we evaluated more than 20,000 wheat, barley, and triticale entries for resistance to stripe rust. The entries included germplasm, breeding lines, rust monitoring nurseries, and genetic populations from various breeding and extension programs. All nurseries were planted at both Pullman and Mt. Vernon locations. Some of the nurseries were also tested in Walla Walla and Lind, WA. Germplasm and breeding lines in the variety trial and regional nurseries also were tested in the greenhouse with selected races of stripe rust for further characterization of resistance. Due to the extremely dry and hot weather conditions, there were no adequte stripe rust in the eastern WA locations although the Pullman sites were inoculated twice. The Mount Vernon site in western WA had severe stripe rust and produced excellent data. The disease data of regional nurseries were provided to all breeding and extension programs, while the data of individual programs' nurseries were provided to the individual breeders. Through these tests, susceptible breeding lines can be eliminated, which should prevent risk of releasing susceptible cultivars and assisted breeding programs to release new cultivars of high yield and quality, good adaptation, and effective disease resistance. In 2021, we collaborated with public breeding programs in releasing and registered 14 wheat varieties. Varieties developed by private breeding programs were also resulted from our germplasm screening program. Through our evaluation, we have established a collection of wheat germplasm with stripe rust resistance, which are valuable sources of stripe rust resistance for further characterization of resistance, identified new effective resistance genes, and for development of wheat varieties with effective resistance. Through our intensive testing, varieties with durable resistance to stripe rust have been developed. In 2021, we completed a study of identifying a gene for durable high-temperature adult-plant (HTAP) resistance in a wheat near-isogenic line (NIL) for all-stage resistance gene *Yr17* originally from wild grass *Aegilops ventricosa* through ethyl methanesulfonate (EMS) mutagenesis, which separated the HTAP resistance from the *Yr17* resistance. Through phenotyping and genotyping a mapping population, we identified a gene for HTAP resistance and mapped it to the translocated part of chromosome from *Ae. ventricosa* , with the location similar to *Yr17* . This study shows the usefulness of the wheat varieties carrying the *Ae. ventricosa* translocation and the importance of combining all-stage resistance with HTAP resistance in developing wheat varieties with durable resistance. In 2021, we completed the phenotyping and genotyping experiments of three whole-genome associate studies (GWAS) including more than 1,300 wheat germplasm lines and are analyzing the data. In 2021, we obtained good stripe rust phenotypic data of 3 bi-parental mapping populations at the Mount Vernon location to validate resistance loci previously identified through the bulked analysis of 40 crosses. We selected new wheat germplasm lines with single new genes or combinations of genes for resistance to stripe rust to make them available for breeding programs and provided seeds to several breeding programs in the United States.	All 2021 germplasm tests were completed, and the data were provided to collaborators on time, although the Pullman sites did not have good rust data due to the drought and hot weather conditions. The 2022 winter wheat nurseries were planted in fields in September and October, 2021. The 2022 spring crop nurseries will be planted in March-April, 2022. We have added the Central Ferry location for the field germplasm screening as the site has the irrigation system. The greenhouse tests of the 2021 spring nurseries and the 2022 winter wheat nurseries have been conducted during this winter, and will be completed by May 2022. All experiments of the molecular mapping studies scheduled for 2021 have been completed. Mapping populations of winter wheat were planted in fields in October, 2021 and those of spring wheat will be planted in April, 2022 for stripe rust phenotype data.	The data of variety trials and regional nurseries were sent to growers and collaborators through e-mails and websites. Summary information of varieties were sent to growers and collaborators through rust updates and recommendations through e-mails, websites, Seed-Buying Guide, and variety release documents. Test data of individual breeding programs were sent to the individual breeders. New genes and molecular markers were reported in scientific meetings and published in scientific journals (see the publication and presentation lists in the report main file).

3. Improve the integrated management of rust diseases.	**1) Data of fungicide efficacy, dosage, and timing of application for control stripe rust. 2) Potential new fungicides. 3) Stripe rust yield loss and fungicide increase data for major commercial varieties. 4) Stripe rust forecasts and updates. 5) Guidance for rust management.** The information is used for developing more effective integrated control program based on individual varieties. Disease updates and recommendations will allow growers to implement appropriate control.	In 2021, stripe rust was forecasted and monitored throughout the 2021 crop season, and rust updates and advises were provided on time to growers. Low stripe rust was forecasted in March and the occurred level was the lowest for the last 30 years due to the extreme dry and hot weather conditions. The recommendations prevented unnecessary use of fungicides, saving growers multimillion dollars. In 2021, we planted field nurseries at Pullman, WA for evaluating 15 fungicide treatments on winter wheat and spring wheat, and 23 winter and 23 spring wheat varieties, plus a non-treated check in each nursery. Due to the dry and hot weather conditions, there was no significant differences in rust severity and no significant difference in grain test weight among the treatments including the non-treated check in the winter wheat fungicide testing nursery, but 10 of the fungicide treatments produced significantly higher grain yields (14-21%) than the non-treated check. However, none of the fungicide treatments in the spring nursery produced higher grain yield than the non-treated check. Similarly, no significant differences in both grain yield and test weight were observed between the fungicide applied and non-applied plots of all 24 winter and 24 spring wheat varieties.	For this objective, all tests scheduled for 2021 were conducted, although the fungicide and variety nurseries did not have adequate rust. For the 2021-22 growing season, the winter wheat plots of the fungicide and variety yield loss studies were planted in October 2021, and the spring plots will be planted in April 2022. The tests will be completed in August (for winter wheat) and September (for spring wheat), 2022.	The results were communicated to growers and collaborators through e-mails, project reports and reviews, and published in scientific journals.

Publications:

Scientific Journals:

Carter, A. H., Balow, K. A., Shelton, G. B., Burke, A. B., Hagemeyer, K. E., Stowe, A., Worapong, J., Higginbotham, R. W., Chen, X. M., Engle, D. A., Murray, T. D., and Morris, C. F. 2021. Registration of 'Devote' soft white winter wheat. Journal of Plant Registrations 15(1):121–131. https://doi.org/10.1002/plr2.20079.

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Popular Press Articles:

January 7, 2021. 2021 First Stripe Rust Forecast and 2020 Variety Yield Loss and Fungicide Tests. Xianming Chen, E-mail sent to cereal group. https://striperust.wsu.edu/2021/01/12/2021-first-stripe-rust-forecast-and-2020-variety-yield-loss-and-fungicide-tests-january-7-2021/

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Presentations and Reports:

In 2021, Xianming Chen and associates presented invited talks at the following regional, national, and international meetings:

“Races of *Puccinia striiformis* f. sp. *tritici* and stripe rust resistance relevant to the hard red winter wheat region” for the Plenary Session of Stripe Rust at 2021 Hard Winter Wheat Rust Symposium, April 6, 2021, Oral presentation (Virtual meeting).

“Recent Progress in Stripe Rust Research” at Hermiston Irrigated Cereal Field Day, June 14, 2021, Oral presentation (Virtual meeting).

Attended the American Phytopathological Society (APS) Pacific Division Annual Meeting (Virtual) and presented "Molecular characterization of international collections of wheat stripe rust pathogen *Puccinia striiformis* f. sp. *tritici*" (Authors: Qing Bai, Anmin Wan, Meinan Wang, Deven See, and Xianming Chen), Student oral presentation, June 16-18, 2021 (Virtual meeting).

Attended the APS Plant Health 2021 annual meeting (virtual) and presented 1) "Stripe rust epidemics of wheat and barley and races of *Puccinia striiformis* identified in the United States in 2020" (Authors: Meinan Wang and Xianming Chen), poster presentation; 2) "Population diversity, differentiation, and dynamics of barley stripe rust pathogen *Puccinia striiformis* f. sp. *hordei* in comparison with wheat stripe rust pathogen *P. striiformis* f. sp. *tritici* in the United States" (Authors: Qing Bai, Anmin Wan, Meinan Wang, Deven See, and Xianming Chen), Qing Bai oral presentation, August 1-4, 2021 (Virtual meeting).

Attended the Global Plant Health Assessment Workshop and presented an invited talk "Wheat Health Assessment", October 4-8, 2021 (Toulouse France & Virtual).

Attended the Borlaug Global Rust Initiative (BGRI) 2021 Technique Workshop and presented poster "Identification of High-temperature Adult-plant (HTAP) Resistance to Stripe Rust through Developing EMS Mutants from the *Yr17* Near Isogenic Line and Molecular Mapping of the HTAP Resistance Gene to the *Aegilops ventricosa* Translocation Chromosomal Region". October 6-8, 2021 (Virtual).

Reports:

Report of race summaries of the 2020 stripe rust collection in the US. March 2021. https://striperust.wsu.edu/races/data/

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Chen, X. M., Evans, K. C, Wang, M. N., Sprott, J., Bai, Q., Liu, L., Li, Y. X., Mu, J. M., and Kudsk, A. M. 2021. Cereal Rust Management and Research in 2020. Page 22 in: 2021 Field Day Abstracts: Highlights of Research Progress, https://s3.us-west-2.amazonaws.com/css.wsu.edu/wp-content/uploads/2021/06/10071231/FDA-2021.pdf

Washington Grain Commission
Wheat and Barley Research Annual Progress Reports and Final Reports

PROJECT #: 30109-3156

Progress report year: 3 of 3 Final report for current project

Title: Club wheat Breeding

Researcher(s): **Kimberly Garland Campbell, Arron Carter**
Cooperator: **Mike Pumphrey**

Executive summary:

The acres of the club wheat cultivar ‘Pritchett’ increased from 15,183 acres in 2020 to 49,934 in 2021. ‘Castella’ club wheat was available as registered seed in fall of 2020 and occupied 13,873 acres in 2021. Other club wheat cultivars included ‘ARS Crescent’ (23,330 acres), ‘Bruehl ‘(15,104 acres), and ‘Coda’ (600 acres). A small amount of ‘Cara’ was grown in Idaho. The spring clubs ‘Melba’ (7306 acres) and ‘JD’ (3077 acres) rounded out the total club wheat which amounted to 105,224 acres, which was slightly reduced from total 2020 acreage (119,124). However, the winter club acreage in 2021 was increased significantly from 77,999 acres in 2020. Since spring wheat production was devastated by the drought in 2021, the winter club increase sustained the club wheat market. There is currently a shortage of club wheat grain, and the premium is high. White club bids were between $10.20 and $13.75 with an average of $12.12 in Portland on Jan 7, 2022 as compared to soft white wheat (maximum 10.5% protein) bids averaging $10.69. This approximately $1.50 premium is on the high side for sustainability for club wheat purchases. When the premiums are high, the markets shift to other classes. Unfortunately, the poor crop season and sowing conditions in 2021 also resulted in a shortage of club wheat seed for the future.

Our major goal is to develop club wheat cultivars with the excellent club wheat end use quality that is expected by markets in Asia, and with competitive crop performance. To that end, we released ‘Cameo’ in Feb. 2021. Although the main club wheat production region is central Washington in the < 15-inch rainfall zone, growers in the higher rainfall regions continue to grow the very old club wheat cultivars ‘Cara’ and ‘Coda’. The spring club wheat cultivars ‘J.D.’ and ‘Melba’ are also popular. While spring club wheat will continue to be an important tool in rotations, there was a need for a new winter club targeted the Palouse region of Idaho, Oregon and Washington. As compared to other club wheat cultivars grown in the high rainfall region, Cameo has better agronomic performance than other clubs in trials on the Palouse, better stripe rust resistance than ARS Crescent, and tolerance to eyespot, soilborne wheat mosaic virus, acid soils and Hessian fly. Cameo has consistent high test weight, mid-season maturity, moderate height, excellent club wheat quality, moderate tolerance to low falling numbers, similar to that of ARS Crescent, and it consistently grades as white club. The pedigree of Cameo is ARSC96059-2/IL01-11934//ARSC96059-2-0-16.

Pritchett and Castella have been productive in the traditional club wheat growing region and Pritchett maintained grain yields as well as many soft white wheat cultivars, even under the severe drought conditions of 2021 (Tables 1 and 2). There is still a great need for new club wheat cultivars with the snow mold resistance and emergence of Bruehl, combined with the tolerance to low Falling Numbers that is more typical of ARS Crescent.

New entries with better resistance to snow-mold, ARSX12015-68CBW and WA8317, which also has two-gene IMI resistance, and ARS12097-8D were entered in the WA Cereal Variety trials in the dry zone in 2020 and 2021. Unfortunately, although they did well in 2020, the three lines were not better than existing cultivars for grain yield and suffered more than those cultivars in the 2021 drought (Tables 1 and 2). Therefore, they were not advanced. In the high rainfall zone, ARSX09500-17CBW performed well at Mayview and Walla Walla in 2021, likely due to relatively early maturity.

In 2022, the breeding lines, ARS12097-12C (X010679-1C/IL06-14262), ARS13659-4C (Bruehl///(J010049/Brundage 96/Mohler)-2), and ARS141114-64C (Xerpha/X06132-45C) were entered into the WA Cereal Variety Testing dry trials. All had previously been selected have some tolerance to snow mold, excellent club end use quality, and were competitive in the very dry year of 2021. In the high rainfall trials, ARSX09500-17CBW (ARSC96059-2/VA03W-412//ARSC96059-2-0-17) was repeated and ARS14DH1014-C (ARS-Amber/X010301-4-2C) with earlier maturity, excellent standability, excellent club wheat quality and resistance to stripe rust was entered for 2022.

Each year of the project, we made over 150 crosses to develop new club wheat populations. We evaluated mini-bulk breeding and speed breeding techniques in the greenhouse and discovered that we can save about 20 days off of normal winter wheat generations using these techniques which allows us to advance material through the greenhouse faster and serves as a cost-effective alternative to doubled haploids. Therefore, populations are being advanced in the WSU plant growth facility, and selected for height and club wheat head type prior to planting in the field at F4 headrows. Several populations were developed to introgress two-gene IMI resistant into club wheat. Since the soft white wheat cultivars 'Curiosity' and 'Mela' were used as resistance donors, these crosses will also be useful to incorporate better snow mold resistance. With our collaborators, we evaluated nurseries at 14 locations in Washington, Idaho and Oregon in all years of the project (Table 3). Since 2020, genotype data is generated for all lines in yield trails in the club wheat breeding program. These data are used for marker assisted selection, for cross prediction and to generate genomic selection models.

In 2020 we evaluated all of plots in our yield trials in Lind and Pullman for resistance to low falling number using spike wetting tests. We discovered that, although ARS Crescent performs well for falling number in grower fields as compared to Bruehl, it was rated as susceptible to sprouting in spike wetting tests conducted at the WSU Plant Growth Facility. We suspect that the resistance in ARS Crescent is enough to maintain falling number in grower fields but not enough to sustain resistance in under the pressure of the spike wetting test. While we could select for greater dormancy using the spike wetting test alone, we are concerned that this increased dormancy would negatively impact fall emergence in the dry locations. There are a few winter wheat lines such as Otto soft white winter wheat, that have good emergence and the ability to maintain acceptable falling numbers in most environments. Therefore, we made several crosses between Otto and the club wheats to select for a moderate degree of tolerance to falling number and good emergence. We are evaluating molecular markers for association with falling number tolerance in our breeding program.

