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Washington State University Wheat and Barley Research Progress Reports

WASHINGTON GRAIN COMMISSION

2018-2019 Fiscal Year

2018-19 WSU Wheat & Barley Research Progress Reports to the Washington Grain Commission

Researcher / Title of Project **Page #**

~~**Burke** / *Weed Management in Wheat*~~ 1

~~**Burke** / *Herbicide Resistance and Susceptibility in Wheat and Weeds*~~ 5

Carter / *Field Breeding Hard White and Red Winter Wheat* 7

Carter / *Use of Biotechnology for Wheat Improvement* 11

Carter / *Field Breeding Soft White Winter Wheat* 16

Chen / *Control of Wheat and Barley Rusts* 20

Chen / *FINAL REPORT Control of Wheat and Barley Rusts* 30

Esser / *Evaluation of Barley Varieties* 55

Esser / *Evaluation of Wheat Varieties* 57

Garland Campbell / *Evaluation and Selection for Cold Tolerance in Wheat* 64

Garland Campbell / *Club Wheat Breeding* 66

Haggerty / *Assessment of Soil Acidity on Soil-Borne Pathogens, Weed Spectrum, Herbicide Activity Yield, and Crop Quality on Dryland Wheat Production* 73

Lyon / *Extension Education for Wheat and Barley Growers* 75

Morris / *Quality of Varieties and Pre-Release Lines:* Genotype & *Environment – "G & E" Study* 77

Morris / *Supplemental Support for Assessing the Quality of Washington Wheat Breeding Samples* 80

Morris / *Evaluation of alternative technologies for determining Falling Number: The Chopin 'Amylab FN', and 'Testogram' quick method* 82

Morris / *Defining the relationship between Falling Number and Sponge Cake* 85

Murphy / *Barley Improvement for Yield, Adaptation and Quality* 89

Murray / *Control of Strawbreaker Foot Rot and Cephalosporium Stripe in Winter Wheat* 92

Murray / *Enhancing Resistance to Snow Mold Diseases in Winter Wheat* 99

Paulitz / Management of Nematode Diseases with Genetic Resistance 103

Pumphrey / *Fusarium Crown Rot on Wheat: Prebreeding and Development of Tools for Genetic Disease Management* 110

Pumphrey / *Evaluation of WSU Wheat Breeding Lines for Management of Hessian Fly and Development of DNA Markers for Resistance Breeding* 113
Pumphrey / *End-Use Quality Assessment of Washington State University Wheat Breeding Lines* 115
Pumphrey / *Improving Spring Wheat Varieties for the Pacific Northwest* 117
Pumphrey / *Greenhouse and laboratory efforts for spring wheat variety development* 119
Sanguinet / *A Genetic Arsenal for Drought Tolerance, Getting to the Root of the Problem* ... 121
Steber / *Developing Washington Wheat with Stable Hagberg Falling Numbers* 123
Zhang / *Intelligent Prediction and Association Tool to Facilitate Wheat Breeding* 126

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,** TD Murray, XM Chen, KG Campbell, CF Morris

Executive summary: One hard red winter wheat line was released in 2015. Sequoia (WA8180) is a standard height hard red winter wheat targeted to the <12" rainfall zones of Washington. This line has good end-use quality, average protein content, very good test weight, good stripe rust resistance, and good yield potential. What makes this line stand out from other lines is its ability to emerge from deep planting and dry soils. This line will be a benefit to growers in the low rainfall zones in moisture limiting conditions. This variety has replaced many of the Farnum acres and was in commercial production in 2018. Apart from this line, there are additional lines being testing in variety testing for release potential, under both low and high rainfall conditions. WA8268 is a hard red line adapted to the high rainfall zones of the state with excellent yield potential, disease resistance, and aluminum tolerance. In 2017 and 2018, WA8268 was in the top significant group for yield with newly released cultivars LCS Jet and LCS Rocket. As such, we have begun seed increase of this line. Additionally, WA8289 was a top yielding line in both WSU and OSU VTP trials. Continued emphasis has been 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, snow mold resistance, and aluminum tolerance. We have identified lines with aluminum tolerance and are testing them for release potential. 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. One of these, WA8252, appears to have very high market potential in Idaho under irrigation. Our next main target is to develop hard red cultivars with herbicide resistance. These include lines with imazamox tolerance, CoAxium resistance, and some novel traits identified within the WSU weed science program. These lines have the potential for large market share within the state to improve wheat cropping systems.

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. Emergence capabilities are a desired trait to reduce risk to planting failures under deep planting conditions when moisture is limited. WA8268 and WA8289 are two WSU hard red lines targeted to high rainfall conditions and will provide growers with a high yielding line with good disease resistance adapted to PNW growing conditions. WA8252 is a hard white winter wheat line which is being tested by different companies for performance potential and is under consideration for release. Current and future hard red and white lines are targeted to lead to and maintain a sustainable production of hard wheat in the PNW.

WGC project number: 3193
WGC project title: Development of hard red winter wheat
Project PI(s): AH Carter
Project initiation date: July 1, 2016
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 2015 we released Sequoia, and was in commercial production in 2018, replacing many of the Farnum acres. We have 3 low rainfall and 3 high rainfall hard red breeding lines in statewide testing for release consideration. WA8268 has been performing very well in high rainfall trials and WA8248 has shown excellent aluminum tolerance. WA8289 has shown good potential in WA and OR VTP trials. We had over 3,500 plots and 10,000 rows of hard material under evaluation at various stages of the breeding process for 2018. 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 been on developing lines with herbicide tolerance as well.	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 16 locations in 2018. This includes emergence, winter survivability, heading date, test weight, plant height, and grain yield. Our Kahlotus and Ritzville trial gave a very good screen for emergence potential. Our snow mold locations gave a good rating of snow mold tolerance. All other locations had very good stand establishment gave us very good information for selection. Similar numbers of entries, locations, and data were planted in 2018 for 2019 evaluation	Evaluation is done annually at multiple locations across the state.	In 2018 we communicated results of this project through the following venues: 12 peer-reviewed publications; 4 field day abstracts; 6 invited speaker presentations; 8 poster presentations; 7 popular press interviews; 3 grower meeting presentations; 12 field day presentations; 2 seed dealer presentations; participation in the Tri-State Grain Growers Convention; and hosting of 4 trade teams.
	Biotic and Abiotic stress resistance	Lines were screened for emergence, cold tolerance, snow mold, stripe rust, eyespot foot rot, nematodes, Cephalosporium stripe, SBWMV, 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 milling characteristics were advanced to baking trials. Data should be back in early 2019. Lines with inferior performance will be discarded from selection in 2019. We screened nearly 1200 early generation lines for end-use quality in 2018.	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, 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 now since that material has matured more emphasis is on the hard red material. Imazamox material is in final screening and lines for release potential should be identified in 2019. Other material will be coming out of the greenhouse for future screening in 2019	Evaluation is done annually at multiple locations across the state	
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 and Rht8, as well as standard height cultivars.	Crosses made through the project #5195 will be evaluated under field conditions upon MAS completion.	
	Stripe rust genes	Multiple different stripe rust resistance genes have been introgressed into out germplasm which are under evaluation in Mount Vernon, Central Ferry, and Pullman.	Crosses made through the project #5195 will be evaluated under field conditions upon MAS completion.	
	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 completion.	
	Low PPO genes	Initial selection for lines with low PPO enzyme activity are ongoing and will continue to be tested in 2019.	Crosses made through the project #5195 will be evaluated under field conditions upon MAS completion.	

	CoAxium herbicide resistance	Crossing has begun and markers are currently being used for confirm resistance. Once confirmed, field testing will occur to select lines with release potential.	Crosses made through the project #5195 will be evaluated under field conditions upon MAS completion.	
	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 completion.	

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

Project #: 5195

Progress Report Year: *_1_ of _3__*

Title: Use of biotechnology for wheat improvement

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

Executive summary: In 2018 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 main focus for marker-assisted selection are foot rot resistance, stripe rust resistance, herbicide tolerance, and end-use quality. These are our primary focus due to very good markers having been developed and the importance of these traits in Washington. Additional traits include aluminum tolerance, SBWMV, dwarfing genes, low PPO, Fusarium head blight, Hessian fly, Cephalosporium, and nematode resistance. Over 12,000 data points were collected on 240 populations to confirm presence of desired genes based on marker profiling. These have been advanced to field testing to confirm presence of the selected genes. Markers were also used to screen all advanced breeding lines to identify presence of known genes. This information was used for selection and advancement purposes (in conjunction with field data) as well as for selecting lines which should be cross-hybridized to create future populations. The process of marker-assisted selection is an ongoing process, and at any given point we either have lines planted for analysis, in the laboratory undergoing marker profiling, or on increase in the greenhouse after selection to advance seed into field evaluations. Our genomic selection efforts are proceeding and we have models for end-use quality and snow mold tolerance. In the greenhouse, we made approximately 900 crosses consisting mainly of soft white and hard red germplasm. These are being advanced to the F1 generation, and then divided between our DH production and MAS protocol. We planted ~3,800 DH plants in the field in 2018 for evaluation. The remaining DH lines are undergoing increase in the greenhouse and will have a similar number ready for yield evaluation in 2019. 150 crosses have been submitted for DH production in 2018. We also have about 100 specialty crosses to introgress traits from non-PNW adapted material. Extra focus has been put on developing CoAxium wheat lines, and markers have selected fixed populations which are being advanced in the greenhouse in preparation for field planting. Hessian fly populations are on increase, and will shortly be sent to Idaho for phenotypic confirmation and selection of resistance.

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 pests and diseases, and agronomic adaptability and stability of released cultivars. All cultivars released (Otto, Puma, Jasper, Sequoia, Purl) have benefited through this project by incorporation of disease 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 as a whole 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, 2017
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 2018, 155 populations were screened for the Pch1 gene for foot rot resistance. Of these, lines with the gene were advanced in the greenhouse and field selection will occur this coming year. Since more lines are being advanced with Pch1, fewer populations are segregating for the gene as we recycle lines back into the breeding program.	Each year new crosses are made to Pch1 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 2017 we communicated results of this project through the following venues: 8 peer-reviewed publications; 2 field day abstracts; 4 invited speaker presentations; 6 poster presentations; 5 popular press interviews; 4 grower meeting presentations; 2 wheat workshop presentations; 12 field day presentations; 2 seed dealer presentations; participation in the Tri-State Grain Growers Convention; and hosted 3 trade teams.
	Stripe rust resistant lines	In 2018, 100 populations for stripe rust resistance (Yr5, Yr15, Yr17, Yr18, YrEltan) were screened for and selected upon for upcoming field testing.	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 2018, 10 F2 populations were screened for the genes Gpc-B1. Lines which had previously been selected for Gpc-Bi and Bx7oe have been advanced to yield testing. These lines have now been put back into the breeding cycle as parents. As such, many populations being advanced are fixed for the presence of these genes. Lines previously selected for GBSS genes (waxy) and the glutenin genes have also been advanced to yield testing. We also have DNA extracted to test for low PPO and GBSS gene in the upcoming year.	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	
	Herbicide Resistance	In 2018 we continued to make selection on populations carrying 2 genes for imazamox resistance using markers. Many lines now in crossing carry both, and markers are only used to confirm, no select, homozygosity. Populations of CoAxium wheat have been selected on using markers and will be moved to field trials in the coming year.		

	Reduced height lines	In 2018, 10 segregating populations were screened for identification of Rht genes. All breeding lines in field trials were screened to identify which dwarfing gene they carry in order to aid in selection and crossing decisions. Previous populations were planted at Lind to be screened for emergence potential.	Each year new crosses are being made to incorporate Rht genes into the breeding program. We also verify presence of dwarfing genes in all material to assist with selection of lines with enhanced emergence potential.	
	Genomic selection	With the assistance of Dr. Zhang and Dr. Godoy, we have begun genomic prediction model building. Lines from the 2015-2018 breeding program have been genotyped as well as a large training panel. Models built were used to assist with selection in the 2018 crop year. End-use quality is the first trait we are developing models for and validating. We also have models for snow mold and will be working on models for agronomic and SRI traits in 2019.	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
Genotyping advanced breeding lines	Provide useful information regarding genetic diversity and gene profiles to better estimate crossing potential	In 2018, the advanced germplasm was screened with DNA markers for about 20 traits 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 marker data has been very important to allow crosses to be made which maximize the number of genes we return to breeding populations.	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 2018 we made approximately 900 crosses which were targeted for herbicide resistance, low rainfall and high rainfall production. These crosses were mainly in soft white backgrounds, with about 15% of the crosses in hard material. Crosses were advanced to the F2 stage under greenhouse conditions. We also made about 100 crosses for introgression of the below mentioned traits. Seed grow outs of all these lines were also done under greenhouse conditions. Over 25,000 plants were grown and harvested in the greenhouse in 2018.	This is done annually, with the number of crosses/populations varying	
	Single-seed descent	No SSD populations were developed this year.		

	Doubled haploid	In 2018 we submitted 200 crosses for DH production. We are advancing roughly 3,700 DH lines in the greenhouse to get enough seed to plant in yield plots in the fall of 2018. We planted about 2,800 DH lines in the field for 2019 yield testing at both Pullman and Lind, with another 1,000 in single rows for additional observation and selection.	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 and CoAxium traits, and certain herbicides (in coordination with Dr. Burke). The populations are being made and increased in the greenhouse for field selection. Currently there are no markers for many of these genes, although some are in development. The idea was either to select based on field conditions or have populations ready once the markers were identified. These populations are either currently planted in the field for observations, undergoing marker screening, or undergoing phenotypic selection in the greenhouse.	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	All advanced breeding lines are screened and selected for coleoptile length. This includes 220 lines from 7 different trials	Screening and selection will be completed in 2018. Superior lines will be planted in the field and crossed back into the breeding program.	
	Foot rot	Advanced populations are being screened for foot rot resistance. Resistant lines will be used in the breeding program to incorporate this trait through a diversity of backgrounds	Screening and selection will be completed in 2018. Superior lines will be 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 be completed in 2018. Superior lines will be planted in the field and crossed back into the breeding program.	

	Stripe rust	An advanced population was screened for stripe rust resistance and that analysis is now complete. We identified over 20 QTL in PNW germplasm, about half of which appear to be novel. These lines are now being crossed to additional breeding lines and cultivars, and selection will be done with the recently identified markers to incorporate this resistance through a diversity of backgrounds. We continue to work on other populations to identify new genes for stripe rust resistance and develop markers for them. We also screen material in the greenhouse for resistance.	Screening and selection will be completed in 2018. Superior lines will be 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,** TD Murray, XM Chen, KG Campbell, CF Morris

Executive summary: A new club cultivar, developed in coordination and collaboration with the USDA breeding program, was approved for release in 2015 and will be named Pritchett. This is targeted to replace Bruehl in the non-snow mold areas, with improved disease resistance, yield potential, and cold hardiness. In the 2018 VT trails, Jasper continues to be one of the top yielding lines across >12" precipitation zones. Puma was in high demand and is now the #5 cultivar grown in the state, continuing to perform well across production zones. Otto, a 2011 release from this program, continues to maintain demand. Since 2015 it has been planted on over 200,000 acres. Nine advanced breeding lines were entered into WSU's Variety Testing (VT) Program, four in the low rainfall zones and five in the high. In 2018 we released Purl (WA8234), a SWW with excellent yield potential, high test weight, stripe rust resistance, eyespot resistance, and the first line we know of with confirmed nematode resistance and aluminum tolerance. Registered seed is being produced. WA8275CL+ (Stingray CL+) is another line which has performed very well in trials, and is on Registered seed increase as well. Over 2,000 unreplicated yield-trial plots were evaluated at either Pullman or Lind and over 41,000 F4 head rows and DH rows were evaluated in Pullman, Lind, and Waterville. Over 2,900 DH lines were planted for 2018 evaluation. High selection pressure is continually placed on disease resistance, emergence, flowering date, end-use quality, straw strength, etc. Multiple screening locations have been established to evaluate germplasm for: stripe rust resistance, foot rot resistance, snow mold resistance, good emergence, aluminum tolerance, soil borne wheat mosaic virus resistance, Cephalosporium tolerance, and nematode resistance. The program has also employed efforts to develop herbicide resistant cultivars and advanced lines have been entered into Variety Testing. Many lines have been performing very well and some are on breeders seed increase in preparation for variety release proposal. We continue to put a strong emphasis on soft white wheat in the program, and have begun to modify our breeding schemes to account for marker-assisted selection, genomic selection, and doubled-haploid production.

Impact: Traditionally, over 85% of the wheat crop in our state is winter 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 45% of the acres. These include Bruehl, Eltan, Masami, Xerpha, Otto, Puma, Jasper, Curiosity CL+, and MelaCL+. Measured impact is demonstrated with increasing acres of past cultivars, release of new cultivars (Pritchett) and upcoming lines Purl and Stingray CL+.