Pritchett was rated as resistant to soil borne mosaic virus over multiple years of testing by Dr. C. Hagerty of OSU. This resistance was originally present in Bruehl, and is associated with the SBMV-1 and SBMV-2 molecular markers indicating that we can select for resistance using marker assisted selection. Although soil borne mosaic virus has not emerged as a great threat to wheat production in the PNW, it is good to know that we have resistance present in adapted germplasm.

Each year we evaluate over 2500 breeding lines from breeding programs throughout the U.S. for resistance to stripe rust. This collaborative project has enabled us to made crosses to several good sources of Hessian fly and wheat barley dwarf virus resistance which are are being advanced for selection. In addition, several USDA-ARS developed cultivars possess resistance to local races of Hessian Fly, as tested at the Univ. of Idaho. These include ARS Selbu, Castella, Cameo and the breeding line ARSX09500-17CBW.

We were unable to visit with our collaborators of the Japanese Flour Miller's Association in person in 2020 and 2021 due to the pandemic but we were able to meet in virtual conferences. From that interaction, we started to investigate additional methods to measure cake quality including image analysis and texture classification. These trials are ongoing. Released club wheat cultivars continue to be listed as desirable or most desirable in the 'Preferred Varieties Brochure sponsored by the Washington, Oregon and Idaho Wheat commissions and the USDA-ARS Western Wheat Quality Laboratory.

Impact

The integration of genomic selection, speed breeding, doubled haploid breeding, and new methods of analyzing data enables us to continue to be efficient with grower dollars and produce club wheat cultivars that are competitive as well as additional soft wheat germplasm with specific useful traits for other breeders. Better resistance to low falling number will stabilize markets and reduce grower risk. The USDA-ARS club wheat breeding program is the only one with a primary focus on club wheat. Club wheat remains a highly desired product in the the PNW grain market giving growers additional choices in marketing strategy. The most significant measurable impact is the acreage devoted to club wheat cultivars developed from this project and the increase in acreage of winter clubs in 2021.

Table 1.

Summaries from 2020 WSU Cereal Variety Testing Program
By Rainfall Zone. Club Wheats are in Italics

	>20 in.					16-20 in.				
Name	***Colton***	***Fairfield***	***Farmington***	***Pullman***	***Ave.***	***Dayton***	***Mayview***	***St John***	***Walla Walla***	***Ave.***
ARS Crescent	130	135	137	124	131	127	104	130	132	123
ARS09X492-6CBW	125	137	139	144	136	124	98	128	132	121
ARSX12016-45CBW	129	125	132	147	133	120	97	115	124	114
Castella	125	130	131	145	133	123	57*	115	134	107
OR5170022	107	114	114	118	113	115	92	117	118	110
Pritchett	125	130	131	145	133	131	97	124	132	121
M-press	140	142	131	142	139	131	110	119	146	127
Norwest Duet	125	130	131	145	133	126	111	127	138	126
Purl	125	130	131	145	133	132	94	130	139	124
lsd	16	11	17	15	6	13	15	11	21	7

	12-16 in.						<12 in.					
Name	***Almira***	***Anatone***	***Creston***	***Lamont***	***Reardan***	***Ave.***	***Bickleton***	***Connell***	***Harrington***	***Horse Heaven***	***Lind***	***Ave***
ARS Crescent	77	75	73	95	127	89	27	69	67	40	70	56
ARS12015-68CBW	64	75	75	85	111	82	24	61	57	36	60	48
Bruehl	73	66	81	88	101	82	25	64	54	39	58	47
Castella	74	59	88	95	119	87	25	56	51	38	60	46
OR5170022	64	70	79	84	97	79	19	60	41	29	60	42
Pritchett	81	73	72	95	117	88	29	62	54	39	59	49
WA8317	69	69	84	85	106	83	26	61	60	38	58	49
Otto	66	72	81	94	108	84	27	57	49	39	57	46
Devote	66	70	88	89	108	85	25	64	60	45	61	51
M-press	79	71	95	91	122	92	29	68	57	38	56	50
Norwest Duet	82	78	78	95	122	91	32	67	68	37	59	53
Purl	74	83	82	88	114	88	27	65	51	40	60	48
lsd	10	11	13	8	14	4	3	14	15	8	12	4

* The low score at Mayview for Castella is likely due to deer and elk feeding.

** Shaded entries are in the same highest lsd group.

Table 2. Summaries from 2021 WSU Cereal Variety Testing Program
By Rainfall Zone, Club Wheats are in Italics

	> 20 in.					16-20 in.				
Name	*Colton*	*Fairfield*	*Farmington*	*Pullman*	*Average*	*Dayton*	*Mayview*	*St. John*	*Walla Walla*	*Average*
ARS Crescent	59	37	74	58	57	36	55	90	77	74
ARS14DH1122-26	59	34	78	61	58	34	50	82	74	69
ARSX09500-17CBW	59	38	83	68	62	42	57	98	85	80
Cameo (ARS09X492-6CBW)	63	41	89	73	66	41	58	95	78	77
Castella	64	35	82	69	63	51	--	100	76	--
Pritchett	65	35	79	76	64	47	61	96	77	78
LCS Hulk	66	38	75	72	63	53	58	93	78	76
M-Press	67	35	76	71	62	51	59	93	80	77
Norwest Duet	70	43	84	68	66	42	58	98	83	80
Piranha CL+	70	40	104	83	74	54	58	101	83	82
Purl	68	32	78	69	62	46	58	98	81	79
LSD	5	4	6	7	3	10	10	12	10	5
Ave	67	37	84	74	65	48	58	93	81	77

	12-16 in.						<12 in.						
	Almira	*Anatone*	*Creston*	*Lamont*	*Reardan*	*Average*	*Bickelton*	*Connell*	*Harrington*	*Horse Heaven*	*Lind*	*Ritzville*	*Average*
ARS Crescent	40	41	56	95	61	59	15	40	53	22	39	40	35
ARSX12015-68CBW	40	31	54	95	56	55	13	32	43	18	34	34	29
ARSX12097-8D	39	31	51	92	54	53	14	43	54	21	37	44	35
Castella	36	--	62	70	59	--	15	38	57	24	42	42	36
OR5170022	21	27	38	85	41	42	8	37	41	14	29	38	28
Pritchett	39	39	61	108	58	61	18	43	52	23	48	49	39
WA8317	35	26	37	93	50	48	13	36	39	17	35	37	30
Devote	45	35	62	97	60	60	17	44	48	25	50	49	39
M-Press	44	38	68	103	64	63	18	42	56	23	43	49	38
Norwest Duet	40	37	60	103	60	60	16	47	51	21	47	43	38
Otto	33	30	54	83	62	52	14	44	44	22	44	47	36
Piranha CL+	37	44	65	107	69	65	19	48	52	24	45	49	40
LSD	7	7	7	14	8	4	2	7	5	3	6	7	2
Ave	39	37	58	98	60	58	17	43	50	23	41	45	36

* The missing data for Castella at Mayview and in average are due to Elk and Deer feeding.

** Shaded entries are in the same highest LSD group for the trial

Table 3. Locations used in USDA-ARS club wheat breeding program for evaluation of breeding lines.

Location	Cooperators	Rationale for location
Harrington, WA	WSU Winter Wheat, WSU Variety Testing, Wagner	Emergence, low rainfall wheat-fallow, traditional club wheat production region.
Kahlotus, WA	WSU Winter Wheat, Moore	Emergence, low rainfall, wheat-fallow production region.
Lind, WA	WSU Dryland Experiment Station	Emergence, low rainfall, wheat-fallow production region.
Ritzville WA	WSU Winter Wheat, Schoesler	Emergence, low rainfall, wheat-fallow production region, traditional club wheat production region
St Andrews, WA	WSU Variety Testing	Winter Survival, low rainfall, wheat-fallow production region.
Farmington, WA	WSU Winter Wheat, Pfaff	Annual production region, stripe rust, cold spring, productive but low pH soil.
Genesee, ID	Kambitsch Farm Univ. of Idaho	Highly productive, heavy soils, annual production region
Pendleton, OR	CBARC, Oregon State Univ.	Early maturity, terminal heat stress, mild winter, intermediate rainfall.
Pullman, WA	Spillman Farm	Annual production region, stripe rust, stem rust, Cephalosporium stripe and eyespot diseases.
Walla Walla, WA	WSU Winter Wheat, Moore	Early maturity, weed pressure, intermediate rainfall, stripe rust.
Central Ferry, WA	USDA Plant Introduction Unit	Stripe rust resistance, eyespot resistance, seed increase location
Rockford, WA	WSU Winter Wheat,	Aluminum toxicity, low pH
Mansfield, WA	WSU Winter Wheat,	Snowmold resistance, winter survival
Waterville, WA	WSU Winter Wheat,	Snowmold resistance, winter survival

WGC Project Number:	3019-3156			
WGC Project Title:	Club wheat breeding			
Project PI(s):	Kim Garland Campbell, Arron Carter, Michael Pumphrey			
Project Initiation Date	07/01/2019			
Project Year:	3			
Objective	Deliverable	Progress	Timeline	Communication
Develop agronomically competitive club wheat cultivars targeted to the diversity of rainfall and production zones on the PNW.	Club cultivar releases	Release of Pritchett, Castella, and Cameo.	Cultivar releases targeted one per rainfall zone every three years	Presentations at annual field days, plot tours, and you-tube videos. Wheat life articles and peer reviewed publications. Garland-Campbell, Kimberly. Garland Campbell, Kimberly. "The origins of club wheat" *Wheatlife* 64.10(2021): 41-43.
Develop club breeding lies and cultivars for the <15-inch rainfall zone with improved resistance to snow mold and fusarium crown rot, improved emergence, and winter survival.	Club cultivar releases are entered into Western Regional and State Extension Trials	Pritchett and Castella are targeted to the <15-inch rainfall region. Four-6 lines entered regional trials each year.	Yearly entry of breeding lines into regional trials	Garland Campbell, Kimberly, et al. "Registration of 'Castella' soft white winter club wheat." *Journal of Plant Registrations* 15.3 (2021): 504-514. Garland-Campbell, Kim, et al. "Registration of 'Pritchett' soft white winter club wheat." *Journal of Plant Registrations* 11.2 (2017): 152-158.
Develop club breeding lies and cultivars for the >15-inch rainfall zone with improved resistance to eyespot, cephalosporium stripe, aluminum, and cereal cyst nematodes.	Club cultivar releases are entered into Western Regional and State Extension Trials	Cameo is targeted to the > 15-inch rainfall region. Four-6 lines entered regional trials each year.	Yearly entry of breeding lines into regional trials	Garland-Campbell, Kim, et al. "Registration of 'Cameo' soft white winter club wheat." *Journal of Plant Registrations* in review, submitted Dec. 2021. Wen, Nuan, et al. "Distribution of cereal cyst nematodes (Heterodera avenae and H. filipjevi) in Eastern Washington State." *Plant disease* 103.9 (2019): 2171-2178.
Develop club wheat breeding	Club cultivar	The breeding line ARSX09500-	Yearly entry of breeding	

lines with early spring green up, targeted to SE Washington.	releases are entered into Western Regional and State Extension Trials	17CBW has this trait and has performed well in testing in SE WA.	lines into regional trials	
Objective 2. Release germplasm and cultivars with the excellent end use quality characteristic of club wheat and with resistance to preharvest sprouting and late maturity alpha amylase (LMA)	Club wheat breeding lines will maintain stable falling numbers.	Castella and Cameo have more stable falling numbers (above 300) than Pritchett and Bruehl.	New breeding lines assessed yearly in Washington Cereal Variety Trials.	Sjoberg, Stephanie M., et al. "Unraveling complex traits in wheat: Approaches for analyzing genotype× environment interactions in a multi-environment study of falling numbers." *Crop Science* 60.6 (2020): 3013-3026. Sjoberg, Stephanie M., et al. "Application of the factor analytic model to assess wheat falling number performance and stability in multienvironment trials." *Crop Science* 61.1 (2021): 372-382.

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PROJECT #: 30109-3157

Progress report year: 3 of 3 Final

Title: Evaluation and Selection for Cold Tolerance in Wheat

Cooperators: K. Garland Campbell, K. Sanguinet, A.H. Carter

Executive summary:

In 2021, we rated over 600 wheat breeding lines and cultivars from public breeding and variety testing programs for survival. In 2020, and despite the slowdown due to the pandemic, we rated 924 breeding lines and cultivars from public winter wheat breeding and variety testing programs for survival. This compared well with 2019 when we tested 936 lines. Breeders used this information for selection of new experimental lines. We have evaluated the Washington Extension Winter Wheat Trials every year since 2001. The survival results for the top varieties grown according to the Washington Grain Commission Variety Survey are below (page 2). We are still analyzing data for the 2021 crop year. We observed association between our testing results and the winter injury that occurred in WA in April of 2020 and in survival notes from the Cereal Variety trials that have been collected between 2018-2020. Therefore, we are confident that our evaluation of freezing tolerance using programable freeze chambers at the WSU Plant Growth Facility represents real world winter survival due to cold injury.

We conducted a genome-wide association study of wheat from the WSU winter wheat and ARS winter wheat programs and a doubled haploid population of Cara/Xerpha. We also did a QTL analysis in a population involving the very cold tolerant Canadian winter wheat Norstar, in collaboration with Dr. Debbie Laudencia of USDA-ARS in Albany CA, Dr. Brian Fowler (retired) of Univ. of Saskatchewan. We previously identified allelic variation at the genes for vernalization response (VRN) and for the genes controlling general cold tolerance response (CBF) genes on the group 5 chromosomes. These genes impact vernalization requirement and cold tolerance. We have now identified QTL for cold tolerance on the multiple chromosomes including 1A, 1B, 1D, 2A, 2B, 2D, 3B, 3D, 4A, 4B, 5A, 5B, 6B, 7A, and 7B. Some of these genes are major and we can use marker assisted selection to fix them in our breeding lines. Genomic selection models will be most useful to improve freezing tolerance in PNW wheat. We also know that resistance to soil borne diseases like eyespot, fusarium crown rot and snow mold is critical for winter survival in wheat.