WGC project number: 6195
WGC project title: Field Breeding Soft White Winter Wheat
Project PI(s): AH Carter
Project initiation date: July 1, 2017
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 Otto in 2011. Puma (WA8134) was released in 2012. Jasper was released in 2014. Otto became the #1 grown cultivar in the state in 2015, replacing much of the Eltan acres. Puma is currently the #5 cultivar in the state. Released lines have high yield potential, excellent disease resistance, and market accepted end-use quality. We also co-released Pritchett in 2015 in collaboration with the USDA. This line is intended to replace some Bruehl acres. We have 4 breeding lines in statewide testing for consideration under low rainfall production systems and 5 in statewide testing for consideration under high rainfall production. One of these lines is a two-gene imazamox resistant lines, named Stingray CL+, which is under variety release consideration. We have over 10,000 plots and 30,000 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 17 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 continued head row selection at Lind due to the ability to screen for emergence and cold tolerance along with an extra location near Waterville to screen for snow mold.	Evaluation is done annually at multiple locations across the state.	In 2018 we communicated results of this project through the following venues: 12 peer-reviewed publications; 4 field day abstracts; 6 invited speaker presentations; 8 poster presentations; 7 popular press interviews; 3 grower meeting presentations; 12 field day presentations; 2 seed dealer presentations; participation in the Tri-State Grain Growers Convention; and hosting of 4 trade teams.
	Disease resistance	Disease resistance is recorded on our 17 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 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 2018.	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. One line has shown very good promise and is on increase for seed production in 2018. Two additional lines are in variety testing for additional release consideration. Novel traits are being incorporated into germplasm through collaboration with Dr. Ian Burke. Crossing to CoAxium resistance is ongoing and field trials will begin next year.	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 completion.	
	Stripe rust genes	We constantly have material coming out of the MAS program for stripe rust. In 2018 we evaluated multiple populations in both early and preliminary yield trials. 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 completion.	
	Foot rot genes	We have many populations being screened for foot rot resistance. 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 completion.	
	Cephalosporium	No markers are currently being used for this introgression. All selection is being done under field conditions. We recently completed an association mapping study, and have identified germplasm which can be used for crossing and pyramiding QTL together.	Evaluation will be done in field locations in WA in 2019	

	Aluminum tolerance	Field screening of breeding lines for aluminum tolerance is being conducted under field conditions. We recently completed an association mapping study, and have identified germplasm which can be used for crossing and pyramiding QTL together. Field screening has identified multiple lines that appear to have tolerance. Further screening will be done in 2019 to confirm this.	Evaluation will be done in field locations in WA in 2019	
	Hessian Fly	In collaboration with Dr. Nilsa Bosque-Perez we screened 12 F2 populations with new sources of resistance to Hessian Fly. Resistant plants were returned to the breeding program for further crossing. Populations will be screened in 2019 to confirm resistance and moved to field testing to evaluate other traits.	Additional populations will be screened in 2019 after backcrossing	
	Nematodes	Nematode screening has been done in collaboration with Dr. Paulitz and Dr. Campbell. Advanced material was screened in 2018 for cereal cyst resistance, and data was used to help make selections for what will be evaluated in 2019.	Additional populations will be screened in 2018	
	End-use quality	Seed of bi-parental mapping populations have been submitted for quality analysis and an association mapping panel for end-use quality was grown for analysis in 2016. This data will be included in genomic selection prediction models. Material continues to be screened for quality performance, with an increased effort on low PPO lines.	Validated genomic prediction models will be available for selection in 2019.	

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Washington Grain Commission
Wheat and Barley Research Annual Progress Report

Project #: 5682

Progress Report Year: 3 of 3 (2018)

Title: Control of Rusts of Wheat and Barley

Cooperators: K. Campbell, A. Carter, R. Higginbotham, S. Hulbert, K. Murphy, M. Pumphrey, & D. See

Executive summary: During 2018, studies were conducted according to the objectives of the project proposal and all objectives specified for the third year have been successfully completed. 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 and mechanisms of interactions between the pathogen and plants.

Impact: 1) Stripe rust was reasonably forecasted in 2018. Rust updates and advises were provided on time to growers based on the forecasts using prediction models and our field surveys, which effectively protected both winter wheat and spring wheat crops from potentially significant yield losses under the severe stripe rust epidemic. 2) We identified 19 (including 11 potentially new) races of the barley stripe rust pathogen and 27 (including 3 new) races of the wheat stripe rust pathogen in the US, of which 14 and 25 were detected in Washington, respectively. Seven of the new barley stripe rust races and all three new wheat stripe rust races were from Washington. The virulence information is used to guide breeding programs for using effective resistance genes in developing resistant varieties. 3) We sequenced 30 wheat stripe rust mutant isolates and used the data to identify candidate virulence genes. 4) We evaluated more than 40,000 wheat, barley, and triticale 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 2018, we collaborated with breeders in releasing, pre-releasing, or registered 12 wheat varieties. The germplasm evaluation data were also used to update the Seed Buyer’s Guide for growers to choose resistant varieties to grow. 5) We completed characterization and molecular mapping of resistance genes in PNW wheat varieties Madsen, Eltan, and Skiles, mapped 6, 5, and 6 genes for stripe rust resistance, respectively, and determined the genetic mechanisms of the durable but different levels of resistance in these varieties. We also collaborated with other programs in mapping a large number of stripe rust resistance genes in various wheat germplasm collections through the genome-wide association approach. 6) We provided seeds of our developed wheat germplasm lines to several breeding programs in the US and other countries for developing stripe rust resistant varieties. Use of these lines by breeding programs will diversify resistance genes in commercial varieties. 7) We tested 31 fungicide treatments for control of stripe rust on both winter and spring wheat and provided the data to chemical companies for registering new fungicides. 8) We tested 24 winter wheat and 24 spring wheat varieties for yield loss caused by stripe rust and yield increase by fungicide application. The data of the fungicides and varieties are used for guiding the integrated control of stripe rust. 9) In 2018, we published 26 journal articles and 10 meeting abstracts.

Outputs and Outcomes:

WGC project number: 5682				
WGC project title: Control of Rusts of Wheat and Barley				
Project PI(s): Xianming Chen				
Project initiation date: 7/1/2016				
Project year: 3 of 3 (2018)				
Objective	**Deliverable**	**Progress**	**Timeline**	**Communication**
1. Conduct disease forecast and field survey for guiding disease management	**1) Stripe rust predictions.** Accurate prediction before the rust season will allow growers to prepare for appropriate control measures including choosing resistant varieties to plant and possible fungicide application. **2) Field disease monitoring updates and recommendations.** Disease updates and recommendations will allow growers to implement appropriate control.	All planned studies for the project in 2018 have been completed on time. There is no any delay, failure, or problem in studies to this objective. Forecasts of wheat stripe rust epidemic were made in January based on the November and December weather conditions and in March based on the entire winter weather conditions using our prediction models. Further forecasts were made throughout the season based on rust survey data and past and forecasted weather conditions. These forecasts and rust updates were reported to wheat growers and researchers. Field surveys were conducted by our program and collaborators throughout the Pacific Northwest (PNW) and other regions throughout the country. In the eastern PNW, the times of first observations of stripe rust were about normal in various locations and stripe rust epidemic levels were also about normal in the moderate level in commercial fields with necessary fungicide application in fields of susceptible and moderately susceptible varieties. However, in our experimental fields near Pullman, stripe rust developed to extremely severe level in winter wheat plots and severe level in spring wheat plots, causing 70.5% and 66.4% yield losses in winter and spring wheat plots, respectively. The timely applications of fungicides on susceptible and moderately susceptible wheat varieties prevented major yield loss. Barley stripe rust was much lower than wheat stripe rust, similar to 2017. Leaf rust of wheat was normal in western and observed in eastern PNW; leaf rust of barley in the western PNW was less than the previous years, but absent in the eastern PNW. Stem rust of wheat and barley was absent in the PNW in 2018.	All studies and services were completed on time.	The rust forecasts and survey data were communicated to growers and other researchers through e-mails, telephones, websites, project reports, presentations at growers' meetings, field days, public magazines like Wheat Life, and publications in scientific journals (for detailed information, see the lists in the main report file).

2. Identify races and characterize populations of the wheat and barley stripe rust pathogens for providing useful pathogen information to breeding programs for developing resistant varieties and to growers for managing diseases.	**1) New races. 2) Information on distribution, frequency, and changes of all races and virulence factors. 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 races for screening wheat and barley germplasm and breeding lines. The information is also used for disease management based on races in different regions.	In 2018, we collected and received 314 stripe rust samples throughout the country and 70% of the samples were from Washington. We have completed about 90% of the race ID work for the 2018 samples as scheduled by this time. So far we have detected 27 wheat stripe rust races (including 3 new races) and 19 barley stripe rust races (including 11 new races), of which 25 wheat and 14 barley stripe rust races have been detected in Washington. The distribution and frequency of each race and virulence factor in WA and the whole country have been determined. Predominant races have been identified. The race and virulence information 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 breeding lines for stripe rust resistance. We have used molecular markers developed in our lab to study the stripe rust pathogen and determined the population changes in the past and present. We sequenced more isolates of the stripe rust pathogen and developed more SP-SNP markers to study rust pathogen populations and identify virulence genes.	The race identification work for the 2018 stripe rust samples will be completed by late February, 2019, as scheduled. The race ID work for 2019 samples will start in March. Molecular work of the 2017 samples and DNA extraction of the 2018 samples will be completed by June, 2019 as scheduled.	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).
3. Screening wheat and barley germplasm for supporting breeding programs to develop rust resistant varieties	**1) Stripe rust reaction data of wheat and barley germplasm and breeding lines. 2) Reactions to other diseases when occur. 3) Resistant germplasm for use in breeding programs. 4) New varieties for growers to grow.** The stripe rust data will allow breeding programs to get rid of susceptible lines or select lines for further improvement, and more importantly for releasing new varieties with stripe rust resistance combined with other desirable traits for growers to grow.	In 2018, we evaluated more than 40,000 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 and evaluated at both Pullman and Mt. Vernon locations under natural stripe rust infection. 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. Disease data of regional nurseries were provided to all breeding and extension programs, while data of individual breeders' 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 2018, we collaborated with public breeding programs in releasing and registered 12 wheat varieties. Varieties developed by private breeding programs were also resulted from our germplasm screening program.	All 2018 germplasm tests were completed and the data were provided to collaborators on time. The 2018-19 winter wheat nurseries were planted in September and October 2018. The 2019 spring crop nurseries will be planted in March-April, 2019. The greenhouse tests have been conducted during the winter, and will be completed by May, 2019.	The data of nurseries were sent to growers and collaborators through e-mails, websites, Seed Buyer's Guide, and variety registration journal publications

4. Identify and map new stripe rust resistance genes and develop new germplasm for use in breeding programs to diversify resistance genes in new varieties	**1) New stripe rust resistant sources. 2) New resistance genes with their genetic information. 3) Molecular markers for resistance genes. 4) New germplasm with improved traits.** 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.	Through the germplasm screening, 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 2018, We completed characterization and molecular mapping of resistance genes in PNW wheat varieties Madsen, Eltan, and Skiles, mapped 6, 5, and 6 genes for stripe rust resistance, respectively, and determined the genetic mechanisms of the durable but different levels of resistance in these varieties. We also collaborate with other laboratories in mapping of numerous stripe rust resistance loci in various wheat germplasm collections through genome-wide association study approach, and published 9 papers on molecular mapping and mechanisms of stripe rust resistance genes. 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 directly provided seeds to a few US breeding programs. In 2018, we phenotyped 40 mapping populations for stripe rust responses to map stripe rust resistance genes.	All experiments scheduled for 2018 were successfully completed. Mapping populations of winter wheat were planted in fields in October 2018 and those of spring wheat will be planted in April, 2019 for stripe rust phenotype data. Populations with adequate phenotype data are genotyped with molecular markers for mapping resistance genes. Progenies of new crosses will be advanced in fields in 2019.	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)

5. Improve the integrated control strategies by screening new chemicals and determining potential yield losses and fungicide responses of individual varieties	**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.** The information is used for developing more effective integrated control program based on individual varieties for growers to use to control stripe rust.	In 2018, we evaluated 31 fungicide treatments, plus a non-treated check, on both winter wheat and spring wheat for control of stripe rust in experimental fields near Pullman, WA. On winter wheat, 30 treatments significantly reduced rust severity and increased grain yield. The treatments with only the late (Feekes 8) application produced the better control results than those of only early application (Feekes 5). Twenty two treatments significantly increased test weight compared to the non-treated check. Seven treatments, which all had only the early application, did not significantly increase yield compared to the non-treated check, while the remaining 24 treatments produced significantly higher grain yield. On spring wheat, all 31 fungicide treatments significantly reduced stripe rust severity. Twenty two treatments significantly increased grain test weight compared to the non-treated check. Thirty treatments significantly increased grain yield, and the increases ranged from 9.1 bushel per acre (26%) to 60 bushes (172%). Best treatments were identified. In 2018, we tested 23 winter wheat and 23 spring wheat varieties commonly grown in the PNW, plus highly susceptible checks. For winter wheat, stripe rust caused 70.5% yield loss on the susceptible check and from 0 to 40.7% (average of 10.1%) on commercially grown varieties. Fungicide application increased yield by 0 to 40.2% (average of 12.4%) on commercially grown varieties. For spring wheat, stripe rust caused 66.0% yield loss on the susceptible check and from 0 to 47.5% (average 13.8%) yield losses on commercial varieties. Fungicide application increased grain yields by 0 to 90.6% (average 20.1%) on commercial varieties. These results can be used by chemical companies to register new fungicides and used by growers for selecting resistant varieties to grow and use suitable fungicide application for control stripe rust on varieties without an adequate level of resistance.	For this objective, all tests scheduled for 2018 were successfully completed. For the 2018-19 growing season, the winter wheat plots of the fungicide and variety yield loss studies were planted in October, 2018 and the spring plots will be planted in April, 2019. The tests will be completed in August (for winter wheat) and September (for spring wheat), 2019.	The results were communicated to growers and collaborators through e-mails, presentations in growers meetings, field days, plot tours, project reports and reviews, and published in scientific journals (see the publication and presentation lists in the report main file).

Publications:

<u>*Scientific Journals*:</u>

Wu, J. H., Wang, Q. L., Xu, L. S., **Chen, X. M.**, Li, B., Mu, J. M., Zeng, Q. D., Huang, L. L., Han, D. J., and Kang, Z. S. 2018. Combining SNP genotyping array with bulked segregant analysis to map a gene controlling adult-plant resistance to stripe rust in wheat line 03031-1-5 H62. Phytopathology 108(1):103-113.

Yuan, C. Y., Wang, M. N., Skinner, D. Z., See, D. R., Xia, C. J., Guo, X. H., and **Chen, X. M**. 2018. Inheritance of virulence, construction of a linkage map, and mapping of virulence genes in *Puccinia striiformis* f. sp. *tritici* by virulence and molecular characterization of a sexual population through genotyping-by-sequencing. Phytopathology 108(1):133-141.

Kidwell, K. K., Pumphrey, M. O., Kuehner, J. S., Shelton, G. B., DeMacon, V. L., Rynearson, S., **Chen, X. M.**, Guy, S. O., Engle, D. A., Baik, B.-K., Morris, C. F., and Bosque-Pérez, N. A. 2018. Registration of 'Glee' hard red spring wheat. Journal of Plant Registrations 12(1):60-65.

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Johnson, J., Chen, Z., Buntin, G., Babar, M. A., Mason, R., Harrison, S., Murphy, P., Ibrahim, A., Sutton, R., Simoneaux, B., Bockelman, H., Baik, B., Marshall, D., Cowger, C., Browng, G., Kolmer, J., Jin, Y., **Chen, X. M.**, Cambron, S., and Mergoum, M. 2018. 'Savoy': an adapted soft red winter wheat cultivar for Georgia and the south east regions of the USA. Journal of Plant Registrations 12(1):85-89.

Belcher, A., Cuesta-Marcos, A., Smith, K. P., Mundt, C. C., **Chen, X. M.**, and Hayes, P. M. 2018. TCAP FAC-WIN6 elite barley GWAS panel QTL. I. Barley stripe rust resistance QTL in facultative and winter six-rowed malt barley breeding programs identified via GWAS. Crop Science 58(1):103-119.

Godoy, J., Rynearson, S., **Chen, X. M.**, and Pumphrey, M. 2018. Genome-wide association mapping of loci for resistance to stripe rust in North American elite spring wheat germplasm. Phytopathology 108(2):234-245.

Wang, L., Zheng, D., Zuo, S. X., **Chen, X. M.**, Zhuang, H., Huang, L. L., Kang, Z. S., and Zhao, J. 2018. Inheritance and linkage of virulence genes in Chinese predominant race CYR32 of the wheat stripe rust pathogen *Puccinia striiformis* f. sp. *tritici*. Frontiers in Plant Science 9(2):120.

Tao, F., Wang, J. J., Guo, Z. F., Hu, J. J., Xu, X. M., Yang, J. R. **Chen, X. M.**, and Hu, X. P. 2018. Transcriptomic analysis reveals the molecular mechanisms of wheat higher-temperature seedling-plant resistance to *Puccinia striiformis* f. sp. *tritici*. Frontiers in Plant Science 9(2):240.

Chen, X. M., Evans, C. K., Sprott, J., and Liu, Y. M. 2018. Evaluation of foliar fungicide treatments for control of stripe rust on winter wheat in 2017. Plant Disease Management Reports 12:CF073.

Chen, X. M., Evans, C. K., Sprott, J., and Liu, Y. M. 2018. Evaluation of foliar fungicide treatments for control of stripe rust on spring wheat in 2017. Plant Disease Management Reports 12:CF074.

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Kidwell, K. K., Kuehner, J. S., Marshall, J., Shelton, G. B., DeMacon, V. L., Rynearson, S., **Chen, X. M.**, Guy, S. O., Engle, D. A., Baik, B.-K., Morris, C. F., and Pumphrey, M. O. 2018. Registration of 'Dayn' hard white spring wheat. Journal of Plant Registrations 12(2):222-227.

Berg, J. E., Hofer, P., Kephart, K. D., Stougaard, R. N., Lamb, P. F., Miller, J. H., Wichman, D. M., Eckhoff, J. L., Eberle, C. A., Nash, D. L., Holen, D. L., Cook, J. P., Gale, S., Jin, Y., **Chen, X.**, Moore, M. D., Kennedy, K. A., and Bruckner, P. L. 2018. Registration of 'Spur' hard red winter wheat. Journal of Plant Registrations 12(2):228-231.

Haley, S.D., Johnson, J.J., Peairs, F. B., Stromberger, J. A., Hudson-Arns, E. E., Seifert, S. A., Anderson, V. A., Rosenow, A. A., Bai, G. H., **Chen, X. M.**, Bowden, R. L., Jin, Y., Kolmer, J. A., Chen, M-S., and Seabourn, B. W. 2018. Registration of 'Langin' hard red winter wheat. Journal of Plant Registrations 12(2):232-236.

Feng, J. Y., Wang, M. N., See, D. R., Chao, S. M., Zheng, Y. L., and **Chen, X. M.** 2018. Characterization of novel gene *Yr79* and four additional QTL for all-stage and high-temperature adult-plant resistance to stripe rust in spring wheat PI 182103. Phytopathology 108(6):737-747.

Zhang, H. T., Qiu, Y. C., Yuan, C. Y., **Chen, X. M.**, and Huang, L. 2018. Fine-tuning of PR genes in wheat responding to different *Puccinia* rust species. Journal of Plant Physiology and Pathology 6:2.

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Li, M. J., **Chen, X. M.**, Wan, A. M., Ding, M. L., and Cheng J. S. 2018. Virulence characterization of stripe rust pathogen *Puccinia striiformis* f. sp. *tritici* population to 18 near-

isogenic lines resistant to wheat yellow rust in Yunnan Province. Journal of Plant Protection 45(1):75-82.

Xia, C. J., Wang, M. N., Yin, C. T., Cornejo, O. E., Hulbert, S. H., and **Chen, X. M.** 2018. Genomic insights into host adaptation between the wheat stripe rust pathogen (*Puccinia striiformis* f. sp. *tritici*) and the barley stripe rust pathogen (*Puccinia striiformis* f. sp. *hordei*). BMC Genomics 19:664.

Farrakh, S., Wang, M. N., and **Chen, X. M.** 2018. Pathogenesis-related protein genes involved in race-specific all-stage resistance and non-race specific high-temperature adult-plant resistance to *Puccinia striiformis* f. sp. *tritici* in wheat. Journal of Integrative Agriculture 17(11):2478-2491.

Xia, C. J., Wang, M. N., Yin, C. T., Cornejo, O. E., Hulbert, S. H., and **Chen, X. M.** 2018. Resource Announcement: Genome sequences for the wheat stripe rust pathogen (*Puccinia striiformis* f. sp. *tritici*) and the barley stripe rust pathogen (*Puccinia striiformis* f. sp. *hordei*) Molecular Plant-Microbe Interactions 31(11):1117-1120.

Niu, Z. X., Chao, S. M., Cai, X. W., Whetten, R. B., Breiland, M., Cowger, C., **Chen, X. M.**, Friebe, B., Gill, B. S., Rasmussen, J. B., Klindworth, D. L., and Xu, S. S. 2018. Molecular and cytogenetic characterization of six wheat-*Aegilops markgrafii* disomic addition lines and their resistance to rusts and powdery mildew. Frontiers in Plant Science 9(11):1616.

Haley, S. D., Johnson, J. J., Peairs, F. B., Stromberger, J. A., Hudson-Arns, E. E., Seifert, S. A., Anderson, V. A., Bai, G. B., **Chen, X. M.**, Bowden, R. L., Jin, Y., Kolmer, J. A., Chen, M. S., and Seabourn, B. W. 2018. Registration of 'Avery' hard red winter wheat. Journal of plant Registrations 12.362-366.

Cobo, N., Plfüger, L., **Chen, X. M.**, and Dubcovsky, J. 2018. Mapping QTL for resistance to new virulent races of wheat stripe rust from two Argentinean wheat varieties. Crop Science 58(6):2470-2483.

Popular Press Articles:
January 4, 2018. 2017 Fungicide and Variety Yield Loss Tests and 2018 First Stripe Rust Forecast. E-mail sent to growers and cereal groups.

March 8, 2018. Stripe Rust Forecast and Update, March 8, 2018. E-mail sent to growers and cereal groups.

April 10, 2018. Stripe Rust Update April 10, 2018. E-mail sent to growers and cereal groups.

May 8, 2018. Stripe Rust Update May 8, 2018. E-mail sent to growers and cereal groups.

June 1, 2018. Stripe rust Update June 1, 2018. E-mail sent to growers and cereal groups.

June 14, 2018. Cereal rust management and research in 2017. Pages 69-70 in: 2018 Dryland Field Day Abstracts, Highlights of Research Progress, Washington State University.

July 31, 2018. High-Temperature Adult-Plant Resistance: How Warm is Warm Enough? By Tim Murray, Wheat & Small Grains Extension, CAHNRS & WSU Extension. http://smallgrains.wsu.edu/high-temperature-adult-plant-resistance-how-warm-is-warm-enough/?utm_campaign=auto-draft&utm_source=auto-draft-2018-24&utm_medium=email&utm_content=link-17

December 20, 2018. Vogel's science legacy brings revolutionary wheat ideas to life. By Seth Truscott. https://news.wsu.edu/2018/12/19/vogels-science-legacy-brings-revolutionary-wheat-ideas-life/?utm_source=WSUNews-enewsletter&utm_campaign=wsunewsenewsletter&utm_medium=email

Presentations and Reports:

In 2018, Xianming Chen presented invited talks at the following national and international meetings:

"Stripe rust epidemiology and management and biology, genetics, functional genomics, and evolution of the stripe rust pathogen". Department of Plant Pathology, Washington State University, January 22, 2018 (about 60 people)

"Stripe rust races in the United States in 2017" at the Cereal Rust Workshop, Fargo, North Dakota, March 13, 2018 (30 people).

"Secretome of the stripe rust pathogen and genomic differences between the wheat and barley forms" at the Cereal Rust Workshop, Fargo, North Dakota, March 14, 2018 (30 people)

"Integrated control of stripe rust" in the Department of Plant Science, University of Idaho, Moscow, Idaho, March 23, 2018 (about 40 people)

"Sustainable control of stripe rust through developing wheat cultivars with durable, high-level resistance" at the Third McFadden Symposium at South Dakota State University, Brookings, South Dakota, May 2, 2018 (60 people)

"Sustainable control of stripe rust through developing wheat cultivars with high level, durable resistance." in Northwest A&F University, Yangling, Shannxi, China, May 28, 2018 (100 people).

"Virulence monitoring of wheat stripe rust in the US, China, Ecuador, Italy, and Mexico" at the Rust Surveillance Meeting during the International Congress of Plant Pathology, Boston, Massachusetts, August 2, 2018 (30 people)

"Different fungicide sensitivities and mutants of DMI target gene CYP51 identified in the *Puccinia striiformis* populations in the United States" at the 2018 International Cereal Rusts and Powdery Mildews Conference, Skukuza, South Africa, September 26, 2018 (about 160 people)

"Virulence factors of *Puccinia striiformis* f. sp. *tritici* in the United States from 1968 to 2017 and in other countries from 2013-2017" at the 2018 International Cereal Rusts and Powdery Mildews Conference, Skukuza, South Africa, September 26, 2018 (about 160 people)

"Improving Stripe Rust Control through Characterization of Genomics and Populations of the Pathogen and Diversification of Host Resistance Genes" at the 2018 Yangling International Agri-Science Forum, Yangling, Shaanxi, China, November 6, 2018 (300 people)

"Control of Stripe Rust through Understanding Pathogen Biology and Improving Cultivar Resistance" in Sichuan Academy of Agricultural Sciences, Chengdu, Sichuan, November 9, 2018 (50 people)

"Improving Control of Stripe Rust through Understanding Pathogen Biology and Improving Cultivar Resistance" in Southwestern University of Science and Technology, Mianyang, Sichuan, China, November 10, 2018 (100 people)

"Recent Progress in Stripe Rust Research in the United States" in the College of Plant Protection, Northwest A&F University, Yangling, Shaanxi, China, November 16, 2018 (50 people)

"Stripe rust management" at the 45th Annual Hermiston Farm Fair, Seminars & Trade Show, Hermiston, Oregon, November 29, 2018 (60 people)

In 2018, Xianming Chen, students, and/or associates presented posters or oral presentations at the following national and international meetings:

Poster entitled "Durable and high level stripe rust resistance in wheat cultivar Madsen conferred by five QTL for all-stage or HTAP resistance" at the 2018 Borlaug Global Rust Initiative Technical Workshop, Marrakech, Morocco, April 13-17, 2018 (300 people)

Poster entitled "Virulence characterization of *Puccinia striiformis* f. sp. *tritici* collections from China, Italy, Mexico, and Ecuador" at the 2018 International Congress of Plant Pathology, Boston, Massachusetts, July 28 - August 3, 2018 (about 2000 people)

Poster entitled "Two major and five minor QTL confer adult plant resistance to stripe rust in winter wheat cultivar Skiles" at the 2018 International Congress of Plant Pathology, Boston, Massachusetts, July 28 - August 3, 2018 (about 2000 people)

Poster entitled "Genomic basis for host adaptation in *Puccinia striiformis*" at the 2018 International Congress of Plant Pathology, Boston, Massachusetts, July 28 - August 3, 2018 (about 2000 people)

Washington Grain Commission
Wheat and Barley Research Final Progress Report

Project #: 5682
Progress Report Year: 3 years (2016-2018)
Title: Control of Rusts of Wheat and Barley
Cooperators: K. Campbell, A. Carter, R. Higginbotham, S. Hulbert, K. Murphy, M. Pumphrey, & D. See

Executive summary: During the three years (2016-2018), studies were conducted according to the objectives of the project proposal and all objectives specified for the three year have been successfully completed. 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 and mechanisms of interactions between the pathogen and plants.

Impact: 1) Stripe rust was accurately forecasted in 2016-2018. Rust updates and advises were provided on time to growers based on the forecasts using prediction models and our field surveys, which effectively protected both winter wheat and spring wheat crops from potentially significant yield losses under the severe stripe rust epidemics in these years, saving growers multimillion dollars. 2) We identified 9, 14, and 19 races of the barley stripe rust pathogen and 69, 64, and 27 races of the wheat stripe rust pathogen in 2016, 2017, and 2018, respectively in the US. During the three years, 17 new races of barley stripe rust and 66 new races of wheat stripe rust were identified, and most of the races were detected in Washington. Significant virulence changes were identified and the virulence information is used to guide breeding programs for using effective resistance genes in developing resistant varieties. 3) We sequenced more than 250 stripe rust isolates and used the data to study the pathogen evolution mechanisms, identify candidate virulence genes, and monitor population changes. 4) We evaluated more than 35,000 wheat, barley, and triticale entries each year 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 2016-2018, we collaborated with breeders in registration of 16 varieties and releasing 8 wheat varieties and 2 barley varieties. The germplasm evaluation data were also used to update the Seed Buyer’s Guide for growers to choose resistant varieties to grow. 5) We mapped 25 resistance genes in wheat germplasm and PNW varieties and 4 genes in barley varieties for stripe rust resistance using the bi-parental approach, and determined the genetic mechanisms of durable resistance. We collaborated with other programs in mapping a large number of stripe rust resistance genes in various wheat and barley germplasm collections through the genome-wide association approach. 6) We developed 29 new wheat germplasm lines with a single or combined two genes on the same chromosome arms for more efficient use in breeding programs and provided seeds of these materials and our previously developed wheat germplasm lines to breeding programs in the US and other countries. 7) We tested 32, 23, and 31 fungicide treatments for control of stripe rust on both winter and spring wheat in 2016, 2017, and 2018, respectively. 8) In each year, we tested 24 winter wheat and 24 spring wheat varieties for yield loss caused by stripe rust and yield increase by fungicide application. The data of the fungicides and varieties are used for guiding the integrated control of stripe rust. 9) During the three years, we published 84 papers in peer-reviewed journals, a book special for stripe rust, and 33 conference proceedings and abstracts.

Outputs and Outcomes:

WGC project number: 5682				
WGC project title: Control of Rusts of Wheat and Barley				
Project PI(s): Xianming Chen				
Project initiation date: 7/1/2016				
Project year: 3 years (2016-2018)				
Objective	**Deliverable**	**Progress**	**Timeline**	**Communication**
1. Conduct disease forecast and field survey for guiding disease management	**1) Stripe rust predictions.** Accurate prediction before the rust season will allow growers to prepare for appropriate control measures including choosing resistant varieties to plant and possible fungicide application. **2) Field disease monitoring updates and recommendations.** Disease updates and recommendations will allow growers to implement appropriate control.	All planned studies for the project in 2016-2018 have been completed on time. There were no delays, failures, or problems in studies and services to this objective. In each year, stripe rust epidemic was accurately predicted and rust situations were monitored throughout the growing seasons. The forecasts, field survey updates, and recommendations were sent to growers and relevant parties to implement appropriate measures to control stripe rust. As the results, severe stripe rust epidemics, which had the potential to cause yield losses of 71.4% in 2016, 74.7% in 2017, and 70.5% in 2018 on susceptible winter wheat and 54.5% in 2016, 48.1% in 2017, and 66.4% in 2018 on susceptible spring wheat, or average of 8.0%, 13.7%, 10.1% on winter wheat and 19.9%, 7.4%, and 13.8% on spring wheat of commercially grown varieties in the three years, respectively, were successfully prevented. The successful control of stripe rust in each of the three years saved Washington growers about 15 million bushels of wheat grain, worthy more than 75 million dollars in each year.	All studies and services were completed on time.	The rust forecasts and survey data were communicated to growers and other researchers through e-mails, telephones, websites, project reports, presentations at growers' meetings, field days, public magazines like Wheat Life, and publications in scientific journals (for detailed information, see the lists in the main report file).

2. Identify races and characterize populations of the wheat and barley stripe rust pathogens for providing useful pathogen information to breeding programs for developing resistant varieties and to growers for managing diseases.	**1) New races. 2) Information on distribution, frequency, and changes of all races and virulence factors. 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 races for screening wheat and barley germplasm and breeding lines. The information is also used for disease management based on races in different regions.	In 2016-2018, we collected/received and tested a total of 1,172 stripe rust samples throughout the country with 60-70% of the samples from Washington. From the samples, we identified 69, 64, and 27 races of the wheat stripe rust pathogen and 9, 14, and 19 races of the barley stripe rust pathogen in 2016, 2017, and 2018, respectively. During the three years, we identified 66 new races of wheat stripe rust and 17 new races of the barley stripe rust pathogen. Most of the races were detected in Washington. The distribution and frequency of each race and virulence factor were determined, and predominant races were identified. The race and virulence information is used to guide breeding programs for using effective resistance genes in developing resistant varieties. Predominant races and some of the new races with unique virulence patterns are used in screening varieties and breeding lines for stripe rust resistance. During the three years, we sequenced more than 250 stripe rust isolates and used the data to study the pathogen evolution mechanisms and identify candidate virulence genes. Based on the sequence data, we identified more 800 stripe rust specific secreted protein (SP) genes and developed SNP markers for these genes to study pathogen virulence and population structures. We established a core set of 18 SSR markers. Using the SSR markers and 92 previously developed SP-SNP markers, we completed a study of US stripe rust isolates from 1968 to 2009 and obtained useful results for understanding the stripe rust population changes over the past 40 years. We have been using these markers in studying the populations from 2010 to 2018.	The race identification work for the 2016 and 2017 stripe rust collections have been completed. The 2018 stripe rust samples will be completed by late February, 2019, as scheduled. Most of the molecular work with the 2010 to 2017 samples has been completed. The 2018 samples will be completed by June, 2019 as scheduled.	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).