Even though we have learned a lot about control of cold tolerance from the QTL associated with differences in the DNA code of specific genes controlling growth and flowering, we know that flowering and cold tolerance are influenced by epigenetic responses. Epigenetics refers to changes in gene expression that are caused by exposure to different environments rather than changes due to differences in the DNA code. Previously, Dr. Dan Skinner started with a single seed of the winter wheat 'Norstar', grew it using exposure to cold to induce flowering and harvested the seed from that plant. He then exposed several of the seeds to cold as usual for winter wheat and harvested those seeds. He called these "cold-induced flowering (CIF-Norstar)". He also maintained some of the seeds at room temperature (no cold exposure) but he did expose

then to longer daylengths (or longer photoperiod). Wheat is daylength sensitive and flowers in response to lengthening days. Initially, few tillers flowered on the plants that were not exposed to cold. After three generations, he was able to harvest a normal amount of grain from each plant. This version of Norstar was named photoperiod induced flowering (PIF-Norstar). We hypothesized that these differences in the control of flowering were due to different gene expression, rather than to changes in the DNA code itself. We want to know which genes are affected by these differences in epigenetic expression. Our rationale is that, even if we incorporate all the DNA allelic variation (differences in DNA code) that is associated with cold tolerance in wheat; we may still alter the cold tolerance of a cultivar based on how we treat the seed during the breeding process.

We used a technique called RNA-seq to analyze gene expression data for epigenetic effects of exposure to cold in the CIF and PIF Norstar lines. We exposed 6-week-old plants of the two different Norstar lines to freezing temperature from 0-24 hours. Then we extracted RNA from each type of Norstar at each time period and analyzed it for differences in gene expression between the CIF-Norstar and PIF-Norstar lines. A large percentage of genes were expressed differently between the two Norstar lines at all time points (Fig. 1). In addition, these genes were both up-regulated and down-regulated in the CIF-Norstar vs. the PIF Norstar (Fig. 2).

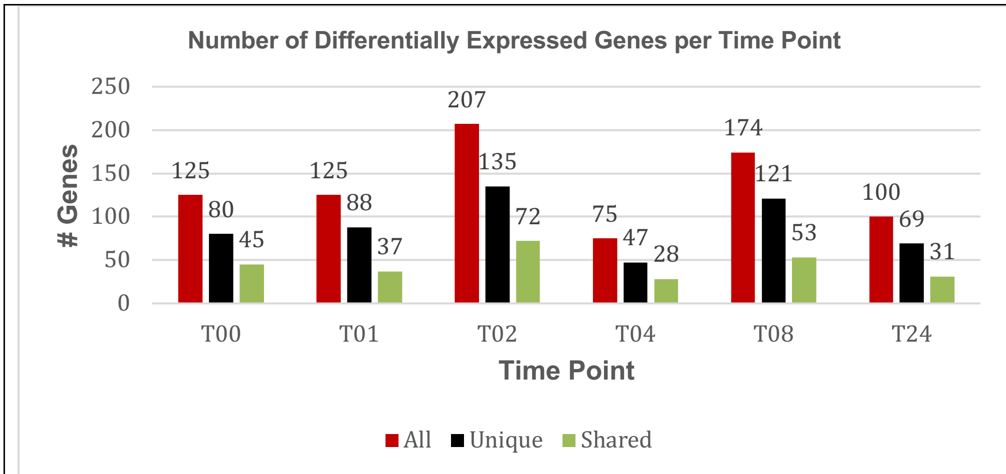

Fig. 1. The number of differentially expressed genes at each time (0-24 hours) for Cold induced flowing (CIF-Norstar) vs. Photoperiod induced flowering (PIF-Norstar). The green bars are genes that were expressed in both CIF and PIF Norstar. The black bars (unique) are the genes that were different between the two Norstar lines.

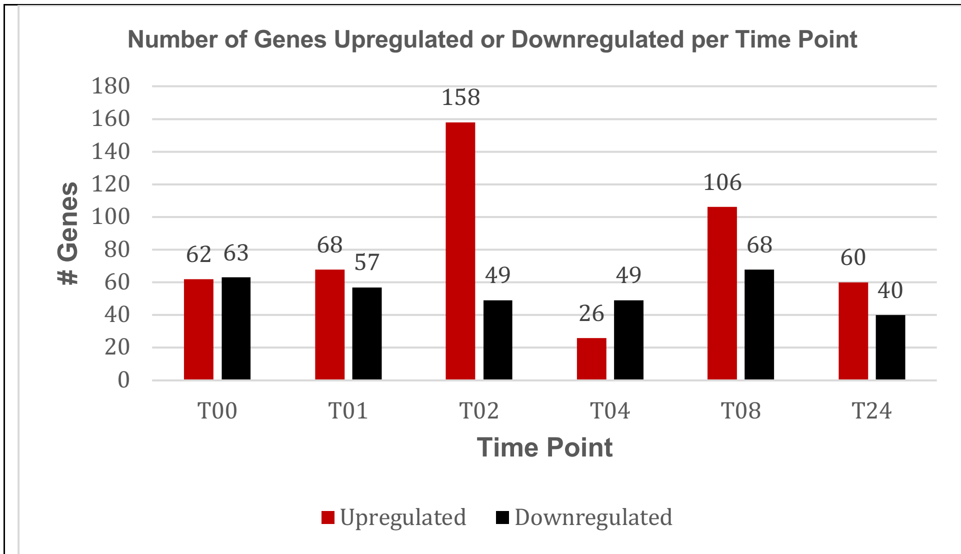

Fig. 2, Of the genes that are differentially expressed between the Cold induced flowering (CIF-Norstar) and the Photoperiod induced flowering (PIF-Norstar), some are upregulated and others are downregulated. A large number of genes are upregulated after two hours of exposure to freezing temperatures.

Thirty of these genes, located on different chromosomes are of particular interest. They are (Table 1). Several genes interact with genes known to be involved in cold tolerance, copper metabolism in plants, and membrane structure. We are investigating these results to better understand the genetic and epigenetic mechanisms that control cold tolerance in winter wheat.

Impact

- The data from these cold tolerance trials was published in the seed buyers guide (Table 2) so that farmers can select winter wheat varieties that are less sensitive to winter kill.
- Our results from screening the regional nurseries, and screening breeding lines has been used by winter wheat breeders to select for resistance to winter injury.
- Varieties released from the WSU winter wheat breeding program have consistently excellent cold tolerance and this tolerance has been maintained because of testing using the procedures developed by this project.
- Because of the high correlation between our artificial screening trial and winter survival in the field, we can incorporate better cold tolerance into our early generation breeding lines.
- We have identified molecular markers that are being used by breeders to select for winter survival.

Table 1. Location and proposed function of important differentially expressed genes between cold induced and photoperiod induced flowering Norstar lines during a 0-24 hour freeze treatment.	
Location (EnsemblPlants)	**Proposed_Function (InterPro)**
Chromosome 1A: 16,930,826-16,935,085	Ankyrin repeat; Zinc finger
Chromosome 1A: 57,680,271-57,682,134	Protein BIG GRAIN 1-like
Chromosome 1A: 252,499,278-252,521,296	WD40-repeat-domain
Chromosome 1A: 252,499,278-252,521,296	WD40-repeat-domain
Chromosome 1A: 567,316,488-567,329,062	GBF-interacting protein 1, N-terminal; UBA-like superfamily
Chromosome 2A: 171,835,609-171,840,193	Autonomous transposable element EN-1 mosaic protein (EN-1/SPM)
Chromosome 2B: 255,050,138-255,056,090	EF-domain; Ser/Thr kinase
Chromosome 2B: 386,305,098-386,312,126	Calcium permeable stress-gated cation channel 1, N-terminal transmembrane domain; 10TM putative phosphate transporter, cytosolic domain
Chromosome 2D: 107,399,802-107,407,399	Glycosyltransferase 2-like; Sugar transferase
Chromosome 2D: 507,747,730-507,757,643	Heavy metal-associated domain (HMA); Superoxide dismutases (SODs) copper chaperone
Chromosome 2D: 553,385,507-553,388,909	Major Facilitator Superfamily (MFS); Proton-dependent oligopeptide transporter (POT) family
Chromosome 3D: 398,401,967-398,407,146	Glycosyl transferase; HAD(-like) superfamily
Chromosome 4A: 143,433,126-143,436,996	CALMODULIN-BINDING PROTEIN60
Chromosome 4B: 38,783,518-38,792,831	CHASE-domain; HATPase; His-Kinase domain
Chromosome 4B: 481,492,246-481,493,603	FAS1 domain superfamily
Chromosome 4D: 93,841,069-93,841,966	Late embryogenesis abundant protein, LEA_2 subgroup
Chromosome 5A: 356,474,101-356,507,274	Armadillo-type fold; E3 ubiquitin ligase; WD40-repeat-containing domain; Zinc finger
Chromosome 5A: 361,446,165-361,448,993	CHCH; possible Cu interacting
Chromosome 5B: 402,733,811-402,734,204	ZF-HD homeobox protein, Cys/His-rich dimerization domain

Chromosome 5B: 703,291,249-703,292,516	Blue (type 1) copper protein; Cupredoxin; Phytocyanin
Chromosome 5D: 549,854,716-549,859,435	RPM1-ineracting protein 4/NOI4
Chromosome 6A: 80,695,452-80,708,832	Squalene cyclase; Terpene synthase
Chromosome 6D: 152,255,321-152,260,592	Sel1-like repeat; Tetratricopeptide-like helical domain superfamily
Chromosome 6D: 332,807,360-332,814,746	RNA-modification via methylation, pseudouridylation, and thiouridylation
Chromosome 6D: 338,399,729-338,413,289	DWNN domain (apoptosis); E3 ubiquitin-protein ligase RBBP6 family; Zinc finger, RING/FYVE/PHD-type
Chromosome 7A: 122,175,829-122,187,343	GBF-interacting protein 1, N-terminal; UBA-like superfamily
Chromosome 7B: 169,462,792-169,467,243	CBF1-interacting co-repressor CIR, N-terminal domain; Pre-mRNa splicing factor
Chromosome 7B: 504,808,145-504,813,117	GDP-fucose protein O-fucosyltransferase
Chromosome 7B: 632,793,180-632,796,098	Pentatricopeptide repeat (PPR), post-transcriptional processes; Tetratricopeptide-like helical domain superfamily
Chromosome 6A: 573,490,463-573,495,427	Homeobox domain; Myb domain; SANT/Myb domain

Table 2. Freeze Survival 0f Top Acreage Winter Varieties in WSU Cereal Variety Testing program, 2016-2020.								
Ranking Based On 2020 Variety Acreage Survey								
	Percent Survival	**95% LCL**	**95% UCL**			**Percent Survival**	**95% LCL**	**95% UCL**
Soft White Wheat					**Club Wheat**			
UI Magic CL+	27%	9%	44%		ARS Crescent	65%	47%	82%
Curiosity CL+	80%	63%	98%		Bruehl	54%	37%	72%
Norwest Duet	54%	37%	72%		Pritchett	56%	38%	73%
Otto	58%	43%	73%					
Norwest Tandem	52%	32%	72%		**Hard Winter Wheat**			
M-press	33%	13%	53%		LCS jet	40%	23%	58%
Mela CL+	67%	49%	84%		Keldin	64%	47%	82%
Eltan	73%	62%	84%		SY Clearstone CL2	70%	52%	87%
Resilience CL+	44%	26%	62%		LCS Rocket	14%	0%	31%
Puma	50%	32%	67%		WB 4303	75%	55%	95%
SY Dayton	26%	9%	44%					
PNW Hailey	65%	41%	90%		**Checks**			
LCS Art deco	26%	8%	43%		Norstar	86%	75%	97%
Jasper	32%	14%	49%		Stephens	39%	28%	50%
LCS Hulk	68%	51%	86%					
Sy Assure	28%	8%	48%					
LCS Drive	23%	3%	43%					
WB 1604	42%	24%	60%					
LCS Sonic	51%	33%	68%					
Bobtail	28%	8%	49%					
SY Raptor	4%	0%	29%					
SY Ovation	17%	0%	37%					
Rosalyn	23%	5%	41%					
UI Castle CL+	30%	12%	48%					
Madsen	29%	9%	49%					
Freeze Tests were conducted under controlled conditions in The WSU Plant Growth Facility between 2016 And 2020.								
These were severe survival trials. Field survival is likely to be greater, but these results have correlated with field survival over multiple years.								
The precision of Confidence Intervals varies because some lines have been tested more than others.								

WGC project number: **3019-3157**
WGC project title: **Evaluation And Selection for Cold Tolerance in Wheat**
Project PI(s): **Kimberly Garland-Campbell, Karen Sanguinet and Arron Carter.**
Project initiation date: **7/1/19**
Project year: **Year 3 FINAL**

Objective	Deliverable	Progress	Timeline	Communication
1. Evaluate Washington winter wheat variety trials and the hard spring wheat trials.	Ratings for freezing tolerance for commonly grown and new winter wheat cultivars and hard spring cultivars and breeding lines.	The Washington Cereal Variety Trial Winter wheat nurseries were evaluated for cold tolerance in artificial screening trials. The Washington Hard Red Spring Wheat Trials were evaluated for cold tolerance.	June 2019 - June 2022.	Presentation at grower meetings, Wheat commission meetings, Wheat Life and Research Review. Published on WSU small grains Web-site. This information is incorporated into the WSU small grains variety selection tool. tool. https://varietyselection.cahnrs.wsu.edu/
2. Evaluate cold tolerance of new breeding lines in US regional nurseries in order to identify germplasm to use in crossing for better winter survival.	Ratings for freezing tolerance for advanced wheat germplasm from the US that can be used as new sources of cold tolerance for the PNW.	The Western Regional Winter wheat nurseries was evaluated for freezing tolerance in artificial screening trials.	June 2019 - June 2022.	Email results to regional nursery cooperators and publish on regional nursery web sites. Yates, Scott. "Wheat farmers never stop and neither does their wheat" Wheatlife. 2020. 63.11:43-45.
3. Evaluate cold tolerance of advanced breeding lines contributed by regional winter wheat breeding programs, including the WSU and USDA-ARS wheat breeding programs.	Ratings for breeding lines contributed by regional wheat breeders that will facilitate their selection decisions.	We evaluated freezing tolerance for breeding lines from the WSU Winter wheat and the USDA club wheat breeding programs and reported the data to the breeders. These data were used for selection.	June 2019 - June 2022.	Several cultivars released with excellent cold tolerance, including Devote, Piranha, Castella and Pritchett.

4. Evaluate cold tolerance of F3-F5 (early generation) wheat populations that are segregating for cold tolerance and select resistant progeny.	Selections made for cold tolerance in early populations.	This was not accomplished due to less testing during the pandemic and equipment failures, but we did release Castella club wheat in 2019, which was selected using this strategy.	June 2019 - June 2022.	Presentation at Research Review. Peer reviewed publications. Direct communication with wheat breeders.
5. Identify genes controlling cold hardiness in winter wheat.	New molecular markers and genomic selection indices for cold tolerance in PNW winter wheat and Hard red spring wheat.	We analyzed several mapping populations and identified or confirmed consistent QTLs for markers on multiple chromosomes that are being used for marker assisted selection for cold tolerance. Our epigenetic work identified several genes that differ in expression between Norstar that is induced to flower based on cold, or based on photoperiod. We are following up on 30 of these genes.	June 2019 - June 2022.	Presentation at Research Review. Peer reviewed publications. Direct communication with wheat breeders.

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(Begin 1 page limit)
Project #: 3184

Progress Report Year: 2 of 3 (maximum of 3 year funding cycle)

Title: Breeder Quality Trials

Cooperators: Kim Garland-Campbell, Arron Carter, Mike Pumphrey, Clark Neely

Executive summary: A new program commenced in FY 2019/20 to ‘pre-screen’ experimental breeding lines before they are entered into the WSU Wheat Variety Trials. This pre-screening was aimed at increasing the likelihood that newly released soft white wheat varieties meet industry standards before gaining substantial acreage and influencing the overall quality of the grain being exported from the Inland PNW. Quality data generated from this trial in 2020 and 2021 has been analyzed using the standard *t*-Score and the results (and interpretation) returned to the breeder. The data can also be included in the analysis used for the *Preferred Variety* brochure. The check variety has been drawn from the adjoining Variety Testing nursery.

Impact: Being a relatively new program, we are not able to evaluate the long-term impact of the project. However, we anticipate that the project will provide value to growers in two significant ways: First, it documents and highlights the quality of varieties so that breeders –public and private –are aware of the importance of quality and will hopefully include quality in their selection and variety release decisions.

(End 1 page limit)

Outputs and Outcomes:

Following is a summary of experimental lines evaluated under this program (harvest 2021): There were 31 SWW lines submitted and they were evaluated at seven locations. The SWW lines were submitted by WSU (Dr. Arron Carter), AgriPro, Limagrain, and Westbred. There were four SWS lines submitted and were evaluated from five locations. The SWS lines were submitted by WSU (Mike Pumphrey), Westbred, and AgriPro. In total there were 203 samples evaluated.

WGC project number: 3184				
WGC project title: Breeder Quality Trials				
Project PI(s): Kiszonas & Neely				
Project initiation date:				
Project year (2 of 3-yr cycle):				
Objective	Deliverable	Progress	Timeline	Communication
Evaluate 10 advanced breeding lines from each of 4 programs at 5 locations	Complete end-use quality evaluation and t-Scores	Completed each year by early spring after prior year harvest	Completed by early spring after prior year harvest	End-use quality data, t-Score, and interpretation shared with originating breeder

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(Begin 1 page limit)
Project #: 4721

Progress Report Year: 1 of 3 (maximum of 3 year funding cycle)

Title: Quality of Varieties & Pre-Release Lines: Genotype & Environment 'G&E' Study

Cooperators: Kim Garland-Campbell, Arron Carter, Mike Pumphrey, Clark Neely

Executive summary: The 2021 harvest sample analysis is roughly half done; the project is on-going. As in previous years, all quality data were/will be analyzed using the *t*-Score statistic. The quality *t*-Scores for each soft white winter, club, soft white spring and club, hard red winter, hard red spring, and hard white winter and spring varieties are summarized using 'Grain', 'Milling', 'End-Product', and 'Overall' Scores. Varieties in each market class/sub-class are then ranked by the Overall Score. All varieties and advanced breeding lines with three or more years of data are included in the final listing.

Using these results and analyses, the WWQL works closely with the WGC to develop the, *"Preferred WHEAT VARIETIES for Washington based on end-use quality"* each year with annual updates. Completion of the variety rankings in February represents the first significant accomplishment each year. We coordinate variety classification with Oregon and Idaho cereal chemists.

Impact: This 'G&E' project provides value to growers in two significant ways: First, it documents and highlights the quality of varieties so that growers are aware of the importance of quality and will hopefully include quality in their seed-buying decisions. Data are objective "head-to-head" results on Private and Public varieties. Secondly, the data generated by the G&E study supports in a major way the analysis of new breeding lines and the WSU Variety Release process. This program is also highly visible such that good end-use quality is reinforced as a priority in both private and public breeding programs throughout the region.

(End 1 page limit)

Outputs and Outcomes: Following are recent advanced lines and released varieties that were supported with complete end-use quality analyses:

ALUM	HRS
ARROWHEAD	HRW
ARS09X492-6CBW	CLUB
ARS14DH1122-26	CLUB
ARS14DH1122-44	CLUB
ARSX09500-14CBW	CLUB
ARSX09500-17CBW	CLUB
ARSX12015-68CBW	CLUB
ARSX12097-8D	CLUB
ARSX12099-158	CLUB
ASSURE	SWW
BOBTAIL	SWW
BRUEHL	CLUB
BRUNDAGE96	SWW
BRUNEAU	SWW
CASTELLA	CLUB
CHET	HRS
CLEARSTONE	HRW
COMMAND	SWW
CRESCENT	CLUB
CURIOSITY	SWW
DAYN	HWS
DEVOTE	SWW
DUET	SWW
EARL	HWW
FARNUM	HRW
FUSION	HRS
GLEE	HRS
GUNSIGHT	HRS
HULK	SWW
INCLINE	HRW
JASPER	SWW
JD	CLUB
JET	HRW
KELDIN	HRW
KELSE	HRS
LOUISE	SWS
MADSEN	SWW
MAGIC	SWW
MELA	SWW

MELBA	CLUB
MONARCH	HWW
NORWEST553	HRW
ORCF102	SWW
OTTO	SWW
PIRANHA	SWW
PRITCHETT	CLUB
PUMA	SWW
PURL	SWW
RESILIENCE	SWW
ROSALYN	SWW
RYAN	SWS
SCORPIO	HRW
SEAHAWK	SWS
SELBU2	SWW
SEQUOIA	HRW
SOCKEYE	SWW
SPRINTER	HRW
STEPHENS	SWW
STINGRAY	SWW
TANDEM	SWW
WA8290	SWW
WA8293	SWW
WA8307	SWW
WA8309	HRW
WA8310	HRW
WA8312	CLUB
WA8317	SWW
WA8318	HRW
WA8319	SWW
WA8321	SWS
WA8323	SWS
WA8325	CLUB
WA8330	SWW
WA8335	SWW
WA8336	SWW
WA8337	SWW
WA8342	HRS
WA8343	HRS
WA8344	HRS
WB528	SWW
WB9668	HRS
WHETSTONE	HRW

XERPHA SWW

WGC project number: 4721				
WGC project title: G&E Study				
Project PI(s): Kiszonas				
Project initiation date:				
Project year (1 of 3-yr cycle):				
Objective	Deliverable	Progress	Timeline	Communication
Complete milling and baking analyses	Data set complete	Winter and spring wheat datasets are complete	All tests are complete	Internal
Analyze data set for t-scores	Grain, Milling, Baking, and Overall t-scores are calculated	Final data set is being processed	Complete in January	Internal
Rank varieties, assign quality classification, deliver final consensus to WGC	Final consensus classification of cereal chemists across the PNW	We will meet at the PNW Wheat Quality Council meeting to reach consensus on Classification	We had scheduled a meeting at the PNW Wheat Quality Council	Meeting with PNW cereal chemists from USDA, WSU, U of I, and OSU at the PNW-WQC; then communicate results to WGC

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(Begin 1 page limit)
Project #: 4722

Progress Report Year: 1 of 3 (maximum of 3 year funding cycle)

Title: Supplemental support for assessing the quality of Washington Wheat Breeding Samples

Cooperators: Kim Garland-Campbell, Arron Carter, Mike Pumphrey

Executive summary: This WGC support provides for about 3 months of additional technician time. The additional work is devoted to evaluating breeder samples for quality from early October through mid-January. During this period, spring wheat samples are given priority over winter wheat samples. The aim is to coordinate with the WSU Wheat Quality Program, and complete as many analyses as possible before spring wheat planting decisions are made in early February. In this way, the spring wheat program is made more efficient because inferior quality lines are not planted and grown. The standing goal for WSU winter wheat breeding lines is to complete as many as possible before June 1. Milling and baking evaluations of the 2020-Crop were completed and 2021-Crop testing is well under way at the Western Wheat Quality Lab.

Impact: This work contributes directly to WSU and ARS variety development and release. New varieties need to be fully evaluated for end-use quality so that our customers can purchase predictable, high quality Washington wheat.

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Outputs and Outcomes: We provide breeders with SKCS single kernel size, weight, and hardness, and the variability (SD) of each; grain protein, test weight, flour yield, break flour yield, milling score, flour ash and protein, dough mixing time and type, dough water absorption, Solvent Retention Capacity (SRC) Water, Lactic Acid, Sucrose and Carbonate; SDS Sedimentation, cookie diameter and score, bread volume and score, sponge cake volume, and RVA (Rapid Visco Analyzer) peak pasting viscosity or Flour Swelling Volume (FSV) (RVA and FSV are for starch quality).

WGC project number: 4722				
WGC project title: Supplemental Support for Assessing the Quality of WA Wheat Breeding Samples				
Project PI(s): Kiszonas				
Project initiation date:				
Project year (1 of 3-yr cycle):				
Objective	Deliverable	Progress	Timeline	Communication
Complete spring wheat samples	Full mill & bake data delivered to breeder by early Feb	Will be reported; progress on last year's crop is on track	Starts at harvest when samples come in, ends with completion of last nursery	Data delivered directly to breeder; dialogue may ensue as to interpretation
Complete winter wheat samples	Full mill & bake data delivered to breeder by early June	Will be reported; progress on last year's crop is on track	Starts at harvest when samples come in, ends with completion of last nursery	Data delivered directly to breeder; dialogue may ensue as to interpretation

Washington Grain Commission
Wheat and Barley Research Annual Progress Reports and Final Reports

Project #: 4150-1227

Final Progress Report Year: 3 of 3

Title: Extension Education for Wheat and Barley Growers

Cooperators: Drew Lyon, David Brown, David Crowder, Aaron Esser, Randy Fortenbery, Isaac Madsen, Timothy Murray, Clark Neely, Haiying Tao, Stephen Van Vleet, and Dale Whaley

Executive summary: New resources were added to the Wheat and Small Grains website in 2021. We also released our first phone app: WSU Variety Selection. The new app has been downloaded more than 200 times. The results from the 2021 cereal variety testing program were added to the website, the Variety Selection Tool, and the phone app. The 2021 WSU Weed Control Report was posted as were two new Weed ID quizzes. The Insecticide Mode of Action Tool was added in 2021 along with the Insect ID and Damage Quiz. Twenty-five new episodes of the WSU Wheat Beat Podcast were posted in 2021, a new episode every other week. There were also 26 new Timely Topics posted. The 2021 Wheat Academy was cancelled because of mask mandates necessitated by the COVID-19 pandemic.

Vacant positions on the Extension Dryland Cropping Systems Team remained a problem in 2021. The Team will enter 2022 three county positions down from where it was in 2018, although searches for the Columbia County and Walla Walla County positions will occur in 2022.

Impact: The Wheat and Small Grains website continues to be an important source of information for many people. For the 11-month period of January through November 2021, the site had 66,417 sessions with 52,822 unique users; this compares to 63,155 sessions with 34,808 unique users for the same period in 2020, and 49,175 sessions and 36,002 unique users in 2019. There were 104,950 pageviews, which is down from 114,379 pageviews in 2020 but up from the 88,727 pageviews in 2019. We have 1,015 subscribers to our listserv. We have 907 followers on Twitter, and 621 follows on Facebook. Most of the sessions from the US (36,723) were initiated from the state of Washington (13,476). From January through November, the WSU Wheat Beat Podcast had a total of 10,441 plays. Through November, the Weeders of the West blog had 4,727 pageviews and 95 people are subscribed to the blog listserv.

Deliverables 2019-2021:
WSU Variety Selection Phone App
Insecticide Mode of Action Tool
Weeders of the West (WoW) Blog – 40 posts
Insect & Insect Damage ID Quiz
Soil Nutrient ID Quiz
Herbicide Resistance Resources Page

Wheat Beat Podcast Episodes – 76
Timely Topics – 109
Best management practices for managing herbicide resistance (PNW754)
Integrated management of downy brome in winter wheat (PNW668 revision)
Integrated management of feral rye in winter wheat (PNW660 revision)
Harvest weed seed control: Applications for PNW wheat production systems (PNW730)
Russian thistle management in a wheat-fallow crop rotation (PNW492)
Buckwheat control in wheat (FS158E)
Hessian fly management in wheat (FS331E)
Nitrogen inhibitors: How do they work to reduce N losses? (FS333E)
WSU Weed Control Reports – 2019, 2020, and 2021
WSU Wheat Academy – 2019

WGC project number: 4150-1227 (FY 2019-2022)
WGC project title: Extension Education for Wheat and Barley Growers
Project PI(s): Drew Lyon
Project initiation date: July 1, 2019
Project year (X of 3-yr cycle): 3

Objective	Deliverable	Progress	Timeline	Communication
Add new resources to the Wheat and Small Grains website, including new publications, decision support tools and calculators, videos, and quizzes.	New and updated Extension publications, decision support tools and calculators, videos, and quizzes will be developed. Decision support tools and videos will be priortizied. An article on our Extension actvities will be written annually for Wheat Life magazine.	WSU Variety Selection was developed in 2021 and is the first phone app created by the team. With the release of CoAXium wheat varieties, several Extension publications were updated in 2021. These included publications on jointed goatgrass, downy brome, and feral rye. The Extension publication on prickly lettuce was also updated in 2021. A new insecticide mode of action and comparison tool was developed in 2021.	This will be an ongoing process throughout the duration of the project.	The development of new resources were shared with growers through Timely Topic posts on the Wheat and Small Grains website, news releases, including an annual article in Wheat Life magazine, and at various education events held throughout 2021.
Provide Timely Topics and podcast episodes on a regular and frequent basis.	We will post at least one Timely Topic every other week and one podcast episode in the alternate weeks so that we have at least one new item on the home page every week.	Twenty-five new episodes of the WSU Wheat Beat Podcast were posted in 2021; one every other week. Twenty-six Timely Topics were posted in 2021. Eighteen articles were posted to the Weeders of the West Blog.	The proposed schedule will be initiated at the start of the funding cycle and continue throughout the durationof the project.	Timely Topics, Wheat Beat Podcast episodes, and Weeders of the West articles were posted to the home page of the Wheat and Small Grains website.
Develop a new one-day educational program along the lines of the Wheat Academy that can be held outside of Pullman.	A new one-day educational program held each year in at least one location outside of Pullman.	No progress was made on this objective in 2021.	We would still like to make progress on this objective, but it will not happen in this funding cycle.	When developed, information on the new educational event will be communicated to growers and crop consultants through Timely Topic posts and in future advertisements for the program, including advertising in Wheat Life.
Respond to issues of concern to the wheat industry with educational programming that is timely and relevant.	In-depth educational programs, publications, articles, videos, and decision support tools as called for by the particular issue.	An historically dry year in 2021 resulted in few of the usual problems in wheat. The 2021 podcast with the most listens was Bill Schillinger's episode on stubble height and soil water.	This will be an ongoing process throughout the duration of the project.	Educational resources and programming developed to address issues of concern were shared with growers through Timely Topic posts on the Wheat and Small Grains website and at education events held in 2021.