3. Screening wheat and barley germplasm for supporting breeding programs to develop rust resistant varieties	**1) Stripe rust reaction data of wheat and barley germplasm and breeding lines. 2) Reactions to other diseases when occur. 3) Resistant germplasm for use in breeding programs. 4) New varieties for growers to grow.** The stripe rust data will allow breeding programs to get rid of susceptible lines or select lines for further improvement, and more importantly for releasing new varieties with stripe rust resistance combined with other desirable traits for growers to grow.	In 2016-2018, we evaluated more than 40,000 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, genetics, and extension programs. All nurseries were planted and evaluated at both Pullman and Mt. Vernon locations under natural stripe rust infection. 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. Disease data of regional nurseries were provided to all breeding and extension programs, while data of individual breeders' nurseries were provided to the individual breeders. Through these tests, susceptible breeding lines could 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. During the three years, we collaborated with public breeding programs in registration of 16 wheat varieties and releasing 8 wheat and 2 barley varieties. Varieties developed by private breeding programs were also resulted from our germplasm screening program.	All 2016-2018 germplasm tests were completed and the data were provided to collaborators on time. The 2018-19 winter wheat nurseries were planted in September and October 2018. The 2019 spring crop nurseries will be planted in March-April, 2019. The greenhouse tests of 2018-19 nurseries have been conducted during this winter, and will be completed by May, 2019.	The data of nurseries were sent to growers and collaborators through e-mails, websites, Seed Buyer's Guide, and variety registration journal publications

4. Identify and map new stripe rust resistance genes and develop new germplasm for use in breeding programs to diversify resistance genes in new varieties	**1) New stripe rust resistant sources. 2) New resistance genes with their genetic information. 3) Molecular markers for resistance genes. 4) New germplasm with improved traits.** 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.	Through the germplasm screening, 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 2016-2018, we completed more than 10 studies for characterization and molecular mapping of resistance genes in world germplasm and PNW wheat varieties. We mapped 25 resistance genes in wheat and 4 genes in barley for stripe rust resistance using the bi-parental approach, and determined the genetic mechanisms of durable resistance. We collaborated with other programs in mapping a large number of stripe rust resistance genes in various wheat and barley germplasm collections through the genome-wide association approach. We developed 29 new wheat germplasm lines including 15 carrying a single gene each and 14 carrying two genes from different sources pyramided on the same chromosome arms for more efficient use in breeding programs. We provided seeds of these materials and our previously developed wheat germplasm lines to many breeding programs in the US and other countries. We developed 40 mapping populations from 40 different winter wheat germplasm lines to identify new stripe rust resistance genes.	All studies scheduled for 2016-2018 were successfully completed. The mapping studies of the 40 winter wheat mapping populations will be conducted in the next three years. For these populations, we obtained the first set of the phenotypic data in 2018 and extracted DNA from 10 F5 lines for each of the resistant and susceptible bulks for bulk segregant analyses to identify unique genes. The winter populations were planted in the field in October, 2018 and will be phenotyped again in 2019.	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)

5. Improve the integrated control strategies by screening new chemicals and determining potential yield losses and fungicide responses of individual varieties	**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.** The information is used for developing more effective integrated control program based on individual varieties for growers to use to control stripe rust.	In 2016, 2017, and 2018, we tested 32, 23, and 31 fungicide treatments for control of stripe rust on both winter and spring wheat, respectively. The fungicide efficacy data were used for chemical companies to register new chemicals for control of stripe rust. For example, the new fungicide Trivapro with three active ingredients labeled for control of stripe rust was resulted from our tests during the last three years. The new fungicides not only provide more choices, but also will help prevent or delay the development of possible rust strains with tolerance to widely used fungicides. Each year, we tested 24 winter wheat and 24 spring wheat varieties popularly grown in the PNW for yield loss caused by stripe rust and yield increase by fungicide application. The data of the fungicides and varieties have been used for guiding the integrated control of stripe rust by selecting resistant varieties to grow and use suitable fungicide application for control stripe rust on varieties without an adequate level of resistance. Using the results of studies for this objective, the stripe rust management in the PNW has been continually improved during the past three years. In the three years, potenially huge yield losses under the severe epidemic conditions were successfully prevented.	For this objective, all tests scheduled for 2016-2018 were successfully completed. For the 2018-19 growing season, the winter wheat plots of the fungicide and variety yield loss studies were planted in fields in October, 2018 and the spring plots will be planted in April, 2019. The tests will be completed in August (for winter wheat) and September (for spring wheat), 2019.	The results were communicated to growers and collaborators through e-mails, presentations in growers meetings, field days, plot tours, project reports and reviews, and published in scientific journals (see the publication and presentation lists in the report main file).

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January 17, 2016. Pacific Northwest stripe rust outlook 'moderate'. Matthew Weaver, *Capital Press*, http://www.capitalpress.com/Profit/20160117/pacific-northwest-stripe-rust-outlook-moderate

February, 2016. Initial forecast predicts little stripe rust. Xianming Chen. *Wheat Life*, February 2016, page 14.

February 10, 2016. Stripe rust forecast is good news for wheat growers by Tim Murray. *On Solid Ground*. CAHNRS, WSU. http://cahnrs.wsu.edu/blog/2016/02/stripe-rust-forecast-is-good-news-for-wheat-growers/?utm_campaign=auto-draft&utm_source=on-solid-ground-february-2016-2016-10&utm_medium=email&utm_content=link-19.

March 4, 2016. Stripe Rust Forecast and Update, March 4, 2016. Xianming Chen, E-mail sent to growers and cereal group.

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June 2016, Stripe rust found throughout Pacific Northwest wheat fields. Xianming Chen, *Wheat Life*, June 2016, pages 12-14.

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July 25, 2016. Stripe rust pressure 'severe' in Northwest wheat, expert says. Matthew Weaver. *Capital Press*.

September 29, 2016. Estimates of yield losses caused by stripe rust and increase by fungicide application on PNW wheat varieties. Xianming Chen, E-mail sent to growers and cereal group.

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All 2016 nursery data were sent to growers, cereal group, and/or collaborators.

January 4, 2017. First Forecast of Stripe Rust for 2017 and 2016 Fungicide and Variety Yield Loss Tests. Xianming Chen, E-mail sent to growers and the cereal group.

January, 2017. First Stripe Rust Update of the 2017 Season – January 2017 by Tim Murray. http://smallgrains.wsu.edu/first-stripe-rust-update-of-the-2017-season-january-2017/

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March 2017. Stripe rust in PNW could be severe. By Xianming Chen. http://www.wawg.org/stripe-rust-in-pnw-could-be-severe/

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June 16, 2017. Rust update, June 16, 2017. Email sent to growers and cereal groups.

July 11, 2017. Rust update, July 11, 2017. Email sent to growers and cereal groups.

July 13, 2017. Stripe rust spread slowing down, researcher says. By Matthew Weaver. *Capital Press*, http://www.capitalpress.com/Profit/20170713/stripe-rust-spread-slowing-down-researcher-says

All 2017 nursery data were sent to growers, cereal group, and/or collaborators.

January 4, 2018. 2017 Fungicide and Variety Yield Loss Tests and 2018 First Stripe Rust Forecast. E-mail sent to growers and cereal groups.

March 8, 2018. Stripe Rust Forecast and Update, March 8, 2018. E-mail sent to growers and cereal groups.

April 10, 2018. Stripe Rust Update April 10, 2018. E-mail sent to growers and cereal groups.

May 8, 2018. Stripe Rust Update May 8, 2018. E-mail sent to growers and cereal groups.

June 1, 2018. Stripe rust Update June 1, 2018. E-mail sent to growers and cereal groups.

June 14, 2018. Cereal rust management and research in 2017. Pages 69-70 in: 2018 Dryland Field Day Abstracts, Highlights of Research Progress, Washington State University.

July 31, 2018. High-Temperature Adult-Plant Resistance: How Warm is Warm Enough? By Tim Murray, Wheat & Small Grains Extension, CAHNRS & WSU Extension. http://smallgrains.wsu.edu/high-temperature-adult-plant-resistance-how-warm-is-warm-enough/?utm_campaign=auto-draft&utm_source=auto-draft-2018-24&utm_medium=email&utm_content=link-17

December 20, 2018. Vogel's science legacy brings revolutionary wheat ideas to life. By Seth Truscott. https://news.wsu.edu/2018/12/19/vogels-science-legacy-brings-revolutionary-wheat-ideas-life/?utm_source=WSUNews-enewsletter&utm_campaign=wsunewsenewsletter&utm_medium=email

All 2018 nursery data were sent to growers, cereal group, and/or collaborators.

Presentations and Reports:

In 2016, Xianming Chen presented an invited talk “Wheat Stripe Rust Integrated Control Based on Forecasting, Monitoring, and Resistance” at American Phytopathological Society Rust Symposium, 8-9 March, 2016, Pensacola, Florida. (About 100 people)

In 2016, Xianming Chen presented the following posters at American Phytopathological Society Rust Symposium, 8-9 March, 2016, Pensacola, Florida (About 100 people)

1) “Wheat stripe rust integrated control based on forecasting, monitoring, and resistance”
2) “Virulence changes of *Puccinia striiformis* f. sp. *tritici* in 1968-2015 in the US”

In 2016, Xianming Chen and graduate students, visiting students, and postdoctoral associates presented the following talks or posters at the American Phytopathological Society Pacific Division Meetings at La Conner, WA, June 29-30, 2016 (About 200 people):

1) “Characterization of somatic recombinant isolates of *Puccinia striiformis*, the stripe rust pathogen”
2) “Molecular mapping of stripe rust resistance genes in spring wheat line W18”
3) “Variation of telial formation in the *Puccinia striiformis* f. sp. *tritici* population”
4) “Towards construction of genetic linkages for mapping virulence genes in *Puccinia striiformis* f. sp. *tritici*, the wheat stripe rust pathogen”
5) “Pyramiding stripe rust resistance genes on wheat chromosomes 2B, 4B, and 7B”
6) “Expression profiling of pathogenesis-related protein genes in wheat resistance to the stripe rust pathogen (*Puccinia striiformis* f. sp. *tritici*)”
7) “Virulence characterization of *Puccinia striiformis* f. sp. *tritici* in the US for the past 48 years using the *Yr* single-gene differentials”
8) “Developing a wheat germplasm with linked genes *Yr64* and *Yr65* for resistance to stripe rust”
9) “Development of *Puccinia striiformis* f. sp. *tritici* mutants for avirulence characterization”
10) “Seedling reactions of Mexican wheat varieties and advanced lines to four races of *Puccinia striiformis* f. sp. *tritici*, the stripe rust pathogen”.

In 2016, Xianming Chen presented the following posters at the American Phytopathological Society Annual Meeting, July 31-August 3, 2016, Tampa, Florida (over 2000 people):

1) “Stripe rust epidemics of wheat and barley and races of *Puccinia striiformis* identified in the United States in 2015”
2) “Molecular mapping of effective stripe rust resistance genes in wheat germplasm PI 182126”

In 2016, Xianming Chen presented an invited talk “Recent Progress of Stripe Rust Research in the United States”. November 24, 2016 Northwest A&F University, Yangling, China (about 200 people)

In 2016, Xianming Chen participated or talked about rusts, research progress, and disease management in the following field days:

- 6/16/2016: Lind Field Day (about 100 people)
- 7/13/2016: Farmington Field Day (about 25 people)
- 7/14/2016: St John Field Day (about 25 people)
- 7/14/2016: Lamont Field Day (about 16 people)

In 2017, Xianming Chen presented invited talks at the following national and international meetings:

"Stripe Rust Research and Control in the US" at the North American Wheat Research Initiative Meeting in the CIMMYT-HQ, EL Batan, Mexico, February 14, 2017 (about 30 people)

"Races and Virulence Genes of *Puccinia striiformis* from 1968 to 2016 in the US" at the North American Cereal Rust Workshop, St. Paul, Minnesota, March 29, 2017 (about 40 people).

"Unequal Contributions of Parental Isolates in Somatic Recombination of the Stripe Rust Fungus" at the 19th International Conference of Fungal Genetics. Venice, Italy, June 21, 2017 (about 40 people)

"Pathogenicity of stripe rust and its prevention and control" at the Training Course on Breeding and Production Technologies of Staple Crops in Southeast Asia, Chengdu, Sichuan, China, August 17, 2017 (about 60 people)

"Stripe Rust Research and Control in the US" at the Jinjiang Forum, Chengdu Institute, Chinese Academy of Sciences, Chengdu, Sichuan, China, August 22, 2017 (about 40 people)

"Stripe Rust Research and Control in the US" in the Institute of Crop Science, Sichuan Academy of Agricultural Sciences, Chengdu, Sichuan, China, August 23, 2017 (about 30 people)

"Stripe Rust Research and Control in the US" in the Institute of Plant Protection, Chinese Academy of Agricultural Sciences, Beijing China, August 24, 2017 (about 60 people)

"Stripe Rust Research and Control in the US" in the Institute of Genetics and Cell Developmental Biology, Chinese Academy of Sciences, Shijiazhuang, Hebei, China, August 25, 2017 (about 40 people)

"Stripe Rust Research and Control in the US" in the Institute of Genetics and Developmental Cell Biology, Chinese Academy of Science, Shijiazhuang, Hebei, China, August 25, 2017 (about 50 people)

"Stripe Rust Research and Control in the US" at the Chinese National Wheat Disease Management Workshop, Baoding, Hebei, China, August 26, 2017 (about 200 people)

"Biology, genetics, functional genomics, evolution, and epidemics caused by the stripe rust pathogen" at the 2nd International Conference of Mycology and Mushroom. Chicago, IL, September 25, 2017 (about 100 people)

"Biology, genetics, functional genomics, evolution, and epidemics caused by the stripe rust pathogen" in the College of Plant Protection, Northwest A&F University, Yangling, Shaanxi, China, October 11, 2017 (About 200 people).

In 2017, Xianming Chen, students and/or associates presented posters or oral presentations at the following national and international meetings:

Poster entitled "Identification of effector candidates for avirulence genes in the wheat stripe rust fungus (*Puccinia striiformis* f. sp. *tritici*) by secretome analysis" at the 29th Fungal Genetics Symposium and presented, Pacific Grove, California, March 13-17, 2017 (about 900 people)

Poster entitled "Mapping genes for and developing wheat germplasm with resistance to stripe rust" at the 13th International Wheat Genetics Symposium in Tuln, Austria, April 23-28, 2017 (more than 500 people)

Oral presentation entitled "Secretome characterization and correlation analysis reveal putative pathogenicity mechanisms in the wheat stripe rust fungus *Puccinia striiformis* f. sp. *tritici*" at the American Phytopathological Society Pacific Division meeting, June 28-29, 2017 (student: Chongjing Xia)

Oral presentation entitled "Molecular mapping of stripe rust resistance QTL in Pacific Northwest winter wheat cultivar Madsen" at the American Phytopathological Society Pacific Division meeting, June 28-29, 2017 (student: Lu Liu)

Oral presentation entitled "Virulence and molecular characterization of *Puccinia striiformis* f. sp. *tritici* mutants generated using ethyl methanesulfonate" at the American Phytopathological Society Pacific Division meeting, June 28-29, 2017 (student: Yuxiang Li)

Poster entitled "Stripe rust epidemics of wheat and barley and races of *Puccinia striiformis* identified in the United States in 2016" at the American Phytopathology Society Annual Meeting in San Antonio, TX August 5-9, 2017 (about 1600 people)

Poster entitled "Molecular mapping and comparison of *YrTr1* with other genes on chromosome 1BS for resistance to wheat stripe rust" at the American Phytopathology Society Annual Meeting in San Antonio, TX August 5-9, 2017 (about 1600 people)

In 2017, Xianming Chen participated and talked about rusts, research progress, and disease management in the following field days:

May 31-June 1, 2017. Western Wheat Workers and WEAR 97 meeting at Corvallis, OR (about 40 people)

June 15, 2017. Lind Field Day (about 100 people)

July 7, 2017. Farmington Field Day (about 30 people)

In 2018, Xianming Chen presented invited talks at the following national and international meetings:

"Stripe rust epidemiology and management and biology, genetics, functional genomics, and evolution of the stripe rust pathogen". Department of Plant Pathology, Washington State University, January 22, 2018 (about 60 people)

"Stripe rust races in the United States in 2017" at the Cereal Rust Workshop, Fargo, North Dakota, March 13, 2018 (30 people).

"Secretome of the stripe rust pathogen and genomic differences between the wheat and barley forms" at the Cereal Rust Workshop, Fargo, North Dakota, March 14, 2018 (30 people)

"Integrated control of stripe rust" in the Department of Plant Science, University of Idaho, Moscow, Idaho, March 23, 2018 (about 40 people)

"Sustainable control of stripe rust through developing wheat cultivars with durable, high-level resistance" at the Third McFadden Symposium at South Dakota State University, Brookings, South Dakota, May 2, 2018 (60 people)

"Sustainable control of stripe rust through developing wheat cultivars with high level, durable resistance." in Northwest A&F University, Yangling, Shannxi, China, May 28, 2018 (100 people).

"Virulence monitoring of wheat stripe rust in the US, China, Ecuador, Italy, and Mexico" at the Rust Surveillance Meeting during the International Congress of Plant Pathology, Boston, Massachusetts, August 2, 2018 (30 people)

"Different fungicide sensitivities and mutants of DMI target gene CYP51 identified in the *Puccinia striiformis* populations in the United States" at the 2018 International Cereal Rusts and Powdery Mildews Conference, Skukuza, South Africa, September 26, 2018 (about 160 people)

"Virulence factors of *Puccinia striiformis* f. sp. *tritici* in the United States from 1968 to 2017 and in other countries from 2013-2017" at the 2018 International Cereal Rusts and Powdery Mildews Conference, Skukuza, South Africa, September 26, 2018 (about 160 people)

"Improving Stripe Rust Control through Characterization of Genomics and Populations of the Pathogen and Diversification of Host Resistance Genes" at the 2018 Yangling

International Agri-Science Forum, Yangling, Shaanxi, China, November 6, 2018 (300 people)

"Control of Stripe Rust through Understanding Pathogen Biology and Improving Cultivar Resistance" in Sichuan Academy of Agricultural Sciences, Chengdu, Sichuan, November 9, 2018 (50 people)

"Improving Control of Stripe Rust through Understanding Pathogen Biology and Improving Cultivar Resistance" in Southwestern University of Science and Technology, Mianyang, Sichuan, China, November 10, 2018 (100 people)

"Recent Progress in Stripe Rust Research in the United States" in the College of Plant Protection, Northwest A&F University, Yangling, Shaanxi, China, November 16, 2018 (50 people)

"Stripe rust management" at the 45th Annual Hermiston Farm Fair, Seminars & Trade Show, Hermiston, Oregon, November 29, 2018 (60 people)

In 2018, Xianming Chen, students, and/or associates presented posters or oral presentations at the following national and international meetings:

Poster entitled "Durable and high level stripe rust resistance in wheat cultivar Madsen conferred by five QTL for all-stage or HTAP resistance" at the 2018 Borlaug Global Rust Initiative Technical Workshop, Marrakech, Morocco, April 13-17, 2018 (300 people)

Poster entitled "Virulence characterization of *Puccinia striiformis* f. sp. *tritici* collections from China, Italy, Mexico, and Ecuador" at the 2018 International Congress of Plant Pathology, Boston, Massachusetts, July 28 - August 3, 2018 (about 2000 people)

Poster entitled "Two major and five minor QTL confer adult plant resistance to stripe rust in winter wheat cultivar Skiles" at the 2018 International Congress of Plant Pathology, Boston, Massachusetts, July 28 - August 3, 2018 (about 2000 people)

Poster entitled "Genomic basis for host adaptation in *Puccinia striiformis*" at the 2018 International Congress of Plant Pathology, Boston, Massachusetts, July 28 - August 3, 2018 (about 2000 people)

Washington Grain Commission
Wheat and Barley Research Annual Progress Report

Project #: 4127-1605

Progress Report Year: 3 of 3

Title: Evaluation of Barley Varieties

Investigator: Aaron Esser

Executive summary: In 2018, the Cereal Variety Testing Program (VTP) conducted 12 spring barley variety trials across eastern Washington. The total number of individual barley plots evaluated was 864. Entries in the trials included submissions from every major barley breeding program in the Pacific Northwest. Variety performance information is delivered to barley growers and other clientele through field tours (10 tours in 2018), grower meetings, the variety testing website, emails with preliminary results after harvest (over 200 recipients), the variety selection tool (located at smallgrains.wsu.edu), Wheat Life, seed buying guide, annual technical report, direct contact with clientele, and reports to the Washington Grain Commission. The variety trials are used by WSU breeders for variety release decisions, by pathologists to rate disease reactions, and for county Extension programming.

Impact: The economic impact of the WSU VTP is measured by providing information to growers and seed industry personnel that leads 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). Although current barley acreage in Washington is declining, it is important for the VTP to continue to evaluate the growing list of available barley varieties. It is also important for the program to evaluate new breeding lines for potential variety release. The trials provide a venue for growers to see what's available, and a platform to continue to promote barley production in Washington. Without the VTP, many growers in Washington would not have access to barley variety performance data in their areas of production. Growers who choose to plant barley will see an increased economic return by choosing high yielding barley varieties showcased in the WSU VTP.

Some of the most direct and measurable impacts that this project had in 2018 are as follows: 1. Barley VTP field tours were attended by 188 farmers/clientele. At those tours, I presented a few details about each entry in the trial. 2. As soon as harvest results were available, they were distributed via email to a listserv with 213 members and posted to the project website. 3. The variety testing section of the small grains website (http://smallgrains.wsu.edu/variety/) was the most visited section of the site (23,840 page views).

WGC project number: 4127-1605
WGC project title: Evaluation of Barley Varieties
Project PI(s): Aaron Esser
Project initiation date: July 1, 2016
Project year (X of 3-yr cycle): 3 of 3

Objective	Deliverable	Progress	Timeline	Communication
1. Conduct barley variety trials in eastern Washington	12 spring barley trials 24 entries/trial	2018 trials completed (24 entries/trial) 2019 trials in planning	Trials are planted in the spring, data results are available to growers at the end of the harvest season. Field tours in summer.	Results from the variety trials are communicated via Extension programming and are detailed under Objective #4.
2. Public and privated entries in trials	All widely grown, commuercially availabe varieties included in trials.	2018 barley entries; 54% public, 46% private.	Entries by February 15.	Solicit entires February 1. Maintain positive relationship with breeding programs to ensure future participation.
3. Triasl and data available to other projects	Participation other projects/programs.	Data is used by breeders for varietiey release and promitional materials.	Ongoing cooperation and collaboration that fit with timelines and other listed objectives.	VTP data used for variety release.
4 . Extension Outreach	Grower meetings	1 grower mtg in 2018	Whenever I'm invited	Grower meetings: 1 in 2018
	Field Tours (with County Extension)	10 in 2018 and 10 planned for 2019	June-July	*Field tours: 10 in 2018 (listed below)
	Email list serv	2018 results delivered	October	Email list serve: data sent to 213 members
	Website	up to date with 2018 data	fall winter	23,840 pagviews of the VTP section of the small grains website
	Annual Report	Published in December 2019	December	Annual Report: 2018 Technicl Report 18-3
	WSCIA Seed Buyers Guides	2018 published, 2019 in preparation	January-February	2018 Seed Buyers Guide published January 2018
	Wheat Life	2018 results in February 2019	January	Wheat Life: 1 article planned for 2019
	Variety Selection Tool (http://smallgrains.wsu.edu)	Selection tool needs to be updated with 2018 data	January-February	The variety selection tool has 6,593 page views in 2018
*** 2018 Tour Schedule Barley**				
Location	**Date**	**Attendance**		
Horse Heaven	6-Jun	24		
Walla Walla	20-Jun	5		
Dayton	22-Jun	31		
Moses Lake	25-Jun	35		
Reardan	26-Jun	10		
Mayview	27-Jun	25		
St John	28-Jun	25		
Lamont	28-Jun	8		
Farmington	6-Jul	15		
Palouse	6-Jul	10		
		Total = 188		

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Washington Grain Commission
Wheat and Barley Research Annual Progress Report

Project #: 4127-1604

Progress Report Year: 3 of 3

Title: Evaluation of Wheat Varieties

Investigator: Aaron Esser

Executive summary: In 2018, the Cereal Variety Testing Program (VTP) conducted 24 soft winter, 16 hard winter, 18 soft spring, and 18 hard spring wheat variety trials across eastern Washington. The total number of individual wheat plots evaluated was 8,028. Entries in the trials included submissions from 12 different breeding programs/cooperators. Variety performance information is delivered to wheat growers and other clientele through field tours (21 tours in 2018), grower meetings (1 in 2018), the variety testing website, emails with preliminary results after harvest (over 200 recipients), the variety selection tool (located at smallgrains.wsu.edu), Wheat Life articles, seed buying guides, annual technical report, direct contact with clientele, and reports to the Washington Grain Commission. Grain from variety trials is used to generate information on end use quality, disease reactions, market class grading, and falling numbers.

Impact: The economic value (impact) of the WSU VTP is measured by providing information to growers and seed industry personnel that leads 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). In 2018, there were roughly 2.1 million acres of wheat planted in Washington. If growers use results produced by the VTP to select higher yielding, disease resistant wheat varieties to plant on their farms, one could assume a modest average yield increase of 1 bushel/acre, resulting in 1.9 million bushels of grain. Using an average market price of $5.00/bushel, this would result in a gross increase of $10.5 million to the Washington grain economy. 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. Seed dealers also use VTP data to make decisions about which varieties to offer for their patrons.

Some of the most direct and measurable impacts that this project had in 2018 are as follows: 1. The inclusion of every major wheat breeding program in the VTP trials. This provided growers and industry with a head-to-head comparison of the most widely grown varieties. 2. VTP field tours were attended by 600 farmers/clientele. At those tours, I highlighted each entry in the trial and gave a few details, strengths/weaknesses about each entry. 3. The addition of winter wheat trials at Bickleton and Eureka, and the partnership with OSU on trials at Dayton, Walla Walla and Eureka. 4. The variety testing section of the small grains website (http://smallgrains.wsu.edu/variety/) was the most visited section of the site (29,001 page views).

WGC project number: 4127-1604
WGC project title: Evaluation of Wheat Varieties
Project PI(s): Aaron Esser
Project initiation date: July 1, 2016
Project year (X of 3-yr cycle): 3 of 3

Objective	Deliverable	Progress	Timeline	Communication
1. Conduct wheat variety trials in eastern Washington	a) 24 soft winter wheat trials; 48-54 entries/trial b) 16 hard winter wheat trials: 18 entries/trial c) 18 soft spring wheat trials; 24 entires/trial d) 18 hard spring wheat trials; 36 entires/trial	a) 2019 trials planted; 2018 results finished b) 2019 trials planted; 2018 results finished c) 2019 trials in planning; 2018 results finished d) 2019 trials in planning; 2018 results finished	Trials are planted in the spring or fall, data results are available to growers at the end of the harvest season. Field tours in summer.	Results from the variety trials are communicated via Extension programming and are detailed under Objective #4.
		We are continuing the collaboratiion with OSU on trials at Dayton, Walla Walla and Eureka.		
2. Public and privated entries in trials	All widely grown, commuercially availabe varieties included in trials.	2019 winter trails; 43% public, 57% private. Every major breeding program in the PNW is actively participation in the VTP. 2019 winter entries can be viewd on the variety testing website.	Winter entries by August 15th and spring enties by February 15th	Solicit winter entries by August 1 and spring entries by Februay 1. Maintain positive relationship with breeding programs to ensure future participation.
		2018 spring trials: 51% public and 49% private		
3. Trials and data available to other projects	Participation other projects/programs.	Cooperation with breeders, pathologists, quality lab, FGIS, seed dealers, WSCIA, and Extension	Ongoing cooperation and collaboration that fit with timelines and other listed objectives.	Quality results in G&E study and preferred variety pamphlet, falling number results presented by corresponding project, disease ratings pesented in seed buyers guide and variety selection tool, VTP data used for variety release and PVP applications.
4 . Extension Outreach	Grower meetings	1 grower mtg in 2018	Whenever I'm invited	Grower meetings: 1 in 2018
	Field Tours (with County Extension)	21 in 2018 and 21 planned for 2019	June-July	*Field tours: 21 in 2018 (listed below)
	Email list serv	2018 results delivered	October	Email list serve: data sent to 213 members
	Website	up to date with 2018 data	fall winter	23,840 pagviews of the VTP section of the small grains website
	Annual Report	Published in December 2018	December	Annual Report: 2018 Technicl Report 18-3
	WSCIA Seed Buyers Guides	2018 published, 2019 in preparation	January-February	2018 Seed Buyers Guide published January 2018
	Wheat Life	2 articles written in 2018	January	Wheat Life: 2 article planned for 2019
	Variety Selection Tool (http://smallgrains.wsu.edu)	Selection tool needs to be updated with 2018 data	January-February	The variety selection tool has 6,593 page views in 2018
*** 2018 Tour Schedule Wheat**				
Location	**Date**	**Attendance**	**Crops**	
Horse Heaven	6-Jun	24	Winter Wheat and Spring Wheat	
Ritzville	6-Jun	28	Winter Wheat	
Western Whitman Co. -Dusty	7-Jun	10	Winter Wheat	
Connell	7-Jun	27	Winter Wheat	
Lind Field Day	14-Jun	130	Winter Wheat and Spring Wheat	
Harrington	14-Jun	25	Winter Wheat	
St Andrews	15-Jun	15	Winter Wheat	
Eureka	18-Jun	30	Winter Wheat	
Walla Walla	20-Jun	80	Winter Wheat and Spring Wheat	
Dayton	22-Jun	30	Winter Wheat and Spring Wheat	
Moses Lake	25-Jun	35	Winter Wheat and Spring Wheat	

Creston	25-Jun	1	Winter Wheat	
Reardan	26-Jun	10	Winter Wheat and Spring Wheat	
Mayview	27-Jun	25	Winter Wheat and Spring Wheat	
Anatone	27-Jun	15	Winter Wheat	
Fairfield	28-Jun	27	Winter Wheat	
St John	28-Jun	25	Winter Wheat and Spring Wheat	
Lamont	28-Jun	8	Winter Wheat and Spring Wheat	
Bickleton	29-Jun	30	Winter Wheat and Spring Wheat	
Farmington	6-Jul	15	Winter Wheat and Spring Wheat	
Palouse	6-Jul	10	Winter Wheat and Spring Wheat	
		Total = 600		

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

PROJECT #: 30109-6600

Progress report year: 3 of 3

Title: Evaluation And Selection For Cold Tolerance In Wheat

Cooperators: K. Garland Campbell, D.Z. Skinner, A.H. Carter

Executive summary:

We used the artificial screening system in the greenhouse to evaluate the Washington Extension Soft and Hard Winter Wheat Trials. We have screened these extension trials every year since 2001. The released and experimental lines from the 2018 trials are included in Tables 1 and 2 below.

Since 2013, we have rated 1877 breeding lines from public regional winter wheat breeding programs for survival. All breeding programs had lines that varied in winter tolerance. Breeders have used this information for selection of new experimental lines.

We scored survival in a doubled haploid population derived from Cara/Xerpha and survival ranged from 10% to 99% in this population (Figure 1). We are currently in the process of identifying QTL associated with the resistance in this population. Since both breeding lines are important PNW cultivars, we will discover molecular markers that can be readily used in the WSU and USDA breeding programs.

We scored survival in a large Winter Wheat Core Nursery representing a global collection of winter wheat cultivars. The range in survival in that population follows a linear trend from 0 to 100%. Our best check, Norstar had a survival of 78% so we are particularly interested in the 230 accessions that survived better than Norstar. We are currently in the process of identifying QTL associated with resistance in this global wheat population and hope to identify new sources of cold tolerance, of growth, and development that will be used to continue to improve survival in PNW winter wheat.

We evaluated the large PNW association mapping panel and Western regional nurseries for allelic and copy number variation at the Vrn1/Fr1 and Fr2 loci that are known to be associated with cold tolerance in wheat. Many of these alleles are segregating in our populations. The segregation that we documented at these known genes, for which we have effective KASP markers, is responsible for 38% of the variation for cold tolerance in this population. In addition to the known loci on the group 5 chromosomes, we discovered new loci on the group 1 and group 6 chromosomes. Use of these markers early in the breeding cycle is underway.

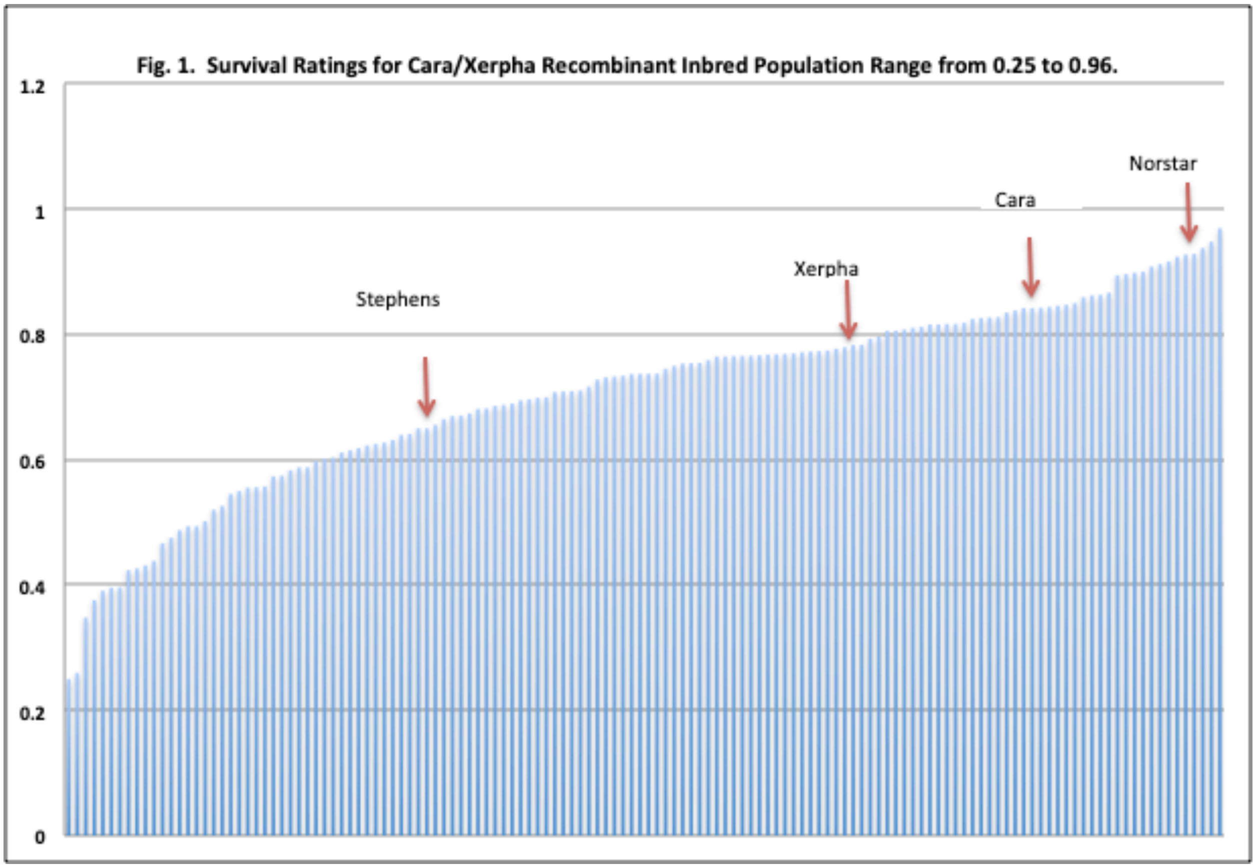
We discovered that freezing tolerance follows a diurnal pattern. In plants grown under 12 hours light/12 hours dark at a constant 3 degrees C (37 degrees F), cold tolerance was significantly greater at the midpoints of the light, and of the dark periods, compared to the end of either light or dark period. This new knowledge will help us to schedule our freezing test runs to achieve the maximum freezing tolerance. It also has implications in the genetic control of freezing tolerance, which seems to involve the day length sensing system in plants.