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Project # 4127-1605

Final Report Year: 3 of 3

Title: EVALUATION OF BARLEY VARIETIES

Researcher: Clark Neely, Variety Testing Program Lead

EXECUTIVE SUMMARY:

The primary goal of the WSU Extension Cereal Variety Testing Program is to provide growers, the agribusiness industry, university researchers, and other interested clientele with comprehensive, objective, and independent information on the adaptation and performance of spring barley cultivars across the intermediate and high rainfall dryland production regions of eastern Washington where barley is grown.

The VTP planted 12 spring barley variety trials in each of the past three years. While all 12 were harvested each year, data from one, two and five trials were not published in 2019, 2020, and 2021, respectively, due to high variation in the data within the trials. All data is posted on our website and email notifications were sent out via the 'prelimdata' list serve when data was available. In the past year, the number of members on this list has increased 67% to 355. We continue to publish our final technical report each year which can be found on our website (http://smallgrains.wsu.edu/variety) and is posted in December. The variety selection tool has continually been updated each year and in spring of 2021 a new mobile app was developed to provide a user-friendly experience on their phone and even off-line access once the app is installed.

Due to COVID-19, in-person field days were cancelled in 2020. In response, the VTP led the effort to organize, record and post virtual field days as our primary Extension outreach that year. A total of four field day playlists were created for each precipitation zone and posted on the WSU CAHNRS YouTube Channel. Three of these clips covered the spring barley variety trials at Reardan, Dayton and Pullman and received a total of 86 views combined. In 2021, we held in-person field days at eight sites (200 attendance) with spring barley variety trials. We continued the virtual field days as well producing two barley variety trial video clips, one each at Dayton and Farmington, which received 26 and 17 views, respectively.

IMPACT:

The economic value (impact) of the WSU VTP is measured by providing information to growers and seed industry personnel leading to variety selections that maximize profitability and minimize risk. Choosing an appropriate barley variety to plant is one of the easiest ways that a grower can increase production and decrease costs (through decreased inputs). Between 70,000 and 84,000 acres of spring barley were harvested each year between 2019 and 2021. When comparing the yield from the top three varieties in each trial and comparing their average yield to the trial average, there is approximately a 437 lb/a yield advantage. When multiplied across acres harvested and using an average sales price of $147/ton, the VTP had the potential to generate an additional $7 million dollars over the past three years as shown in the table below. The VTP strives to disseminate information to growers as widely as possible. Both the variety testing website and the variety selection tool average over 8,000 page views each on an annual basis. Another 1,000+ contacts are made through field days and grower meetings each year. While yield is important there are multiple traits that growers look for in a variety, which vary in importance from region to region. The VTP publishes data on test weight, grain protein, plump seed, plant height, maturity, and stripe rust. An additional impact of the VTP comes through the evaluation of breeding lines, providing valuable information to aid breeders in variety release decisions, leading to new and improved barley varieties available to growers in Washington.

Year	Harvested Barley Acres	Average Yield Gain for Top Five Varieties in Trials	Average Price of Feed Barley	Additional Income Generated
	# acres	lb/acre	$/ton	$
2019	84,000	260	$130	$1,419,600
2020	71,000	630	$134	$2,996,910
2021	70,000	420	$177	$2,601,900
Total	75000	437	$147	$7,018,410

WGC project number: 4127-1605				
WGC project title: Evaluation of Barley Varieties				
Project PI(s): Clark Neely				
Project initiation date: 07-01-2019				
Project year (X of 3-yr cycle): 3 of 3				
Objective	**Deliverable**	**Progress**	**Timeline**	**Communication**
1. Conduct representative and objective barley variety field trial evaluations at locations that represent major production areas of Washington.	12 spring barley trials; 18 entries/trial	2019, 2020 and 2021 trials completed & data finalized	Trials are planted in the spring, data results are available to growers at the end of each harvest season.	Results from the variety trials are communicated via Extension programming and are detailed under Objective #4.
2. Entries in trials will include: currently grown varieties and promising advanced breeding lines from the major public and private breeding programs in the region.	All widely grown, commercially available varieties and promising experimental lines are included in trials.	i.) 2021 barley entries: 28% public, 72% private. Every major spring feed and malt barley breeding program in the PNW is actively participating in the VTP. ii.) 2019, 2020, and 2021 entries, locations, and maps have all been posted on the variety testing website.	Deadline for spring entry requests are February 1 and seed is due February 12.	i.) Send out 'call for entries' letter by mid-January requesting spring barley entries. ii.) Maintain positive relationship with breeding programs to ensure future participation.
3. Provide access to variety trials and harvested grain enabling other researchers and supporting projects to gather information from the trials.	Participation and ratings from other projects/ programs.	Cooperation with breeders, pathologists, seed dealers, WSCIA, other universities, and Extension. Data are used by breeders for variety release and promotional materials.	Ongoing cooperation and collaboration that fit with timelines and other listed objectives.	Stripe rust ratings presented in seed buyers guide and variety selection tool. VTP data used for variety release and PVP applications.
4. Deliver an Extension education program to make the results and interpretation of the variety trials available to growers, the seed industry, and other clientele.	a.) Grower meetings	Participated in VT panel at Tri-state Grower Convention (Dec 2021).	Will attend when invited	Attend in person and present results through powerpoint presentation and handouts when appropriate.
	b.) Field Tours	i.) 2020: 3 video clips recorded on barley variety trials and posted with other field day videos on WSU CAHNRS YouTube Channel (86 views). ii.) 2021: 8 in-person field days (200 attendance); 2 video recordings of barley variety trials posted with virtual field days (43 views). iii.) 10 planned for 2022; virtual field days will be filmed at two locations and posted online.	June-July	*List of Field Days provided below; provide paper handouts of data
	c.) Email List Serv	2019, 2020, and 2021 results delivered; list serve membership increased 67% in 2021	October through December	Email list serve: Data sent to 355 members as it becomes available
	d.) Website	Up to date with 2019, 2020 and 2021 data	October through December	9,950 pageview for 2019 VT data; 8,267 pageviews for 2020 VT data; 6,348 pageview for 2021 VT data
	e.) Annual Report	2019, 2020, and 2021 final reports have all been posted online.	December	The annual report will be published as a WSU technical report online and hard copy upon request.
	f.) WSCIA Seed Buyers Guides	2019 Guide completed; 2020 Guide not published (decision made by WSCIA) 2021 Guide not published (decision made by WSCIA)	January-February	Seed Buyers Guide published in January-February
	g.) Wheat Life	2019, 2020, and 2021 spring barley VT articles completed.	Barley VT article is submitted annually in December.	Article published in Wheat Life in January each year

	h.) Variety Selection Tool (smallgrains.wsu.edu)	Selection tool was updated with new data in 2020 and 2021. Tool to be updated with 2021 data by January 2022. New mobile app developed and released in May 2021 for easier access on mobile devices and off-line.	January 2022	The variety selection tool had 9,406 pageviews in 2021.
*Anticipated 2022 in-person Field Days include: Almira, Dayton, Fairfield, Farmington, Lamont, Mayview, Palouse, Reardan, St. John, and Walla Walla.				

Project # 4127-1604

Final Report Year: 3 of 3

Title: EVALUATION OF WHEAT VARIETIES

Researcher: Clark Neely, Variety Testing Program Lead

EXECUTIVE SUMMARY:

The primary goal of the WSU Extension Cereal Variety Testing Program is to provide growers, the agribusiness industry, university researchers, and other interested clientele with comprehensive, objective, and independent information on the adaptation and performance of winter and spring wheat cultivars across the climatic regions of eastern Washington where wheat is grown.

The Variety Testing Program (VTP) has experienced much change during the course of this three year funding cycle. Aaron Esser handed over the program to me in August of 2019 and a new lead technician was hired on in spring of 2020. We have acquired two new plot tractors equipped with GPS and also upgraded to a new 30' boom sprayer that tripled the tank capacity for more efficient spraying and planting. With additional funds from the WGC the program also acquired a new NIR protein analyzer in 2021 that improves speed of processing samples.

The turnaround time for data getting posted following harvest has improved markedly, particularly with winter wheat, so that yield data is generally available within 48 hours of harvest. This data is posted on our website and an email notification is sent out via the 'prelimdata' list serve. In the past year, the number of members on this list has increased 67% to 355. We continue to publish our final technical report each year which can be found on our website (http://smallgrains.wsu.edu/variety) and is posted in December. The variety selection tool has continually been updated each year and in spring of 2021 a new mobile app was developed to provide a user-friendly experience on their phone and even off-line access once the app is installed. We began compiling all ratings for each wheat class into a single table in 2020, which is easily accessible on the yield data webpage as individual tables (labelled as 'Variety Characteristics' tables) and is also included in the final report. These are updated annually. Environmental conditions in 2021 led to ideal conditions for both excellent snow mold and emergence ratings and those have since been updated and are available in the technical report and through the variety selection tool.

Due to COVID-19, in-person field days were cancelled in 2020. In response, the VTP led the effort to organize, record and post virtual field days as our primary Extension outreach that year. A total of four field day playlists were created for each precipitation zone with a total of 47 separate video clips/topics uploaded on to the WSU CAHNRS YouTube Channel. To date, these recordings have garnered 1,811 views. In 2021, we held 16 in-person field days with 334 in total

attendance. We continued the virtual field days as well producing four field day playlists which have received 169 views.

In response to the growing practice of planting hard red spring wheat in the fall in the basin, the VTP began implementing a fall-planted HRS trial in fall 2020 for our two irrigated sites. In fall 2021, we also added a dryland site as well at Dayton due to grower interest in the area. To compliment the yield data, seed of these entries were given to Dr. Kim Campbell's program to screen for cold hardiness. Previously, spring varieties were not screened for this trait. We also plan to work with Dr. Mike Pumphrey's group to screen winter wheat entries for aluminum tolerance alongside his spring wheat aluminum screening nursery. In 2020, we worked with Dr. Pumphrey and University of Idaho to begin screening winter wheat varieties for Hessian fly resistance, which was not previously done.

IMPACT:

The economic value (impact) of the WSU VTP is measured by providing information to growers and seed industry personnel leading to variety selections that maximize profitability and minimize risk. Choosing an appropriate wheat variety to plant is one of the easiest ways that a grower can increase production and decrease costs (through decreased inputs). Between 2.2 and 2.3 million acres of wheat were harvested each year between 2019 and 2021. When comparing the yield from the top five varieties in each trial and comparing their average yield to the trial average, there is approximately a 6.6 bu/a yield advantage. When multiplied across acres harvested and using an average sales price of $7.24/bu, the VTP had the potential to generate an additional $308 million dollars over the past three years as shown in the table below. The VTP strives to disseminate information to growers as widely as possible. Both the variety testing website and the variety selection tool average over 8,000 page views each on an annual basis. Another 1,000+ contacts are made through field days and grower meetings each year. While yield is important there are multiple traits that growers look for in a variety, which vary in importance from region to region. While more difficult to assess economic impact, traits such as falling numbers, winter survival, rust resistance, hessian fly resistance, aluminum tolerance, emergence, and snow mold resistance unquestionable have the potential to greatly improve yield or decrease inputs for some growers and in certain environments. The data generated by the Western Wheat Quality Lab using samples from the VTP helps also ensure released varieties maintain superior grain quality, thereby maintaining overseas markets for PNW wheat which supports prices. An additional impact of the VTP comes through the evaluation of breeding lines, providing valuable information to aid breeders in variety release decisions, leading to new and improved wheat varieties available to growers in Washington.

Year	Harvested Wheat Acres	Average Yield Gain for Top Five Varieties in Trials	Averaged Price of Wheat	Additional Income Generated
	# acres	bu/acre	$/bu	$
2019	2,215,000	7.2	$5.53	$88,192,440
2020	2,295,000	7.0	$5.70	$91,570,500
2021	2,230,000	5.5	$10.49	$128,659,850
Total	2,246,667	6.6	$7.24	$308,422,790

WGC project number: 4127-1604				
WGC project title: Evaluation of Wheat Varieties				
Project PI(s): Clark Neely				
Project initiation date: 07-01-2019				
Project year (X of 3-yr cycle): 3 of 3				
Objective	**Deliverable**	**Progress**	**Timeline**	**Communication**
1. Conduct representative and objective wheat variety field trial evaluations at locations that represent major production areas of Washington.	a) 24 soft winter wheat trials; 48-60 entries/trial	i.) 2019, 2020 and 2021 trials completed & data finalized ii.) 2022 winter trials planted iii.) Collaborative trials are continuing with OSU at Eureka and Walla Walla.	Each year trials are planted in the spring or fall. Plots are maintained throughout the year and heading dates/plant heights are collected before harvest. Data results are available to growers at the end of the harvest season, which runs from mid-late July through September.	Results from the variety trials are communicated via Extension programming and are detailed under Objective #4.
	b) 16 hard winter wheat trials: 30-36 entries/trial	i.) 2019, 2020 and 2021 trials completed & data finalized ii.) 2022 winter trials planted iii.) Collaborative trials are continuing with OSU at Eureka and Walla Walla.		
	c) 18 soft spring wheat trials; 24 entries/trial	i.) 2019, 2020 and 2021 trials completed & data finalized		
	d) 18 hard spring wheat trials; 18 entries/trial	.) 2019, 2020 and 2021 trials completed & data finalized		
	e) 3 hard red spring fall-planted trials; 18 entries/trial	i.) First trials implemented in 2021; completed ii.) 2022 fall-planted HRS trials planted		
2. Trial entries include: currently grown varieties and advanced breeding lines from major public and private breeding programs in the region.	All widely grown, commercially available varieties and promising experimental lines are included in trials.	i.) 2022 winter trials 46% public, 54% private. Every major breeding program in the PNW is actively participating in the VTP. ii.) 2019, 2020, 2021, and 2022 winter entries, locations, and maps have all been posted on the variety testing website.	i.) Deadline for winter entry requests is August 9 and seed is due by August 13. ii.) Deadline for spring entry requests are February 1 and seed is due February 12.	i.) Send out 'call for entry' letter by mid-July requesting winter entries. ii.) Send out 'call for entry' letter by mid-January requesting spring entries. iii.) Maintain positive relationship with breeding programs to ensure future participation.
3. Provide access to variety trials and harvested grain enabling other researchers and supporting projects to gather information from the trials.	Participation and ratings of characteristics from other projects/ programs.	Cooperation with breeders, pathologists, entomologists, quality lab, FGIS, seed dealers, WSCIA, other universities, and Extension. Data gathered and summarized to produce ratings for falling numbers susceptibility, end use quality, stripe rust resistance, hessian fly resistance, snow mold resistance, strawbreaker foot rot resistance, cephalosporium stripe resistance, aluminum tolerance, emergence, and winter survival. Ratings all finalized and compiled into the final technical report and the variety selection tool.	Ongoing cooperation and collaboration that fit with timelines and other listed objectives.	Quality results in preferred variety pamphlet, falling number results presented by corresponding project, disease ratings presented in seed buyers guide, VTP data used for variety release and PVP applications. All data/ratings included in variety selection tool.
4. Deliver an Extension education program to make the results and interpretation of the variety trials available to growers, the seed industry, and other clientele.	a.) Grower meetings	2019: Participated in Spokane Co. Grower Meeting and PNW Farm Forum 2020: Participated in Adams Co. Grower Meeting; Lincoln Co. Grower Meeting 2021: Participated in VT panel at Tri-state Grower Convention	Will attend meetings when invited.	Attend in person and present results through powerpoint presentation and handouts when appropriate.
	b.) Field Tours	i.) 2020: 4 virtual field days recorded and posted online (1,811 views) ii.) 2021: 16 in-person field days (334 attendance); 4 virtual field days (169 views).	June-July	*List of Field Days provided below; provide paper handouts of data