Table 1. FREEZE TEST SURVIVAL RATINGS FOR 2018 WASHINGTON VARIETY TESTING HARD WINTER WHEAT TRIAL			
Released and Experimental Line Names	Winter Survival Index 1=good, 10=bad	Lower 95% confidence limit	Upper 95% confidence limit
KELDIN	4.9	3.8	5.9
LCS ABRAHAM	10.0	7.6	12.4
LCS AYMERIC	6.8	4.4	9.1
LCS JET	7.6	6.5	8.7
LCS ROCKET	9.0	7.6	10.4
LCS ZOOM (LWW14-73915)	9.8	8.1	11.5
MANDALA	5.7	4.0	7.4
NSA12-2472	9.9	7.4	12.3
OR2130021R	9.9	7.5	12.3
REBALDI	7.6	5.2	9.9
SY TOUCHSTONE	6.2	3.8	8.7
WA 8268	8.5	6.0	10.9
WA 8288	9.1	6.7	11.6
WA 8289	9.9	7.4	12.3
WB4303	1.0	-1.4	3.4
WB4311	2.4	0.0	4.8
XB4542	3.5	1.1	5.9
Checks			
NORSTAR	1.8	1.5	2.2
ELTAN	3.6	3.2	3.9
STEPHENS	6.3	6.0	6.7

Table 2. FREEZE TEST SURVIVAL RATINGS FOR 2018 WASHINGTON VARIETY TESTING SOFT WINTER WHEAT TRIALS (COMBINED)

Released Line Name	Index 1=good, 10=bad	Lower 95% confidence limit	Upper 95% confidence limit
ARS CRESCENT	5.0	4.2	5.8
BOBTAIL	6.1	5.4	6.9
BRUEHL	5.3	4.4	6.2
CASTELLA	6.2	4.8	7.6
CURIOSITY CL+	3.3	2.3	4.2
DYNA-GRO IMPACT	4.2	1.9	6.5
ELTAN	3.6	3.2	3.9
JASPER	6.5	5.4	7.6
LCS ARTDECO	7.0	5.8	8.2
LCS GHOST (LWW14-74143)	7.1	4.8	9.5
LCS HULK	4.3	2.6	6.0
LCS SHARK	6.5	4.8	8.2
LCS SHINE (LWW14-72916)	5.0	2.7	7.4
LCS SONIC	4.6	2.9	6.2
M-PRESS	8.3	6.0	10.7
MADSEN	6.9	6.2	7.7
MELA CL+	3.8	2.8	4.7
NORWEST DUET	6.0	4.6	7.4
NORWEST TANDEM	6.8	4.5	9.1
ORCF102	6.6	5.7	7.5
ORCF103	4.3	3.4	5.2
OTTO	4.8	4.1	5.5
PNW HAILEY	4.4	2.0	6.7
PRITCHETT	5.2	4.0	6.4
PUMA	5.9	5.1	6.7
PURL	5.8	4.4	7.2
RESILIENCE CL+	5.3	3.9	6.7
ROSALYN	7.6	6.7	8.5
SY ASSURE	9.2	6.8	11.5
SY BANKS	7.7	5.4	10.1
SY CANDOR (09PN008#72)	6.5	4.1	8.8
SY COMMAND	7.6	6.0	9.3
SY DAYTON	8.4	6.7	10.0
SY OVATION	8.2	7.0	9.4
SY RAPTOR	9.2	7.5	10.9
UI CASTLE CL+	9.1	7.4	10.8
UI MAGIC CL+	9.6	7.9	11.3
UI PALOUSE CL+	4.7	3.0	6.4
UI SPARROW	6.4	5.4	7.4
WB 1376 CLP	8.8	6.4	11.1
WB 528	4.1	1.8	6.5
WB1376 CLP	5.3	2.9	7.6
WB1529	6.7	5.3	8.0
WB1532	5.9	3.5	8.2
WB1604	5.5	4.2	6.9
WB1783	3.2	0.8	5.5
XERPHA	5.5	4.6	6.3
YS-205	6.9	4.5	9.2

Experimental Line Name	Survival Index 1=good, 10=bad	Lower 95% confidence limit	Upper 95% confidence limit
ARS06132-45C	4.4	2.7	6.1
ARSDH08X103-102C	1.6	-0.1	3.2
ARSDH08X117-83C	2.5	0.2	4.8
ARSWA2J100065C	5.2	2.9	7.6
IDN 15-72458DH	9.7	7.3	12.0
IDO1005	5.1	4.0	6.1
IDO1708	6.6	5.0	8.3
KWS147	5.8	3.5	8.1
KXB-01	3.5	2.1	4.8
LWW15-71945	6.8	4.5	9.1
OR2121086	5.5	4.3	6.7
ORI2150031 Cl+	3.3	1.6	4.9
ORI2150061 Cl+	5.6	3.9	7.2
UIL 07-28017B	3.9	1.6	6.3
UIL 09-15702A	3.4	1.0	5.7
WA 8232	3.9	2.6	5.3
WA 8270	2.3	0.0	4.7
WA 8271	2.6	0.3	5.0
WA 8275 CL+	5.1	2.7	7.5
WA 8286	2.8	0.4	5.2
WA 8290	2.8	0.5	5.2
WA 8291	5.4	3.1	7.8
WA 8293	3.3	0.9	5.8



Impact

- The data from these cold tolerance trials was published in the seed buyers guide so that farmers can select winter wheat that is 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 are able to 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.
- Most breeding programs have both winter tolerant and less tolerant breeding lines. The identification of molecular markers associated with freezing tolerance complements our screening system and increases our current screening capacity from about 1000 varieties and breeding lines to several thousand progeny from segregating populations per year.
- We were able to use USDA equipment funds for the new Wheat Plant Growth Facility to purchase two new freezers. With this equipment, we have expanded our freeze tolerance

ratings to include regional nurseries from other parts of the country. We also use this equipment to conduct freeze trials for winter legumes.

Refereed papers

Kruse, E, Carle, S, Wen, N, Murray, TD, Skinner, DZ, Garland-Campbell, KA, and Carter, A.H, 2017 Genomic Regions Associated with Tolerance to Freezing Stress and Snow Mold in Winter Wheat." G3. G3 (Bethesda). 2017 Mar; 7(3): 775–780. Published online 2017 Jan 30. doi: 10.1534/g3.116.037622
.

Skinner, D.Z., Bellinger, B.S. 2016. Freezing tolerance of winter wheat as influenced by extended growth at low temperature and exposure to freeze-thaw cycles. Canadian Journal of Plant Science. doi: 10.1139/CJPS-2016-0154.

Skinner, D. Z. 2017. Advances in cold-resistant wheat varieties. Chapter 7 In: Achieving sustainable production of wheat. Vol. 1. P. Langridge, ed. ISBN-13: 9781786760166.

Skinner, D.Z., Bellinger, B.S., Hiscox, W., Helms, G. 2018. Evidence of cyclical light/dark-regulated expression of freezing tolerance in young winter wheat plants. PLoS One. https://doi.org/10.137/journal.pone.0198042. Log No. 351005

Abstracts

Carle, S., Horgan, A., Wen, N., Klarquist, E., Sanad, M., Carter, A., Skinner, D.Z., Garland-Campbell, K. 2016. Preparing Wheat for a Frosty Reception: Optimizing Marker Selection and Analysis in Order to Boost Breeding Efficiency for Freezing Tolerance. Crop Science Society of America Meeting, Baltimore MD. Nov. 6, 2018.

Popular Press

Web

Presentations

a. Invited by Mary Palmer-Sullivan, Organizer Washington Grains Commission Research Review to speak on: Report of Progress: “Breeding Club Wheat with Combined Resistance to Rusts, Strawbreaker Foot Rot and Cephalosporium Stripe”, “Improving Emergence of Winter Wheat in Low Rainfall Areas”, “Evaluation of Cold Hardiness in Wheat”, “Club Wheat Breeding”, Pullman WA, Feb. 2000, 2001, 2002, 2003, 2004, 2005, 2006, 2007, 2008, 2009, 2010, 2011, 2012, 2013, 2014, 2015, 2016, 2017, 2018.; Also “Development of Wheat Varieties Resistant or Tolerant to Fusarium Crown Rot”, “Evaluation of Wheat Breeding Lines for Management of Hessian Fly in the Pacific Northwest”, "Managing Nematode Diseases of Wheat" Feb. 2008, 2009, 2010, 2011, 2012, 2013, 2014, 2015, 2016, 2017, 2018

WGC project number: **3019-6600**
WGC project title: **Evaluation And Selection For Cold Tolerance In Wheat**
Project PI(s): **Kimberly Garland-Campbel, Arron Carter and Dan Skinner.**
Project initiation date: **7/1/16**
Project year: **3 of 3**

Objective	Deliverable	Progress	Timeline	Communication
1. Evaluate Washington winter wheat variety trials.	Survival data for all lines in winter wheat variety trials.	In 2018 survival data was collected for the soft and hard winter wheat variety trials.	Data analyzed and included in report.	http://smallgrains.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.	Survival data for lines in US regional nurseries	The Western Regional soft and hard winter wheat trials and the Northern and Southern Performance trials were evaluated.	Data analyzed and will be distributed in Feb. 2019.	Presentation at grower meetings, Wheat commission meetings, field days, plot tours, Wheat Life and Research Review. Refereed publications.
3. Evaluate cold tolerance of spring wheat variety trials.	Survival data for lines in spring wheat variety trials	Hard Spring Variety Trials evaluated.	Data analyzed, still needs to be summarized.	http://smallgrains.wsu.edu/
4. Evaluate cold tolerance of advanced breeding lines contributed by A. Carter, K. Gill, M. Pumphrey, R. Zemetra and others in the PNW as well as those in the ARS breeding program.	Survival data for advanced breeding lines submitted by regional breeders	Survival data was evaluated for the WSU Winter Wheat and the USDA Winter Wheat breeding programs.	Data send to breeders before field season so that selections can be made.	Presentation at grower meetings, Wheat commission meetings, field days, plot tours, Wheat Life and Research Review.
5. Evaluate cold tolerance of F_3-F_5 (early generation) wheat populations that are segregating for cold tolerance and select resistant progeny.	Populations that have been selected for tolerance to deep freezing.	New freezers are installed and protocols are being evaluated.	Populations selected each year, 2019.	
6. Identify genes controlling cold hardiness in winter wheat.	New information about the Fr1, Fr2, and other loci controlling cold tolerance and spring growth in wheat	The Winter Wheat association mapping panel and the Winter Wheat Core Nursery were evaluated. A GWAS was conducted on the PNW Association mapping panel.	Sept 2016-June 2019.	Carle, S., Horgan, A., Wen, N., Klarquist, E., Sanad, M., Carter, A., Skinner, D.Z., Garland-Campbell, K. 2016. Preparing Wheat for a Frosty Reception: Optimizing Marker Selection and Analysis in Order to Boost Breeding Efficiency for Freezing Tolerance. Crop Science Society of America Meeting, Baltimore MD. Nov. 6, 2018. Skinner, D.Z., Bellinger, B.S., Hiscox, W., Helms, G. 2018. Evidence of cyclical light/dark-regulated expression of freezing tolerance in young winter wheat plants. PLoS One. https://doi.org/10.137/journal.pone.0198042. Log No. 351005
7. Determine how cold tolerance interacts with resistance to soil borne disease, specifically snow mold, eyespot, and Fusarium crown rot resistance.	Survival data for wheat populations segregating for resistance to soil borne disease. Selected populations with resistance to cold and to individual diseases.	Lack of freezer space delayed progress. New freezers are being installed.	Trials with specific diseases conducted, one disease per year, 2016-2019.	Kruse, E, Carle, S, Wen, N, Murray, TD, Skinner, DZ, Garland-Campbell, KA, and Carter, A.H, 2017 Genomic Regions Associated with Tolerance to Freezing Stress and Snow Mold in Winter Wheat." G3. G3 (Bethesda). 2017 Mar; 7(3): 775–780.

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

PROJECT No.: 30109-6601
Progress report year: Final: *3 of 3 (maximum of 3 year funding cycle)*
Title: CLUB WHEAT BREEDING

Researchers: K. Garland Campbell, A.H. Carter,
Cooperator: M. Pumphrey,
Emeritus Advisor: R.E. Allan

Executive summary:
We focused club wheat development on two major goals: 1) Development of competitive club wheat cultivars for the < 15 inch rainfall zone with excellent resistance to snow mold, eyespot, stripe rust, sprouting and good emergence and winter hardiness and 2) Development of competitive early maturing club wheat for the > 15 inch rainfall zone with excellent resistance to eyespot, cephalosporium stripe, stripe rust, aluminum toxicity and good straw strength, and excellent test weight.

The new club wheat cultivar, Pritchett, jointly developed by the USDA-ARS and WSU winter wheat breeding programs, was released in 2015, because of its superior agronomic productivity in the targeted region, and superior end use quality combined with resistance to multiple diseases and abiotic stress. This cultivar was available to growers in the fall of 2018. Foundation seed of Pritchett, was produced. Pritchett is targeted to the traditional club wheat growing region in the dry precipitation zones.

ARS Castella (ARS20060123-31C) developed by the USDA-ARS and WSU was released in 2018 as an early maturing club wheat with good performance, excellent stripe rust resistance, aluminum tolerance and tolerance to low falling numbers. Castella has performed better in lower rainfall trials where lodging due to its height has not been a problem.

New club wheat breeding lines have been highly competitive with soft white wheat cultivars in multiple rainfall zones during the past three harvest seasons. In the Washington State Extension Dry Trials the three year yields of Pritchett averaged 6% more than ARS-Crescent and Bruehl in the < 12 inch rainfall zone; equal to ARS-Crescent and 4% better than Bruehl in the 12-16 inch rainfall zone (Table 1). ARS Castella was entered into the WAVT dry trials where yields were 2% better than Bruehl, 8% better than ARS-Crescent and 5% better than Bruehl <12 inch rainfall zones. Castella was equal to Pritchett, and ARS-Crescent and 3% better than Bruehl in the 12-16 inch rainfall zone.

The club wheat ARS Crescent is a complement to Pritchett in the higher rainfall regions (Table 2). ARS Crescent maintained acceptable falling numbers in almost all environments in 2016-2017 and has achieved stable high performance across rainfall zones over multiple years.

Table 1. Three-Year WSU Variety Testing Data from 2016-2018

Variety *club	<12" YIELD (BU/A)	12"-16" YIELD (BU/A)	TEST WT (LB/BU)	PROTEIN (%)
Castella	67	108	60.3	10.0
*Pritchett **	66	109	59.5	
*ARS-Crescent **	62	109	59.8	10.0
*Bruehl **	62	105	58.6	10.3
Curiosity CL+	64	101	60.5	9.9
Norwest Duet	67	116	60.7	10.1
Otto	62	101	60.1	10.6
SY Banks	64	111	59.7	10.3
Xerpha	68	112	60.2	9.9
CV %	9	8	1.5	6.7
LSD (.05)	2	3	0.3	0.3

<12" Precip (Connell, Harrington, Horse Heaven, Lind) 2016-2018, (Ritzville, St. Andrews) 2017-2018, (Bickelton) 2018, 17 loc/years. (Smallgrains.wsu.edu)

12"-16" Precip (Almira, Creston) 2016-2018, (Anatone) 2016-2018, (Lamont) 2016, 2018, (Reardan) 2016-2018, 14 loc/years. (Smallgrains.wsu.edu)

Table 2. Five-Year WSU Variety Testing Data from 2014-2018

Variety *club	16-20" YIELD (BU/A)	>20" YIELD (BU/A)	TEST WT (LB/BU)	PROTEIN (%)
*ARS-Crescent **	103	122	59.5	10.2
Bobtail	110	121	58.0	10.3
LCS Art Deco	110	118	59.5	10.1
Puma	109	118	60.2	10.5
Rosalyn	115	128	58.7	9.9
SY Ovation	109	115	60.4	10.5
Xerpha	108	123	60.1	10.4
CV %	7	6	1.1	4.9
LSD (.05)	2	2	0.2	0.2

16-20" Precip (Dayton, Mayview, St. John, Walla Walla) 2014-2018, 19 loc/years. (Smallgrains.wsu.edu)

> 20" Precip Colton, Fairfield, Farmington, Pullman) 2014-2018, 18 loc/years. (Smallgrains.wsu.edu)

The USDA-ARS Wheat breeding program managed field testing locations at Central Ferry, Lind, Harrington, Pullman, and Farmington WA and at Pendleton OR and Genesee ID. We also evaluated breeding lines at Walla Walla, St. Andrews, Mansfield, Ritzville, and Kahlotus, WA and Corvallis OR in collaboration with the WSU Winter Breeding program, the WSU Cereal Variety Testing Program, OSU-CBARC, the OSU Wheat Breeding program, the University of Idaho and Syngenta. The overall goal of this project has been to remove the agronomic constraints that make club wheat less attractive to growers than soft white wheat.

For the 2017 WA State Extension trials for the dry rainfall zones, we entered two lines: ARS20060123-31C (was in the 2015-16 trials) is derived from a cross between NY89066-7131/B980696//CHUKAR; a tall, early maturing, awnless club that has been very resistant to stripe rust in USDAARS trials; ARSDH08028-111C, and ARSDH08028-44C were derived from a cross between Cara/Xerpha, an awned club that has performed well, where Xerpha is adapted but with better adult plant resistance to stripe rust and excellent milling quality.

For the 2017 WA State Extension trials for the high rainfall zones, we entered two lines: ARSDH08028-44C is an awnless club and new entry for 2017 derived from the Cara/Xerpha cross with excellent stripe rust resistance and moderately early maturity that has performed well in early maturing and higher rainfall regions. ARS20040150-2C is also a new entry for 2017 derived from a cross between Chukar/Cayuga/2*Chukar. Cayuga is a source of preharvest sprouting resistance from NY. This entry was selected to have that resistance. We still need further testing to confirm but the line has performed well on the Palouse with good stripe rust resistance and maturity similar to Chukar.

We entered the following breeding lines into 2018 trials: ARSDH08X117-83C in the WAVT Dry, North Idaho, and Oregon Wheat Elite Yield Trial (OWEYT); ARSWA2J100065C in the WAVT Dry; ARSDH08X103-102C and ARS06132-45C in the WAVT-Wet; ARSDH08X028-9C in the WA/OR cooperative trials and OWEYT; ARSDH08X142-11L, ARSDH08X103-102C, DH08X028-9C, and ARS2J100065-C in the Western Regional Nurseries.

We entered two lines into the 2019 trials: ARSDH08X117-83C and ARS09X492-6CBW.

These club breeding lines are all products of crossing with soft wheat from the Eastern US as additional sources of resistance to rusts, cold tolerance, Hessian Fly and BYDV. We have added an additional head row purification and selection step to the breeding program in order to provide Washington Foundation Seed with quality Breeder seed in a timely manner.

We have greatly expanded our use of genotyping and are in the process of genotyping all our the entries in all of our yield trials using resequencing approaches through North Carolina State University and targeted amplicon sequencing in the USDA Western Small Grains Genotyping laboratory. We are implementing genomic selection for end use quality and cold tolerance and end use quality. Marker assisted selection was conducted using KASP and SSR markers to select for resistance to low falling number, BYDV, eyespot, stripe rust, dough strength, cold tolerance and reduced height.

We evaluated several hundred doubled haploid lines and advanced several to our elite replicated trials. Early generation quality testing using the micro-mill, the polyphenol oxidase assay, and solvent retention capacity tests was performed. Coleoptile testing and survival from freezing was assayed on all breeding lines. All breeding lines were selected for resistance to stripe rust, eyespot, cephalosporium stripe, and Fusarium in inoculated nurseries at Central Ferry and Pullman WA.

We expanded our selection in single row plots to additional locations at Lind WA Pendleton OR and near Waterville. These small plots allow us to select among large populations for emergence, snow mold resistance, and adaptation to early spring green-up. Our expansion into these locations was made possible by the new deep furrow no-till drill that is shared with the WSU Winter wheat project.

Our plot and head row totals for 2019 are listed below:
Total Locations: 13 in the Pacific Northwest plus 2 additional sites in Colorado
Total Winter Plots: = 4315
Spring Plots= 646

Total Headrows: 34,992 individual rows
* includes stripe rust screening rows that we conduct for collaborators
Spring HR= 416

Impact

Club wheat acreage represents a small but significant part of the total WA wheat market. The excellent disease resistance of the club wheat is a built-in premium for growers because the reduced need for fungicides. Because of their disease resistance, club wheat cultivars have been used to incorporate stripe rust resistance and eyespot resistance into other wheat classes. The combination of excellent end use quality, disease resistance, and cold tolerance of new club wheat cultivars allows growers to make planting decisions based on market demands and to maximize choice in marketing strategy. The club wheat breeding program works collaboratively with several other WGC funded projects including the Winter and spring wheat breeding projects, the disease resistance and quality projects, and the drought and preharvest sprouting projects to integrate their results and methods into production of quality cultivars for PNW growers.

Club wheat acreage represents a significant part of the total WA wheat market. The excellent disease resistance of the club wheat is a built-in premium for growers because the reduced need for fungicides. The combination of excellent end use quality, disease resistance, and cold tolerance of new club wheat cultivars allows growers to make planting decisions based on market demands and to maximize choice in marketing strategy.

Presentations:

a. Report of Progress: Washington Grains Commission Research Review, “Club Wheat Breeding”, Pullman WA, Feb. 2016, 2017, 2018.

b. Invited by R. Higginbotham to present at plot and field day tours speaking to approximately 35-50 growers and industry representatives per tour during May, June and July: Connell WA, 2016; Harrington WA, 2016, 2017, 2018; Lacrosse, WA, 2017; Lind WA, 2016, 2018; St. Andrews WA, 2016, 2017; St. John WA, 2017;

c. Invited by Planning Committee, Edgar Mcfadden Symposium to speak on, "Learning from the Daleks and the Silurians to Control Stripe Rust in the Great Plains" at Joint Edgar McFadden Symposium-Hard Winter Wheat Workers Workshop, April 19, 2016. San Antonio TX

Selected refereed manuscripts with applications to this project.

1. Garland-Campbell, K, Carter, AH, Jones, SS, Chen, XM, DeMacon, P, Higginbotham, R, Engle, D, Guy, SO, Mundt, CC, Murray, TD, Morris, CF, See, D, 2017. Registration of "Pritchett" Soft White Winter Club Wheat. J. Plant Reg. 11. DOI: 10.3198/jpr2016.04.0018crc
2. Gizaw, S.A., Garland-Campbell, K., Carter, A.H., 2016. Evaluation of agronomic traits and spectral reflectance in Pacific Northwest winter wheat under rain-fed and irrigated conditions. Field Crops Res. http://dx.doi.org/10.1016/j.fcr.2016.06.018
3. Gizaw, S.A., Garland-Campbell, K., Carter, A.H. 2016. Use of spectral reflectance for indirect selection of yield potential and stability in Pacific Northwest winter wheat. Field Crops Res. Available online 21 July 2016. http://www.sciencedirect.com/science/article/pii/S0378429016302088
4. Campbell KG. Errors in statistical decision making. 2017. In Glaz, B., Yeates, K (Eds.) Applied statistics in agricultural, biological, and environmental sciences. American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America. Online first: doi:10.2134/appliedstatistics.2016.0007
5. Jernigan KL, Morris CF, Zemetra R, Chen J, Garland-Campbell K, Carter AH. 2017. Genetic analysis of soft white wheat end-use quality traits in a club by common wheat cross. Journal of Cereal Science. 76:148-56. https://doi.org/10.1016/j.jcs.2017.06.005
6. Martinez SA, Godoy J, Huang M, Zhang Z, Carter AH, Garland Campbell KA, Steber CM. 2018. Genome-wide Association Mapping for Tolerance to Preharvest Sprouting and Low Falling Numbers in Wheat. Frontiers in Plant Science. 2018;9:141. doi.org/10.3389/fpls.2018.00141

WGC project number:
WGC project title: **Club wheat breeding**
Project PI(s): **Kimberly Garland-Campbell and Arron Carter**
Project initiation date: **7/1/16**
Project year: **3**

Objective	**Deliverable**	**Progress**	**Timeline**	**Communication**
1. Develop agronomically competitive club wheat cultivars targeted to the diversity of rainfall and production zones of the PNW. These cultivars will possess the excellent end use quality characteristic of club wheat. They will also possess excellent resistance to stripe rust. Specific other characteristics will be targeted to individual rainfall regions	Club cultivar releases	The club wheat cultivar Pritchett was available to growers in fall 2018. ARS-Castella was planted as breeders seed in fall 2018.	Sept 2016-June 2019. Cutlivar releases are targeted as one every three years per rainfall zone.	Report of Progress: Washington Grains Commission Research Review, "Club Wheat Breeding", Pullman WA, Feb. 2017. Garland-Campbell, K, Carter, AH, Jones, SS, Chen, XM, DeMacon, P, Higginbotham, R, Engle, D, Guy, SO, Mundt, CC, Murray, TD, Morris, CF, See, D, 2017. Registration of "Pritchett" Soft White Winter Club Wheat. J. Plant Reg. 11. DOI: 10.3198/jpr2016.04.0018crc
2. Develop club breeding lines for the <15 inch rainfall zone with improved resistance to snow mold and fusarium crown rot , improved emergence and winter survival	Germplasm identified with resistance, used to introgress new resistance genes into existing club wheat germplasm. Better combination of traits in club wheat targeted to the <15 in. rainfall zone.	We entered two lines into the 2019 trials: ARSDH08X117-83C and ARS09X492-6CBW.	Sept 2016-June 2019.	Plot and field day tours speaking to approximately 15-30 growers and industry representatives per tour during June, 2018, Harrington, Lind
3. Develop club breeding lines for the > 15 inch rainfall zone with improved resistance to eyespot, cephalosporium stripe, aluminum toxicity, and cereal cyst nematodes.	Germplasm identified with resistance, used to introgress new resistance genes into existing club wheat germplasm. Better combination of traits in club wheat targeted to the >15 in. rainfall zone.	We entered two lines into the 2019 trials: ARSDH08X117-83C and ARS09X492-6CBW.	Sept 2016-June 2019.	"Club Wheat" Drew Lyon interviewed K. Campbell for Wheat Beat Podcast, summer 2018.

4. Release a club wheat cultivar with early maturity targeted to SE Washington and NE Oregon.	Club wheat cultivars with early maturity (2-5d earlier than Pritchett) combined with excellent stripe rust resistance.	Head rows were planted in Pendleton in the fall of 2017 so that earlier maturing selections can be made in that environment.	Sept 2016-June 2019. Our next club wheat release after Pritchett will be targeted to this growing environment	Invited talk, 'Falling Numbers' Northwest Grain Growers Meeting, June 21, 2017. Walla Walla WA
5. Release germplasm with improved resistance tolow falling number	Club wheat breeding lines with stable falling numbers above 300 in all but extreme environments.	All elite lines in the breeding pogram were assayed for LMA using field testing and PHS using spike wetting tests. Lines that were susceptible were not advanced.	Sept 2016-June 2019.	Presentation at grower meetings, Wheat commission meetings, field days, plot tours, Wheat Life and Research Review.
6. Identify an early generation method to assess cake baking quality	Early generation prediction equation for cake baking quality, the key trait for club wheat.	Association mapping and genomic selection for improved baking quality is underway.	Sept 2016-June 2019.	Jernigan KL, Morris CF, Zemetra R, Chen J, Garland-Campbell K, Carter AH. 2017. Genetic analysis of soft white wheat end-use quality traits in a club by common wheat cross. Journal of Cereal Science. 76:148-56. https://doi.org/10.1016/j.jcs.2017.06.005

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

Project #:

Progress Report Year: __2__ of __3__ (maximum of 3 year funding cycle)

Title: Assessment of soil acidity on soil-borne pathogens, weed spectrum, herbicide activity, yield, and crop quality on dryland wheat production.

Principal Investigators:
Christina Hagerty, Assistant Prof. of Cereal Pathology, OSU, CBARC, Pendleton, OR
Paul Carter, Associate Prof., Regional Extension Soil Specialist, WSU, Columbia County, WA

Cooperators:
Kurt Schroeder (U of I), *Tim Murray* (WSU), *Stephen Van Vleet* (WSU), *Judit Barroso* (OSU), *Stephen Machado* (OSU), *Don Wysocki* (OSU).

Executive summary: To initiate this long-term research effort, 24 x 50ft. plots were established in fall 2016 and treated with four ultrafine liquid calcium carbonate treatments (0, 600, 1200, and 2400 lbs/acre) with 4 replications. The plots were soil tested in April 2017 and April 2018 and successfully established different soil acidity levels ranghing from pH 4.85 to pH 6.65. Micro-nutrients were applied based on soil test results and included Zinc, Boron, and Copper. The plots were established in three distinct production zones in order to make the results of this research effort applicable to a wide audience of producers, provide a robust multi-location dataset, and understand how the effects of liming and soil acidity may differ regionally. The three locations include: CBARC Sherman Station in Sherman County, OR (11 in. annual rainfall), the CBARC Pendleton Station in Umatilla County, OR (16 in. annual rainfall), and in Whitman County, WA at the Palouse Conservation Field Station (PCFS) and in a farmer's (Clark) field (18 in. annual rainfall). The project was initiated in 2017, and our first year of yield data do not yet indicate a significant effect of lime application on yield. In 2017, plots were established in spring wheat following fallow (Oregon locations) and re-cropping following chickpeas in Whitman County. In 2018 we began the typical winter wheat-summer fallow rotaion for the Oregon plot sites, and annual cropping system in Washington.

Impact: Soils below a threshold of pH 5.2 are considered poor management and below the critical level for optimum grain production. Most dryland wheat production soils of the PNW are at or below the pH 5.2 critical threshold. This study will help quantify the impact of soil acidity to local wheat production and will serve as a foundation to develop solutions to affordably address soil acidity in the dryland PNW.

The measureable impacts in the most recent funding cycle:

1. Preliminary results indicate that modest applications of agricultural lime are effective to begin to buffer acidic soils in the dryland wheat production region.
2. This project is increasing the awareness about the issue of soil acidity in the PNW. In addition, the project has assured producers that the PNW wheat research community is addressing the soil acidity problem, and ultimately working on economical solutions to help manage soil acidity.

WGC project number:
WGC project title: Assessment of soil acidity on soil-borne pathogens, weed spectrum, herbicide activity, yield, and crop quality on dryland wheat production.
Project PI(s): Christina Hagerty and Paul Carter
Project initiation date: July 1, 2017
Project year (X of 3-yr cycle): This year 2 of 3

Objective	Deliverable	Progress	Timeline	Communication
Quantify impact of soil acidity on soil-borne pathogens	Quantify pathogens in each soil pH treatment, statistically evaluate the relationship between pathogens and pH	Replicated plots ranging from pH 4.85 - pH 6.65 were sucessfully established in three different locations	Fall 2019	Extension programming to communicate results directly to grower clientele and peer reviewed publications to communicate results to the scientific audience
Quantify impact of soil acidity on weed spectrum	Quantify weed spectrum in each soil pH treatment, statistically evaluate the relationship between weeds and pH	Replicated plots ranging from pH 4.85 - pH 6.65 were sucessfully established in three different locations	Fall 2019	Extension programming to communicate results directly to grower clientele and peer reviewed publications to communicate results to the scientific audience
Quantify impact of soil acidity on herbicide activity	Quantify herbicide activity in each soil pH treatment, statistically evaluate the relationship between herbicide activity and pH	Replicated plots ranging from pH 4.85 - pH 6.65 were sucessfully established in three different locations	Fall 2019	Extension programming to communicate results directly to grower clientele and peer reviewed publications to communicate results to the scientific audience
Quantify impact of soil acidity on yield	Quantify yield in each soil pH treatment, statistically evaluate the relationship between yield and pH	Replicated plots ranging from pH 4.85 - pH 6.65 were sucessfully established in three different locations	Fall 2019	Extension programming to communicate results directly to grower clientele and peer reviewed publications to communicate results to the scientific audience
Quantify impact of soil acidity on crop quality	Quantify crop quality in each soil pH treatment, statistically evaluate the relationship between quality and pH	Replicated plots ranging from pH 4.85 - pH 6.65 were sucessfully established in three different locations	Fall 2019	Extension programming to communicate results directly to grower clientele and peer reviewed publications to communicate results to the scientific audience
Understand more about the total picture of the impact of soil acidity on the dryland wheat production system	Synthesize the parameters listed above to understand more about the total impact of soil acidity on the Columbia Basin dryland wheat production region.	Replicated plots ranging from pH 4.85 - pH 6.65 were sucessfully established in three different locations	Fall 2019	Extension programming to communicate results directly to grower clientele and peer reviewed publications to communicate results to the scientific audience

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

Project #: 4150-1224

Progress Report Year: 3 of 3

Title: Extension Education for Wheat and Barley Growers

Cooperators: Drew Lyon, Timothy Murray, David Crowder, Randy Fortenbery, Haiying Tao, Aaron Esser, Stephen Van Vleet, Diana Roberts, Paul Carter, Dale Whaley, and Karen Sowers

Executive summary: The Wheat and Small Grains website (smallgrains.wsu.edu) was launched by the Extension Dryland Cropping Systems Team in early 2014. The website serves as a one-stop shop for all the information WSU Extension has on small grains production. The development of Decision Support Tools has been a priority for the team over the course of this project. We currently have 16 tools or calculators available on the Wheat and Small Grains website. The five most viewed tools in 2018 were the variety selection tool (6,593 pageviews), herbicide MOA tool for wheat (2,321 pageviews), herbicide comparison tool (2,204 pageviews), herbicide efficacy table (1,382 pageviews), and the AMS sprayer mix calculator (574 pageviews). The WSU Wheat Beat Podcast was introduced in 2017 with seven episodes. There were 41 new episodes posted in 2018. We are able to communicate directly with more than 900 subscribers to our subscription listserv, which allows us to push information out to people who are interested in our content. The Wheat Academy continues to be highly valued by participants and has sold out within two weeks of opening on-line registration in every year since the inaugural event in 2014. The biggest unforeseen issue to arise during the duration of this project was the low falling number issue in 2016. We responded by providing information on the topic, including four Timely Topic posts that combined were viewed nearly 2,500 times through November of 2016. Additionally, we added a Wheat Quality Resources page to the Wheat and Small Grains website to make it easier for people to find information on this issue.