		ii.) 19 planned for 2022; 2 virtual field days will be filmed and posted online.		
	c.) Email List Serv	2019, 2020, and 2021 results delivered; list serve membership increased 67% in 2021	August through November	Email list serve: Data sent to 355 members as it becomes available.
	d.) Website	Up to date with 2019, 2020, and 2021 data	August through December	9,950 pageview for 2019 VT data; 8,267 pageviews for 2020 VT data; 6,348 pageview for 2021 VT data
	e.) Annual Report	2019, 2020, and 2021 final reports have all been posted online.	December	The annual report is published as a WSU technical report online and in hard copy upon request.
	f.) WSCIA Seed Buyers Guides	2019 Guide completed; 2020 Guide not published (decision made by WSCIA) 2021 Guide not published (decision made by WSCIA)	January-February	Seed Buyers Guide published in January-February
	g.) Wheat Life	2019: winter VT article completed 2020: spring and winter articles completed 2021: winter and spring VT articles completed 2022: winter VT article to be written in May	Spring VT article: January Winter VT article: May	Articles published in Wheat Life in January and May each year.
	h.) Variety Selection Tool (smallgrains.wsu.edu)	Selection tool was updated with new data in 2020 and 2021. Tool to be updated with 2021 data by January 2022. New mobile app developed and released in May 2021 for easier access on mobile devices and off-line.	January 2022	2019: ~6,000 page views 2020: 10,426 page views 2021: 9,406 page views
*Anticipated 2022 in-person Wheat Field Days include: Horse Heaven, Ritzville, Dusty, Connell, Lind, Harrington, Eureka, Walla Walla, Dayton, Moses Lake, Almira, Reardan, Mayview, Anatone, Fairfield, St. John, Lamont, Bickleton, Farmington.				

Washington Grain Commission
Wheat and Barley Research Annual Progress Reports and Final Reports
Format

Project #

Progress Report Year: __*1*__ *of* _*3*___ *(maximum of 3 year funding cycle)*

Title: **Fusarium Crown Rot on Wheat: Prebreeding and Development of Tools for Genetic Disease Management**

K. Garland-Campbell, T. Paulitz and R. Koenig.

Cooperators: Emily Klarquist, WSU; Nikayla Strauss, WSU; Nuan Wen, WSU**;** Patricia Demacon, WSU; Arron Carter, WSU; Michael Pumphrey, WSU; and Christina Hagerty, OSU

Executive summary:

- As part of the PhD work of Nikayla Strauss, greenhouse methods were further modified and optimized for winter wheat, building on the work of Yvonne Thompson with spring wheat. This included inoculation at the start of vernalization and increasing temperature and water stress at the end of the experiment.
- A new method of assessing Fusarium crown rot was tested. Instead of a 1-9 rating, the number of discolored internodes was counted. The results were highly correlated with the more time-consuming 1-9 rating. A power analysis was conducted on the data and showed that fewer replicates are required with the node rating system, and that a minimum of 8 replicates are needed. The method separated the resistant check (2-49) from the susceptible check (Soft Svevo). This method should be more reproducible and enable quicker screening of material.
- A panel of winter wheat lines were assessed with the above method and identified Norwest Tandem with a high degree of resistance or tolerance.
- The Western Regional Winter Wheat Nursery was screened, and identified WA 8315, WA8321 and WA 8330 with a higher level of tolerance.
- Another panel of spring wheat lines was tested in the greenhouse, but the level of disease was not high enough for reliable ratings.

Impact: The economic impact of this disease continues to be large and affects all growing areas of Washington including both high and low precipitation zones

What measureable impact(s) has your project had in the most recent funding cycle?
-A list of the most susceptible and resistant varieties
-Better methods for greenhouse screening

WGC project number:
WGC project title: **Fusarium Crown Rot on Wheat: Prebreeding and Development of Tools for Genetic Disease Management**
Project PI(s): **K. Garland-Campbell, T. Paulitz and R. Koenig**
Project initiation date: **7/1/2021**
Project year: **Year 1 2021-2022**

Objective	Deliverable	Progress	Timeline	Communication
Objective 1. Screen spring and winter variety trials and breeding lines for resistance in the greenhouse.	Ratings of varieties for *Fusarium* tolerance in the the WSCIA seed buyers guide and other publications.	Most of our efforts in 2021 were aimed at improved our greenhouse screening method. This included inoculation at the start of vernalization and increasing temperature and water stress at the end of the experiment. A new method of assessing Fusarium crown rot was tested. Instead of a 1-9 rating, the number of discolored internodes was counted. The results were highly correlated with the more time-consuming 1-9 rating. A power analysis was conducted on the data and showed that fewer replicates are required with the node rating system, and that a minimum of 8 replicates are needed. The method separated the resistant check (2-49) from the susceptible check (Soft Svevo). This method should be more reproducible and enable quicker screening of material. In 2021, we screened 234 lines (winter wheat, spring wheat and Winter Wheat Regional Nursery). A high level of tolerance/resistance was identified in Norwest Tandem, identified WA 8315, WA8321 and WA 8330.	Greenhouse screening will continue with optimized methods in 2022-2023	Strauss, N. M., Klarquist, E. F., Kaya, J., Thompson, Y. M., Paulitz, T. C. and Garland-Campbell, K. 2021. Screening of Winter Wheat for Fusarium Crown Rot in a Controlled Environment. Frontiers in Plant Science: submitted Strauss, N. M. 2021. Identifying novel disease resistance and drought tolerance genes in a synthetic DNAM population. PhD Thesis, Washington State University.
Objective 2. Look for new sources of resistance in a new set of synthetic wheat that was developed by CIMMYT in Turkey and in other collections	Resistant sources that can be used for variety development.	Crosses have been made with soft white winter wheat lines such as NW Tandem, that are exhibiting more resistance to FCR. We will select progeny during early generation increase using our improved screening system, followed by marker assisted selection for resistance to other soil borne diseases such as strawbreaker foot rot.	Crosses will be evaluated, advanced, and intercrossed in 2022 and 2023.	Strauss, N. M., Klarquist, E. F., Kaya, J., Thompson, Y. M., Paulitz, T. C. and Garland-Campbell, K. 2021. Screening of Winter Wheat for Fusarium Crown Rot in a Controlled Environment. Frontiers in Plant Science: submitted. Strauss, N. M. 2021. Identifying novel disease resistance and drought tolerance genes in a synthetic DNAM population. PhD Thesis, Washington State University.
Objective 3. Breed for Fusarium crown rot resistance using our greenhouse and field screening systems and marker assisted selection for other important traits for wheat in the Pacific Northwest, (for example: eyespot and stripe rust resistance; grain quality, reduced height, and cold tolerance)	Resistant sources that can be used for variety development.	This work has been on hold because of lower staffing during the pandemic. The resistant lines will be crossed to new soft winter wheat populations in 2022.	Greenhouse screening of backcrosses will continue in 2022-2023.	

Washington Grain Commission

Wheat and Barley Research Annual Progress Reports and Final Reports

Project #: **3019 3162**

Progress Report Year: *_3___ of __3__ (maximum of 3 year funding cycle)*

Title: **Improving Spring Wheat Varieties for the Pacific Northwest**

Cooperators: Mike Pumphrey, Vadim Jitkov, Wycliffe Nyongesa, Josh DeMacon, Sheri Rynearson

Executive summary:

The WSU spring wheat breeding program's elite material and recently released varieties continue to be the top performers in statewide variety trials and for growers. Two varieties were approved for release/Foundation seed increase in 2021. *Hale* hard red spring wheat is a superior, broadly adapted replacement for dryland spring wheat acres. *Roger* spring club is early and high yielding and will be the first in its class with Hessian fly resistance. A new 2-gene Clearfield spring club wheat released in 2020*, Hedge Cl+*, had Foundation seed produced in 2021. Hard red spring *Net Cl+* was grown on ~9,000 acres during its first year available in 2021 and seed stocks have been further multiplied. Each variety has very good to excellent end-use quality, which is a primary goal of our program to help maintain and increase the value of Washington wheat.

WSU soft white spring wheat varieties accounted for 95% of certified soft white spring wheat production acres in Washington in 2021. Our widely available soft white spring wheat varieties, *Ryan*, *Seahawk*, *Tekoa*, and *Melba*, have broad adaptation, superior all-around disease, grain and agronomic traits, most desirable end-use quality, and top yield performance. They have been widely adopted by seed dealers in the PNW and Ryan was by far the leading variety in the state with over 220,000 acres planted in 2021. *Glee*, *Chet*, and *Alum* are leading dryland hard red spring wheat varieties, and *Net CL+* has been rapidly adopted. *WSU spring wheat varieties collectively were planted on 80% of the certified spring wheat production acres in Washington in 2021*. The consistency, broad adaptation, disease and pest resistances, sound grain traits, most desirable end-use quality, good falling numbers, and overall performance of these varieties reflects the outputs of comprehensive wheat breeding and genetics research effort supported primarily through funding from this project. *In fact, 64% of all spring wheat acres in 2021 were planted to varieties developed/released through our program over the past 6-7 years.*

Impact:

The WSU spring wheat breeding program is in a unique position to focus on grower opportunities and challenges, large to small. We identify and develop traits, technology, germplasm, and release varieties to meet the needs of the majority of Washington producers, whether the needs are localized or widespread. We emphasize traits like stable falling numbers, Hessian fly resistance, stripe rust resistance, and aluminum tolerance, and hold the entire industry to a greater standard for yield, yield protection, and end-use quality. Our latest releases package excellent yields with superior quality and key yield protection traits. Public wheat breeding programs at WSU and across the country consistently pay back on research dollars invested. *With 80% or more of the spring wheat acres in Washington planted to WSU spring* *wheat varieties in 2021, growers continue to realize a substantial return on research dollars invested in this program*. The yield of our top three released soft white spring wheat varieties (Ryan, Seahawk, Tekoa) averages 105-108% of the top three varieties from other programs, using 2 to 5-year average data from over 70 variety trials across precipitation zones from 2017-2021.

The core staff and operations of the WSU spring wheat breeding program have allowed us to be very successful in leveraging extramural funding over the past three years. The Pumphrey program has active funding, that relies on leverage from this project, from either USDA or FFAR currently totaling $3,442,243 (see current and pending support). In addition, royalty revenue to WSU from seed sales of our spring wheat varieties in Idaho, Oregon, and Montana generate additional revenue that is re-invested in breeding in Washington. For example, Ryan, Seahawk, and Dayn have led soft white and hard white spring wheat acres (and in the top ten regardless of growth habit or class) in Idaho for several years.

Additional impact over the past funding cycle includes publication of scholarly papers, generation of high-quality data for aluminum tolerance, falling numbers, planting and management of many variety trial locations, significant involvement in extension program and information delivery, and assisting numerous collaborating scientists with execution of field and greenhouse experiments for other extramurally funded projects or to develop preliminary data for extramural grant applications. The Pumphrey program has authored or co-authored ~25 peer-reviewed scholarly publication over the past three years that are associated with our breeding efforts.

Outputs and Outcomes: File attached

WGC project number: 3019 3162
WGC project title: Improving Spring Wheat Varieties for the Pacific Northwest
Project PI(s): Mike Pumphrey
Project initiation date: 2019
Project year: 3 of 3

Objective	Deliverable	Progress	Timeline	Communication
Develop biotic and abiotic stress tolerant, high-yielding, and high-quality hard red, soft white, club, and hard white spring wheat varieties for diverse Washington production environments.	New spring wheat wheat varieties that are superior to existing varieties. This effort includes all four market classes of spring wheat and all precipitation regions in Washington state.	WSU released varieties generated significant positive economic impact for PNW growers in 2021 by our varieties being planted on 80% of spring wheat acres. Multi-year yield trial data for the top three WSU SWS wheat varieties across all locations demonstrates that our market-leading varieties produced 105-108% of the top three varieties from other breeding programs. A Hessian fly resistant club wheat, Roger, and a hard red spring wheat, Hale, were approved for release/Foundation seed production in 2021. Our 2-gene Clearfield breeding efforts have matured, and we have released Hedge and Net CL+ to date. Our attention to aluminum tolerance, stripe rust resistance, Hessian fly resistance, and stable falling numbers over the past few grant cycles has resulted in selection of superior lines for these traits.	Recurring annually	WSU Field days, Private company field days, Workshops/meetings/presentations attended/given by Pumphrey: Western Wheat Workers, WSCIA Annual Meeting, WSCIA Board, WA Grain Commission, Trade tours/international buyer groups. Annual Wheat Life contributions as requested
Improve PNW spring wheat germplasm to strengthen long-term variety development efforts/genetic gain.	Enhanced germplasm. Consistent genetic gain for many desirable traits.	Multiple stripe rust, aluminum tolerance, Hessian fly, and quality traits were selected in backcross populations for long-term parent building in 2021. A continued focus in 2021 was backcrossing new Hessian fly resistance genes into spring wheat germplasm. Extensive crossing blocks for irrigated hard red spring wheat germplasm development were also completed. Two large fall-seeded spring wheat trials were conducted in 2021 with irrigation. Backcrossing of the AXigen trait for CoAXium wheat production system was continued into both soft white and hard red spring wheat germplasm.	The payback for this work will fully be realized for many years to come as these lines continue to be crossed into existing breeding lines. We expect this effort to result in introgression of desirable variation for yield, disease resistance, and other agronomic characters.	
Discover/improve/implement scientific techniques and information to enhance current selection methods.	Current projects are development of DNA markers for useful sources of Hessian fly and stripe rust resistance, drought and heat tolerance loci, identification of superior germplasm through geneomic selection, screening for tolerance to aluminum, development of facultative wheat, and the development of high-throughput field phenomics selection methods.	Several specific trials and locations were again evaluated in 2021 to help long term breeding efforts. Scientific products of our efforts through multiple projects over the 3-year project cycle include ~25 publications in high-quality international scientific journals. Information from these research efforts help guide specific germplasm development efforts focused on Hessian fly, stripe rust, genomic selection, high-throuput phenotyping, genomic selection, marker-assisted selection, drought tolerance, heat tolerance, yield, test weight, gluten strenth, etc.	This works has short, medium, and long term goals. We are already using new DNA markers discovered through this work to improve selection for quality and pest resistance.	

Washington Grain Commission
Wheat and Barley Research Annual Progress Reports and Final Reports

Project #: **3163**

Progress Report Year: ___*3_ of _3*___ *(maximum of 3 year funding cycle)*

Title: **Greenhouse and laboratory efforts for spring wheat variety development**

Cooperators: Mike Pumphrey, Josh DeMacon, Sheri Rynearson, Wycliffe Nyongesa, Vadim Jitkov

Executive summary:

Spring wheat varieties with high yields, good grain traits, complex stripe rust resistance, Hessian fly resistance, aluminum tolerance, superior end-use quality, and broad adaptation benefit Washington wheat producers by adding millions of dollars to annual returns. This project supports core efforts of the WSU Spring Wheat Breeding program by providing funding to make crosses and develop breeding populations in the greenhouse, staff support for management and selection of breeding materials in the field and greenhouse, and supports/enables the most effective end-use quality selection procedures for development of superior Washington spring wheat varieties. In addition to routine early-generation grain quality selection carried out through this project, we apply DNA marker technology to elite breeding materials, and conduct research projects and germplasm development of direct relevance to our breeding efforts. This project also supports our two-gene Clearfield and AXigen breeding efforts, Fusarium head blight resistance gene introgression, Hessian fly resistance gene introgression, and expanded irrigated hard red spring wheat breeding efforts. Our progress in each of these areas is consistent, and these outputs continue to shape our overall breeding efforts and directly contribute to variety release and on-farm profitability.

Impact:

Our release of top-yielding spring wheat varieties continues to be of substantial economic benefit to growers in Washington. The consistency, broad adaptation, disease and pest resistances, aluminum tolerance, sound grain traits, most desirable end-use quality, good falling numbers, and overall performance of these varieties reflect the outputs of comprehensive wheat breeding and genetics research efforts. Over the past six years Ryan, Seahawk, Tekoa, Melba, Hedge CL+, Net CL+, Alum, Chet, and Glee have been widely multiplied and/or grown across Washington. Each variety has most desirable quality, is top yielding, pest and disease resistant, and has been accepted and adopted by seed dealers and farmers. <u>Our wheat varieties occupied 80% of total Washington spring wheat acres in 2021 and our soft white spring wheat releases were planted on 95% of acres in this dominant class.</u> All soft white, club, and hard red spring wheat varieties released by the program under Pumphrey's leadership are rated as "Most Desirable" quality. Thus, at least 80% of 2021 spring wheat acres in Washington were most desirable.

Two new releases/Foundation seed increases were advanced in 2021. The first is a top-performing club spring wheat variety that is the first spring club to have Hessian fly resistance:

WA8325 ('Roger'). Roger two-year average yields in 12-16, 16-20, and >20 inch precipitation areas is comparable to the highest yielding soft white spring wheat varieties. 'Hale' (WA8315) is a broadly adapted hard red spring wheat with excellent yield, disease resistance, Hessian fly resistance, quality, and slightly higher protein than our current top-end yielding dryland varieties. Hale has the highest two and three-year average yields across all locations and was a top performer in the highly stressful 2021 trials.

Outputs and Outcomes: File attached

WGC project number: 3019 3163
WGC project title:Greenhouse and laboratory efforts for spring wheat variety development
Project PI(s): Mike Pumphrey
Project initiation date: 2019
Project year: 3 of 3

Objective	Deliverable	Progress	Timeline	Communication
Develop DNA markers and select breeding lines by marker-assisted selection with stripe rust resistance, Hessian fly resistance, and two-gene Clearfield™ herbicide tolerance as well as other traits when desirable.	Elite variety candidates will result, in part, due to these molecular selection activities. Many of these populations will be ideal for marker optimization, new genetic mapping studies, and potentially the basis of new competitively funded projects.	Axigen trait introgression continued, and we have made BC4 materials with this new herbicide tolerance to date. We have developed new DNA markers for a previously undocumented Hessian fly resistance locus that allow us to track resistance in most of our germplasm for the first time. KASP assays have been developed. Two new varieties were released based on marker-assisted selection and other selection efforts through this project.	Activities are cyclical and occur annually throughout the normal breeding cycles. 2021 work was completed on schedule.	Pumphrey attended/presented at numerous virtual WSU field days, workshops/meetings, PNW wheat Quality Council, WSCIA Board Meetings, WA Grain Commission meetings, industry tours. A Wheat Life article was written/contributed in 2021.
Select early-generation breeding lines with good end-use quality potential by eliminating inferior breeding lines prior to expensive and capacity-limited yield tests.	Elimination of lines with inferior end-use quality. This ensures only lines with acceptable end-use quality are tested in the field and maximizes efficiency in field operations. Current analyses include: NIR-protein, NIR-hardness, SKCS-hardness, SDS micro-sedimentation, PPO, and micro-milling.	Another year of selection was succesfully completed in 2021, with approximtaely 3000 lines evaluated through the various quality tests. Markers for PPO and waxy alleles were validated and applied to breeding materials.	Return on investment is realized each year, since lines with poor end-use quality are not tested in expensive and capacity-limited yield tests. This allows for additional yield testing of lines with good end-use quality and more efficient variety development.	PNW preferred varieties brochure lists all releases as Most Desirable Quality.
Conduct greenhouse operations required for variety development, including crossing, doubled haploid development, generation advancement, and seedling assays such as herbicide screening, and stripe rust screening.	Lines for field testing that contain desirable and novel characterisitcs. This is where new varieties are born. Greenhouse operations also allow more rapid breeding cycles by advancing F1 and F5 generations every year as part of of our routine breeding efforts. Seedling evaluation of stripe rust resistance and herbicide tolerance screening are also major greenhouse activities.	We continue to use the expanded greeenhouse space to our advantage to increase breeding and research materials, make crosses, and conduct experiments. COVID-19 has some, but minor impact on our ability to conduct this day to day work.	Annual greenhouse multiplication and crossing completed in 2021, including two large crossing blocks and backcrossing and MAS for Hessian fly, herbicide tolerance, and numerous other markers	Several greenhouse tours led in 2021.

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Wheat and Barley Research Annual Progress Reports and Final Reports

Project #: 3208

Progress Report Year: ___2_ *of* _3___ *(maximum of 3 year funding cycle)*

Title: **End-Use Quality Assessment of Washington State University Wheat Breeding Lines**

Cooperators: *Mike Pumphrey, Arron Carter, USDA-ARS WWQL*

Executive summary:

WSU spring and winter wheat variety development programs heavily emphasize selection for superior end-use quality. Quality evaluation of WSU breeding lines has been ongoing for over 50 years. Effective quality testing is essential for the recent release of new varieties from all market classes that are at or near the top of end-use quality rankings. This project supports a scientist to conduct thousands of quality tests per year for the WSU wheat breeding programs in conjunction with USDA-ARS Western Wheat Quality Laboratory efforts.

The majority of wheat from the PNW is exported to overseas markets. To maintain current markets and penetrate new markets, PNW wheat must possess quality characteristics that make it superior for use in both domestic and overseas markets. Therefore, before it is released, a new variety must be tested to determine if it is suitable for use in specific end-use products. In addition, increased competition from traditional and non-traditional export countries necessitates enhancing the end-use quality of our wheat. The loss of overseas markets would continue to cause a reduction in the demand and therefore the price of wheat, resulting in losses to Washington farmers. Washington wheat growers, as well as grain buyers and exporters, benefit from the availability of wheat varieties that require less inputs and possess superior, consistent end-use quality.

Impact:

Sockeye CL+, Jasper, Puma, Piranha CL+, Devote, Stingray CL+, Otto, Scorpio, Sequoia, Net CL+, Glee, Alum, Chet, Tekoa, Seahawk, Ryan, Melba, Hedge CL+, Hale, and Roger are examples of top-performing and widely grown WSU variety releases that were released by WSU winter and spring wheat breeding programs in recent years that also have very good to excellent end-use quality. One of our primary goals as public breeding programs in Washington State is to set a high bar for end-use quality and continue to raise that bar for long term market health. By releasing lines with superior agronomics, paired with most desirable end-use quality, we provide growers with options that put quality in the decision process, while not sacrificing yield or other agronomic and yield protection traits. Several of our newest varieties are preferentially sourced because of their superior end-use quality, and specific traits like gluten strength and breadmaking quality, low cadmium concentration, partial waxiness, and outstanding cookie and cracker quality. This short, medium, and long-term impact is of paramount importance to the Washington grain industry.

Outputs and Outcomes: File attached

WGC project number: 3208
WGC project title: End-Use Quality Assessment of Washington State University Wheat Breeding Lines
Project PI(s): Mike Pumphrey and Arron Carter
Project initiation date: 1-Jul-20
Project year (X of 3-yr cycle): 2 of 3 year cycle

Objective	Deliverable	Progress	Timeline	Communication
Early to late generation quality testing of WSU experimental lines to aid variety development	New spring wheat and winter wheat varieties that are superior to existing varieties. This effort includes all market classes of spring and winter wheat and all precipitation regions in Washington state.	Over 1200 breeding samples were analyzed by numerous milling and baking quality tests in 2021. **Four new wheat varieties were released in part due to this project and data in 2021. Others are planned for 2022 release.**	The economic return for this work will manifest itself each breeding cycle with superior quality varieties and germplasm.	Progress was discussed at numerous field days (>10), grower meetings (4), the annual Research Review, through WSCIA meetings, Wheat Life, Variety Release Meetings, and direct communication with the WGC.
Support genetic analysis of end-use quality to identify desirable alleles and to predict end-use quality through new genotyping methods	Improved germplasm selection procedures which translate to more efficient, cost-effective, and consistent genetic gain for end-use quality.	Multiple special milling and baking trait experiments were evaluated in 2021, including evalution of DNA markers for PPO and a dough strength locus. The quality of soft white common by spring club lines were analyzed. The quality of new germplasm with Hessian fly resistance and other introgressed traits was determined.	The reward for this work will compound each year and will fully be realized for many years to come as these lines continue to be crossed into existing breeding lines. We expect this effort to result in routine selection of outstanding quality wheat.	

Washington Grain Commission

Wheat and Barley Research Annual Progress Reports and Final Reports

Project #: **3019 3674**

Progress Report Year: *_1___ of __3__ (maximum of 3 year funding cycle)*

Title: **Evaluation of WSU wheat breeding lines for management of Hessian fly and development of DNA markers for resistance breeding**

Cooperators: Mike Pumphrey, Arash Rashed

Executive summary:
Hessian fly (HF) infestations continue to cause significant annual yield losses in spring wheat production areas of Washington and neighboring regions of Oregon and Idaho. Hessian fly is in many ways a silent problem. Moderate infestations are not visually striking, and their occurrence is somewhat variable over space and time. Factors such as weather patterns, crop rotation, variety selection, and tillage or conservation practices can impact HF pressure. Infestation may also be a significant barrier to increased conservation tillage practices in Washington. Advanced breeding lines, new sources of resistance genes *H13*, *H26*, and two unknown resistance sources, along with winter wheat varieties were screened for Hessian fly resistance in 2021. Backcross populations were developed with four new sources of resistance, and progeny advanced to select homozygous resistant lines. Winter wheat populations and varieties were screened to introgress HF resistance into winter wheat. This project supported the screening of all new entries in WSU Variety Testing Program spring wheat trials and winter wheat variety trials. NEW DNA markers that allow diagnostic tracking of the previously unknown spring wheat resistance source that is in most spring wheat varieties were validated and fully implemented in 2021.

Impact:
Spring wheat production has averaged ~30 million bushels in WA in recent years. A conservative state-wide Hessian fly loss estimate of 2% translates to over $4,000,000 per year; yield loss due to HF in moderately to heavily infested areas often exceeds 25% and may be 100% in localized areas. In addition to protecting from $45-$104 per acre via HF resistance, improved variety development can translate to $Millions/year in WA spring wheat farm gate value. Our recent emphasis on winter wheat is due to infestations increasingly observed in winter wheat in the region. While not as severe as spring wheat infestations, we believe the value of Hessian fly resistance in winter wheat is underestimated and increasing.

Our most recently released soft white spring wheat varieties Seahawk, Tekoa, and Ryan, new club release WA8325 (Roger) and hard red spring wheat varieties Hale, Net Cl+, Glee, Alum, and Chet are resistant to Hessian fly because of selection activities carried out by this collaborative project. Given their broad acreage in Washington State, this represents a major economic impact to Washington farmers.

Outputs and Outcomes: attached

WGC project number: 3674
WGC project title: Evaluation of WSU wheat breeding lines for management of Hessian fly and development of DNA markers for resistance breeding
Project PI(s): Pumphrey
Project initiation date: 2021
Project year: 1 of 3

Objective	Deliverable	Progress	Timeline	Communication
Screen WSU Spring breeding populations and advanced breeding lines for resistance to Hessian fly in the laboratory	Information on resistance of elite breeding lines on an annual basis	Over 300 spring wheat lines, 31 winter wheat varieties, numerous breeding populations, and new entries into the WSU Wheat Variety Testing Program were screened in 2021. Data has been shared with Extension personnel, through the Variety Selection Tool, WSCIA Buyer's guide, etc.	Annually	Progress was presented by M. Pumphrey at field days, plot tours, at Wheat Research Reviews for individual states. Presentations continue to be made to the Washington Wheat Commission and WAWG conferences upon invitation. Progress was reported in Wheat Life magazine.
Continue to incorporate "new" Hessian fly resistance genes into breeding lines	Improved germplasm with useful sources of Hessian fly resistance	Several backcrosses have been made to known (H13, H26) and unknown resistance gene donors, using susceptible elite line "Dayn" as the initial recipient parent. BC4-derived Dayn-Hessian fly resistant introgression lines were evaluated for the second year in yield plots and for grain quality in 2021, and elite performers used in routine breeding crosses in fall 2021. Also, JD and Melba were used to introduce four new resistance sources through backcrossing with phenotypic selection. Diagnostic DNA markers for the resistance present in Seahawk, Kelse, and some other spring wheat varieties were fully validated in 2021.	Annually	

Washington Grain Commission
Wheat and Barley Research Annual Progress Report

Project #: 13C-3019-3687 (55); AWD003580

Progress Report Year: *__1__ of __3__ (maximum of 3 year funding cycle)*

Title: *A Genetic Arsenal for Drought Tolerance, Getting to the Root of the Problem*

Cooperators: *Karen A. Sanguinet, Kimberly Garland-Campbell, Timothy Paulitz*

Executive summary: Dryland farms in eastern Washington experience yield losses due to drought stress and disease pressure from soil-borne pathogens and 2021 was no exception. Improving wheat root structure can help to resist such stresses by increasing access to water as well as selecting for traits that confer tolerance to belowground stresses. Changes in tillage practices have changed the soil structure and pathogen load, altering root-microbiome interactions. Thus, there is an urgent need for understanding and improving both the root system and structure to improve stress tolerance. We found cooler canopy temperatures were associated with better yield under drought and healthier roots suggesting that breeding for more efficient root systems can improve the performance of Washington wheat under drought. Lignin content and accumulation has been linked with different stress tolerances and responses in crop plants because it lends rigidity to plant cell walls and increases in response to drought, heavy metals, salinity, and pathogen attack. Therefore, managing overall lignin content is a key step for generating wheat lines with improved stress tolerance. We have been working to understand how lignin content and deposition in winter wheat roots contributes to stress tolerance. To this end, we study a landrace from Iran called AUS28451 and the winter wheat variety Louise, which have different lignin contents in their root systems. We found that both roots and shoots of AUS contain less S lignin than G lignin, whereas Louise has higher amounts of S lignin. S-lignin is correlated with the ability to breakdown biomass (i.e. more S lignin means plant biomass breaks down more easily). We also performed in silico characterization of the *CAD* and *COMT* gene families that help biosynthesize lignin. We have identified root-specific *CAD* and *COMT* genes and are working to understand how they are regulated in response to stress. In addition, we are running qRT-PCR experiments to determine how lignin genes are expressed in roots in response to different environmental cues and in different varieties. We have also identified *cad* and *comt* mutants in the Kronos background to examine loss of function phenotypes and contributions of the subgenome copies to root architecture and stress responses.

Impact: According to USDA data, farmers in Washington planted 70,000 acres of wheat in 2021, down from 90,000 in 2020 with decreased yields of 2.6 million bushels at an average 38 bushels per acre compared to 6.4 million bushels at 90 bushels per acre in 2020. In years where water is sparse like in 2021, wheat yields can decrease by more than half. Our research goal is to improve the reliance of wheat root systems and understand the contribution of lignin to improved drought and stress tolerance. Certainly, there is a long way to go, but our goal is to help breeders and farmers by understanding the physiological constraints to water movement in wheat and hope to improve resource allocation from roots to the shoots as well as optimize lignin composition and ratios.

WGC project number: 13C-3019-3687
WGC project title: A Genetic Arsenal for Drought Tolerance, Getting to the Root of the Problem
Project PI(s): Karen A. Sanguinet, Kim Garland-Campbell, Timothy Paulitz
Project initiation date: 7/1/2021
Project year (X of 3-yr cycle): 1 of 3

Objective	**Deliverable**	**Progress**	**Timeline**	**Communication**
1.Examine accumulation of lignin and other aromatic polymers in wheat roots in Louise, AUS28451 and correlate that with stress responses	Determination of the lignin content of shoots versus roots of Louise and AUS28451 as well as other aromatic polymers that may contribute to stress tolerance. We will be able to determine if lignin or potentially another compound contributes to stress tolerance in AUS roots	In year 1, we were able to determine the lignin content in roots and shoots of AUS28451 via a collaboration with Dr. John Ralph at UW-Madison.	In year 1, lignin and aromatic analysis was performed in shoot and roots of the parental lines. We will continue with selections in subsequent years 2 and 3.	We are currently working on two manuscripts, one describing the total lignin analysis pipeline and the other will be a report of the disease resistancs and stress tolerance of the lines. A paper was submitted in collaboration with Dr. Smertenko's group and an article was published in wheat life in October 2021.
2. Identify the CAD and COMT lignin biosynthetic genes in wheat	Since we determined that there is more lignin of AUS root systems, this will enable us to determine which of the CAD and COMT enzymes contribute to lignin content in both wheat roots and shoots. This will then serve as a marker for breeders to assess lignin content.	In year 1, the *in silico* analysis was performed. Years 2 and 3 will examine activity of the genes via molecular techniques in both shoots and roots and RNA expression analysis.	The in silico analysis of the *CAD* gene familiy was completed in year 1, whereas, year 2 will focus on the *COMT* gene family. Molecular follow-up experiments will be run in year 3.	We have drafted a paper for the CAD gene family in wheat and we are working on qRT-PCR data as a final step prior to submission. Characterization of the COMT gene family will occur in year 2. All data will be shared with growers in field day abstracts, articles, and podcats.
3.Determine the influence of CAD and COMT on root architecture and stress resistance in the Kronos tilling population of wheat	Our data as well as a recent publication in sorghum indicate that there is a link between lignin content, disease responses within the plant and root architecture. Therefore, we will use the Kronos TILLING population of wheat to functionally test the role of mutations in CAD and COMT on stress tolerance and root architecture.	In year 1, mutations in CAD and COMT genes of interest were identified in Kronos. The lines will be grown out and we are working on backcrosses to Kronos. There was some sterility in some of the lines either from other background mutations or from CAD/COMT. The mutant lines once confirmed, will be analyzed for stress tolerance and root growth/architectural traits.	In year 1, mutations in CAD and COMT genes were identified and planted in the greenhouse. The mutants will be assayed for stress responses in years 2 and 3.	Since are working on growing Kronos and crossing the mutant lines, most of the reporting for this aim will not occur until year 3.

Washington Grain Commission
Wheat and Barley Research Annual Progress Report

Project #:3144

Progress Report Year: *_3_ of _3*

Title: ***Breeding Wheat Varieties With Efficient Control of ROS Production***

Cooperators: *Dr. Michael Pumphrey, Department of Crop and Soil Sciences.*

Executive summary: *This project aims to advance toolbox for breeding drought and heat tolerant wheat varieties. Our approach is based on the fact that harsh environmental conductions, including heat and drought, increase production of free radicals also known as Reactive Oxygen Species (ROS). ROS diminish the yield by damaging cells inside plant body. Plants alleviate the ROS damages using so-called "scavenging" mechanisms. Varieties with higher scavenging activity would yield better in hot and dry climates. We want to identify genetic markers with more efficient ROS scavenging and introduce these markers into breeding programs. Previously, our laboratory developed a technique for measuring ROS scavenging under the greenhouse condition.*

In Year 1 *(growth season 2019) the suitability of our technique for analysis of material in the field was tested using 14 spring wheat varieties in Lind, Moses Lake, and Spillman farms. We found that our technique detected variability of the ROS scavenging in the field-grown material. One of the tested varieties, Kelse, was amongst varieties with more efficient ROS scavenging.*

In Year 2 *we collaborated with Dr Pumphrey to phenotype ROS scavenging in 180 RILs of the biparental population Kelse x Scarlet in Lind. This RIL population has been genotyped. It means we can use this material to identify genetic markers of efficient ROS scavenging. The material was collected on May 29 when the maximum day temperature reached 88°F. Despite delays caused by COVID-19 pandemics, we completed the measurements. The results demonstrate significant variability of ROS scavenging activity in the population.*

In Year 3 *in collaboration with Dr. Pumphrey we repeated phenotyping of 180 RILs of the biparental population Kelse x Scarlet in Lind and in Othello. Two replicates were planted at each location. The leaf material in Lind was collected on July 1, 2021 when the air temperature was 93°F. Due to the lack of precipitation in April and May of 2021 the soil was very dry and all plants were very stressed: leaves were curling and plants were*

yellowing. The Othello site was affected to the dust storm that bowed away soil with the fertilized. As a consequence, the amount of fertilizer was not even across the field and plants were of different size and developmental stage. This variability in material was not suitable for measuring peroxisomes. In this way we have lost two replicates out of four. Two replicates measured in Lind were not sufficient to get statistically significant data.
Another activity in Year 3 was measured activity of ROS scavenging enzymes catalase, ascorbate peroxidase and guaiacol peroxidase in Kelse and Scarlet in response to heat and drought stress in the greenhouse conditions. This experiment demonstrated that of three enzymes, only activity of guaiacol peroxidase increased in Kelse under stress conditions, whereas activity of other enzymes was not affected. No differences in the enzyme activity were detected in Scarlet. This outcome is consistent with the hypothesis that ROS scavenging system is more activity in Kelse, but the fact that activity of only one enzyme was increased suggests these three peroxidases is not the key ROS scavenging mechanisms in these varieties.

Impact:

1. We optimized phenotyping ROS scavenging in field trials by developing optimal procedures for sample collection and transportation.
2. *We used this technique to produce phenotyping data on ROS scavenging in the Kelse x Scarlet population under heat and drought stress. This information will be used to identify genetic marker of efficient ROS scavenging. In the long-term this will contribute to breeding drought and heat-tolerant wheat varieties.*
3. *The project provided training to undergraduate student Jessica Fisher, graduate student Kathleen Hickey, and post-doctoral scientist Taras Nazarov.*
4. *The outcomes of this project were used as preliminary data for two successful grant proposals. First, USDA Research and Extension Experience for Undergraduates aims at training students in mechanisms of stress resiliency. Second, Foundation for Food and Agriculture Research (FFAR) proposal that aims at identification of genetic markers of more active ROS scavenging system. Two labs in WSU, Pumphrey and Smertenko, one lab in CIMMYT (Matthew Reynolds) and one lab in Flinders University, Australia (Kathleen Soole) are collaborating on this project. This grant will allow significantly expand the scope and accelerate our research by giving us access to more germplasm and resources. In particular we have funding for one post-doctoral scientist to work on this project as well as funding for reagents, consumables and cost of the field work.*

Outputs and Outcomes:

WGC project number: 3144
WGC project title: **Breeding Wheat Varieties With Efficient Control of ROS Production**
Project PI(s): Smertenko
Project initiation date: June 10, 2019
Project year (X of 3-yr 3 of 3

Objective	Deliverable	Progress	Timeline	Communication
Objective#1. Determine correlation between peroxisome abundance and ROS homeostasis under drought and heat stress.	Measure peroxisome abundance in spring wheat varieties grown under different climate conditions.	Measured peroxisome abundance in 7 soft white and 7 hard spring wheat varieties Diva, Louise, Melba, Ryan, Whit, Seahawk, Tekoa, LCS Luna, SY Selway, Alum, Chet, Dayn, Glee and Kelse grown at Spillman Farm, Moses Lake, and Lind.	Completed	Was communicated at the annual 2020 Review Meeting
Objective#2. Identify spring wheat genotypes with low ROS production.	Screen genetically diverse population for genotypes with more active ROS scavenging	Peroxisome abundance was used as the proxy of ROS scavenging. Measured peroxisome abundance in 180 RIL lines of mapping population Kelse x Scarlet growth in Lind. We collected leaf material on May 29 2020 when the temperature was between 80 and 88°F. It means plants experienced both heat and drought stress. In 2021 we collected material in Lind on June 1 when the temperature was between 92°F and 94°F. We could not collect material in the second location, Othello, because fertilized was blown away with the top layer of soil by strong wind. Two replicated in Lind were not sufficient to generate statistically reliable data.	Completed	Will be communicated at the annual 2022 Review Meeting
	Expression of peroxisome biogenesis genes	We measured transcription level of two peroxisome biogenesis proteins: catalase and PEROXIN11C. We found that transcription of both genes was higher in Scarlet than in Kelse.	Completed	Will be communicated at the annual 2022 Review Meeting
	Measure ROS homeostasis	We measured activity of three ROS scavenging enzymes catalase, ascorbate peroxidase, and guaiacol peroxidase. We found that only activity of guaiacol peroxidase was increased.	Completed	Will be communicated at the annual 2022 Review Meeting
Measurable impact in 1 year	Identify genotypes with low ROS production under drought and heat and start screening breeding populations for low ROS production trait.	Kelse was found to have lower ROS production in field and greenhouse studies.		
Measurable impact in 2 years	Identification of breeding lines with low ROS production under heat and drought.	Kelse x Scarlet mapping population was phenotyped in Lind and generated suitable data. Published one article in Wheat Life. Recorded two Wheat Life podcasts.		

Measurable impact in 3 years	Field trials of lines with low ROS production under heat and drought and laboratory eperimets	Activity of one ROS scavenging enzymes, guaiacol peroxidase was higher in Kelse than in scarlet. Transcription of peroxisome biogenesis genes under head and drought stress is higher in Scarlet than in Kelse. Two grants were funded: USDA and FFAR. Published one article in Wheat Life.		

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Project #: 126593

Progress Report Year: *1 of 3 years (maximum of 3 year funding cycle)*

Title: Intelligent Prediction and Association Tool to Facilitate Wheat Breeding

PI: *Dr. Zhiwu Zhang*

Cooperators: *Dr. Michael Pumphrey, Dr. Kimberly Campbell, and Xianming Chen*

Executive summary: *We updated one software package (GAPIT), released one new software package (MMAP), and published two articles partially under the support of this project in this fiscal year. The GAPIT software package updated for new functions for both GWAS (Genome Wide Association Study) and GS (Genomic Selection) (http://zzlab.net/GAPIT). GAPIT has received over 1500 citations, including the breeders at WSU and USDA-ARS. The manuscript of update GAPIT (version 3) was published by Genomics, Proteomics, and Bioinformatics. MMAP makes it easy for breeders to conduct molecular breeding (http://zzlab.net/MMAP). Users can simply upload genotype and genotype data and download breeding values when the computation is complete on the platform. The MMAP was published by Bioinformatics.*

Impact: *Our collaborative research positions the WSU/USDA-ARS research team as one of the world's leading institutions to conduct fundamental and applied research, publish academic articles, and update and release software packages. Our project's success not only benefits Washington but will also benefit the entire world through the dissemination of knowledge. In short term, breeders can conduct the most of data analyses without frustration on data formatting and selecting different analytical functions. They have more opportunities to find the causative genes controlling traits of interest. They have more confidence to eliminate lines with low genetic potentials to reduce the cost of field trials. In long term, breeders have more chances to retain the genetic lines with desirable genes and recombine them to create superior varieties.*

WGC project number: 126593

WGC Project title: **Intelligent Prediction and Association Tool to Facilitate Wheat Breeding**

Project PI(s): *Zhiwu Zhang, Michael Pumphrey, Arron H. Carter, Kimberly Campbell, and Xianming Chen*

Project initiation date: 1-Jul-21

Project year: 1 of 3

Objective	Deliverable	Progress	Timeline	Communication
1) Enhance Genomic Prediction with Artificial Intelligence	An updated cloud computing platform MMAP implementing both conventional and artificial intelligence genomic prediction methods and conducting optimization to improve prediction accuracy.	We updated the cloud computing platform MMAP with multiple conventional genomic prediction methods and artificial intelligence methods. The platform (https://zzlab.net/MMAP) consists multiple servers using Java Script. One peer review article was published by Bioinformatics, which acknowledged the support from WGC.	December 31, 2021: Add artificial intelligence genomic prediction methods to MMAP cloud computing platform; June 30, 2022: Optimize among conventional and intelligence genomic prediction methods.	1) One article for Wheat Life; 2) One presentation at WGC annual meeting; 3) One presentation at national/international conference; and 4) one paper on academic journal