Impact: The Wheat and Small Grains website saw increased use again in 2018. For the 11-month period of January through November, the site had 42,484 sessions with 29,001 unique users; this was up from 39,747 sessions and 25,534 unique users for the same period in 2017, and 26,603 sessions and 17,679 unique users in 2016. There were 81,854 pageviews in 2018, 80,601 pageviews in 2017, and 26,603 pageviews in 2016. The subscription listserv currently has 919 subscribers. The Wheat Academy continues to be highly valued by participants, with all 75 seats being purchased within two weeks of opening on-line registration in every year since the inaugural event in 2014. Four Timely Topics on low falling numbers received nearly 2,500 pageviews in just four months during the fall of 2016 when this was an issue of great concern to the wheat industry.

WGC project number: 4150-1224
WGC project title: Extension Education for Wheat and Barley Growers
Project PI(s): Drew Lyon
Project initiation date: July 1, 2016
Project year (X of 3-yr cycle): 3

Objective	**Deliverable**	**Progress**	**Timeline**	**Communication**
Add new resources to the Wheat and Small Grains website	Publications, dcision support tools and calculators, videos, quizzes, topic forums, etc. Specific deliverables identified include dynamic weed control tables, an ammonium sulfate spray tank calculator, a soil lime application calculator, and three videos on soil acidification as well as several new publications on this topic. An article will be written annually for Wheat Life magazine on our Extension activities.	All specific deliverables were produced. There are now 16 decision support tools available on the Wheat and Small Grains website. The soil acidification videos and publications are all available on Soil and Water Resources page. A Wheat Life aricle was written each year on some aspect of our Extension activities.	New resources will be added every year for the duration of the grant. The specific deliverables identified will be completed in 2016.	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 education events held throughout the life of the project.
Develop and launch subscription listserv	Subscription listserv	The subscription listserv went live on September 30, 2016. As of December 10, 2018 there were 919 subscribers to the listserv.	The subscription listserv will be available by the end of 2016.	The subscription listserv was announced through Timely Topic posts on the Wheat and Small Grains website and a subscription link is available on the home page of the website.
Improve the Wheat Academy	A highly relavant and popular program will continue to improve and a means of serving more people without losing program quality will be sought.	The Wheat Academy continues to be a highly valued program. The 75 seats have sold out within two weeks of opening on-line registration in every year since the inaugural event in 2014. We have tweaked the event every year in an attempt to improve it, but we have not made any large changes in fear of damaging a very successful education program.	This will be an ongoing process throughout the duration of the grant.	Information on the Wheat Academy was shared with growers through the Wheat and Small Grains website, through news releases, and other educational events. We also made much of the information delivered at the Academy avaialble to people through the website.
Respond to issues of concern as they arise	In-depth educational programs, publications, and decision support tools as called for by the particular issue.	Low falling numbers were a widespread problem in 2016. Growers had many questions on the topic. The Extension Dryland Cropping Systems Team worked with Camille Steber, USDA-ARS, the WSU wheat breeders, WAWG, and the WSDA to provide information on this topic. Four Timely Topics were posted to the Wheat and Small Grains website. Through November of 2016, these four Timely Topics received nearly 2,500 pageviews. Additionally, a Grain Quality Resources page was added to the Wheat and Small Grains website.	This will be an ongoing process throughout the duration of the grant.	Educational resources and programming developed to address issues of concern will be shared with growers through the Wheat and Small Grains website, news releases, and education events held throughout the year.

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

Project #: 4721

Progress Report Year: *1 of 3*

Title: Quality of Varieties & Pre-release Lines: Genotype & Environment-"G&E" Study

Cooperators: Ryan Higginbotham, Kim Garland-Campbell, Arron Carter, Mike Pumphrey, Kulvinder Gill

Executive summary: The 2018 harvest sample analysis is more than half done; the project is on-going with the most recent project covering the past three years. 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.

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.

Outputs and Outcomes:

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

4J71366C	Pritchett	winter club
KXB-01	--	--
WA8118	Sprinter	HRS
WA8124	Ryan	SWS
WA8143	Curiosity CL+	SWW
WA8155	Mela CL+	SWW
WA8158	--	HWW
WA8162	Seahawk	SWS
WA8165	Chet	HRS
WA8166	Alum	HRS
WA8169	Jasper	SWW
WA8177	--	SWW
WA8180	Sequoia	HRW
WA8184	Earl	HWW
WA8187	Resilience CL+	SWW
WA8189	--	SWS
WA8189	Tekoa	SWS
WA8193	Melba	spring club
WA8212	--	SWW
WA8232	--	SWW
WA8235	--	SWW

Advanced winter lines under consideration August 2018:
WA8271, WA8268, WA8275, and WA8252

SOFT WHITE WINTER

UI Castle	UI	MD
Bobtail	OSU	MD
Brundage96	UI	MD
Kaseberg	OSU	MD
Bruneau	UI	MD
UI Palouse	UI	MD
Jasper	WSU	MD
UI WSU Huffman	UI/WSU	MD
Puma	WSU	MD
ARS-Selbu	ARS	D
Mary	OSU	D
ORCF101	OSU	D
SY Ovation	SY	D
LCS Drive	LCS	D
Skiles	OSU	D
LCS Shark	LCS	D
SY Command	SY	D
WB523	WB	D
UI Sparrow	UI	D
UI Magic	UI	D
Eltan	WSU	D
SY Dayton	SY	D
WB528	WB	D
Otto	WSU	D
Resilience CL+	WSU	D
Norwest Duet	OSU/LCS	D
Stephens	OSU	D
SY Assure	SY	A
LCS Hulk	LCS	A
Madsen	ARS	A
ORCF103	OSU	A
LCS Artdeco	LCS	A
Mela CL+	WSU	A
Rosalyn	OSU	A
WB1604	WB	A
WB1070CL	WB	A
Norwest Tandem	OSU/LCS	A
Curiosity CL+	WSU	A
ORCF102	OSU	A
WB1529	WB	A
WB1066CL	WB	A
Xerpha	WSU	LD
WB456	WB	LD
SY Banks	SY	LD
SY107	SY	LD
WB1783	WB	LD

SOFT WHITE SPRING

UI Stone	UI	MD
Diva	WSU	MD
Tekoa	WSU	MD
WB6341	WB	MD
Louise	WSU	MD
Alturas	UI	MD
SY Saltese	SY	MD
Ryan	WSU	MD
Whit	WSU	MD
Seahawk	WSU	MD
Babe	WSU	MD
WB6121	WB	D
WB1035CL+	WB	UCS

CLUB

ARS Castella	ARS	MD
ARS Crescent	ARS	MD
Cara	ARS	MD
ARS Pritchet	ARS	D
Bruehl	WSU	D

SPRING CLUB

Melba	WSU	MD
JD	WSU	MD

HARD WHITE WINTER[1]

UI Silver	UI	MD
Earl	WSU	A

HARD WHITE SPRING[1]

UI Platinum	UI	MD
WB Hartline	WB	D
Dayn	WSU	D

ABBREVIATIONS

WSU	*Washington State University*
OSU	*Oregon State University*
UI	*University of Idaho*
ARS	*Agricultural Research Service*
SY	*Syngenta*
WB	*WestBred/Monsanto*
LCS	*Limagrain Cereal Seeds*

[1]Hard white wheats are scored for export quality requirements such as bread quality and potential noodle quality.

HARD RED WINTER

WB4623CLP	WB	MD
UI SRG	UI	MD
Whetstone	SY	MD
Norwest 553	OSU	D
AP503 CL2	SY	D
LCS Evina	LCS	D
Farnum	WSU	D
LCS Rocket	LCS	D
Sequoia	WSU	D
Keldin	WB	A
LCS Jet	LCS	A
Esperia	Societa Produttori Sementi Spa	A
SY Touchstone	SY	LD
Residence	Cebeco	UCS
Estica	Cebeco	UCS
Symphony	Tanio Tech	UCS

HARD RED SPRING

Hollis	WSU	MD
SY605 CL	SY	MD
Alum	WSU	MD
SY Steelhead	SY	MD
SY Selway	SY	MD
Glee	WSU	MD
Chet	WSU	MD
Jedd	WB	MD
LCS Luna	LCS	MD
LCS Iron	LCS	D
WB9411	WB	D
WB9668	WB	D
WB9229	WB	D
Jefferson	UI	D
Kelse	WSU	D
Bullseye	SY	D
WB9518	WB	D
WB 9879CLP	WB	A
Buck Pronto	LCS	A

2017 QUALITY RANKINGS

Varieties are listed by statistical quality rankings by class. When making a decision between varieties with similar agronomic characteristics and grain yield potential, choose the variety with the higher quality ranking. This will help to increase the overall quality and desirability of Pacific Northwest (PNW) wheat.

Most Desirable (MD)—These varieties generally have high test weights, appropriate protein content (kernel properties), and excellent milling and end-use properties.

Desirable (D)—The kernel, milling, and end-use qualities of these varieties range from good to very good. The quality attributes of these varieties are desirable in international trade.

Acceptable (A)—The kernel, milling, and end-use qualities of these varieties range from acceptable to good. Individual varieties may possess minor flaws. The quality attributes of these varieties are acceptable in international trade.

Least Desirable (LD)—These varieties have displayed low quality characteristics for this class of wheat. The intrinsic quality of PNW wheat will be improved if these varieties are not planted.

Unacceptable Except Customer-Specific Uses (UCS)—One or more critical flaws in quality are present in these varieities and will not make suitable products for this class of wheat. Production of these varieties should be targeted to specific end-uses and kept strictly segregated from general commercial channels.

These rankings are based on the results of the *Genotype and Environment Study (G&E)* quality testing conducted by the USDA Western Wheat Quality Laboratory, the Washington State Univeristy Wheat Quality Program, the University of Idaho Wheat Quality Laboratory, and the Oregon State University Cereal Quality Laboratory, including relevant breeding nurseries.

End-use quality determinations were based on results from grain, milling and product quality tests.

The quality scores presented here reflect a minimum of three years' data in the G&E study, using a reference variety for each class. The scores are reviewed yearly as new data becomes available, and are subject to change. Varieties not listed have not been tested or have less than three years of data. For complete results, please visit the website: www.wsu.edu/~wwql/php/index.php

For agronomic information, please consult: 1) the Washington State Crop Improvement Association Certified Seed Buying Guide; 2) WSU Uniform Cereal Variety Testing Program (http://variety.wsu.edu); 3) North Idaho Extension Cereals Program (http://cals.uidaho.edu/cereals/nidaho); 4) Oregon Elite Yield Trials (http://cropandsoil.oregonstate.edu/wheat/state_performance_data.htm).

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Preferred Wheat Varieties *is provided courtesy of: The Washington Grain Commission, the Oregon Wheat Commission, and the Idaho Wheat Commission.*
The G and E Study *is financially supported by the WGC, OWC, and IWC.*

2018 PREFERRED WHEAT VARIETIES

BASED ON END-USE QUALITY

WASHINGTON
OREGON
NORTH IDAHO

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

Project #: 4722

Progress Report Year: *1 of 3*

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 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 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 2017-Crop were completed and 2018-Crop testing is well under way at the Western Wheat Quality Lab.

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).

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.

WGC project number:	4722			
WGC project title:	Supplemental Support for Assessing the Quality of Washington Wheat Breeding Samples			
Project PI(s):	Craig F. Morris and Doug Engle			
Project initiation date:	**1-Jul-18**			
Project year:	3			

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 interpetation,
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 interpetation,

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

Project #:

Final Report Year: *1 of 1*

Title: **Evaluation of alternative technologies for determining Falling Number: The Chopin 'Amylab FN', and 'Testogram' quick method**

Cooperators: Craig Morris, Alecia Kiszonas, Doug Engle

Executive summary: Falling Number per se is not a wheat or flour quality problem. Falling Number attempts to *predict* flour quality performance in various end-products. However, the Falling Number test is deeply entrenched in our marketing and grading system, especially for export. The current Falling Number technology was developed in 1961, and has received minor improvements over the years in hardware and protocol. Chopin Technologies has developed a new instrument that emulates and attempts to improve on the Perten Falling Number. Key features include: 1) no glass tubes, these are replaced with a stainless steel tube that opens at the bottom for easy clean out, 2) no boiling water, the sample tube is heated with solid state direct heat, and 3) no external cooling system required. Two testing protocols are the 'traditional' Hagberg-Perten Falling Number, and a quick 90-second 'Testogram'. The Testogram results are aimed at predicting the Falling Number.

Impact: New technologies may help growers and marketers obtain more accurate and timely assessment of sprout and LMA. This project is evaluating the new Chopin AmyLab with a standard and rapid 'Testogram' tests.

Deliverables: A robust, objective evaluation of the AmyLab and quick Testogram assays compared to traditional Perten Falling Number.

Outputs and Outcomes:

The 500 samples (250 in replicate) were processed through the Perten Falling Number (FN), Chopin AmyLab Falling Number (AmyLab), and Chopin Testogram (Testogram) assays. The samples were also analyzed for moisture and protein. The FN, AmyLab, and Testogram were all analyzed within one week of a sample being ground with the Perten grinder (0.8 mm screen size).

The original dataset had calculated correlations as follows:
FN vs. AmyLab R^2 = 0.78
FN vs. Testogram R^2 = 0.25
AmyLab vs. Testogram R^2 = 0.18

The FN vs. AmyLab FN test were not particularly promising, and the quick Testogram assay was particularly poor. We have been in communication with Chopin, and using our data, their engineers developed a new algorithm to try and better relate the Testogram results. The new correlations were as follows:
FN vs. New Testogram R^2 = 0.24
AmyLab vs. New Testogram R^2 = 0.22

Clearly, there was little improvement. Chopin is in the process of making hardware/firmware changes and are releasing a new AmyLab/Testogram instrument. We continue to work with Chopin as the instrument 'evolves'. Because the study was performed on an instrument/protocol that essentially no longer exists (due to the changes Chopin is making), the results will not be submitted for publication as originally planned.

WGC project number:	new proposal
WGC project title:	Evaluation of alternative technologies for determining Falling Number: The Chopin 'Amylab FN', and 'Testogram' quick method
Project PI(s):	Craig Morris
Project initiation date:	**1-Jul-18**
Project year:	1

Objective	Deliverables	Progress	Timeline	Communication
Evaluate Chopin AmyLab	Precision, reproducibility, ease of use assessment	New project, will communicate to WGC	We will begin as soon as funding becomes available	WGC, Wheat Life, regional/national wheat industry; we plan to publish the results in peer-reviewed journal
Compare AmyLab with Perten Falling Number	Correlation, prediction power	New project, will communicate to WGC	We will begin as soon as funding becomes available	WGC, Wheat Life, regional/national wheat industry; we plan to publish the results in peer-reviewed journal

Evaluate 'Testogram' 90-sec procedure	Correlation with FN, precision, reproducibility	New project, will communicate to WGC	We will begin as soon as funding becomes available	WGC, Wheat Life, regional/national wheat industry; we plan to publish the results in peer-reviewed journal

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

Project #:

Final Report Year: *1 of 1*

Title: Defining the relationship between Falling Number and Sponge Cake

Quality Cooperators: Craig Morris, Alecia Kiszonas, Doug Engle

Executive summary: Falling Number *per se* is not a wheat or flour quality problem. Falling Number attempts to predict flour quality performance in various end-uses. Our 2016 research showed that Falling Number is a poor predictor of end-use quality: cookies (low moisture) are minimally affected, whereas Japanese sponge cake quality is generally poorer with lower Falling Numbers, but there is a large amount of unexplained variation. Falling Number was originally designed to measure α-amylase, but in the context of pre-harvest sprouting (PHS). The relationship between Falling Number, Late Maturity α-Amylase (LMA) and end-product quality are poorly understood. We are addressing the following objectives:
Objective 1. Determine the effect of α-amylase and proteases on Falling Number in PHS, LMA and 'sound' grain lots.
Objective 2. Determine the effect of protein content on Falling Number in PHS, LMA and 'sound' grain lots.
Objective 3. Determine the effect of α-amylase (alone, LMA) vs. α-amylase when it is accompanied by proteases, lipases and other germination enzymes (PHS).

Impact: Growers should have tests the accurately measure the true quality and value of grain. Prior research indicates that FN may not fulfill this requirement. To move forward, we need a better understanding of α-amylase from pre-harvest sprouting (PHS) vs. Late Maturity α-Amylase (LMA), the effect of PHS beyond just α-amylase (for example proteases), Falling Number, and end-product quality

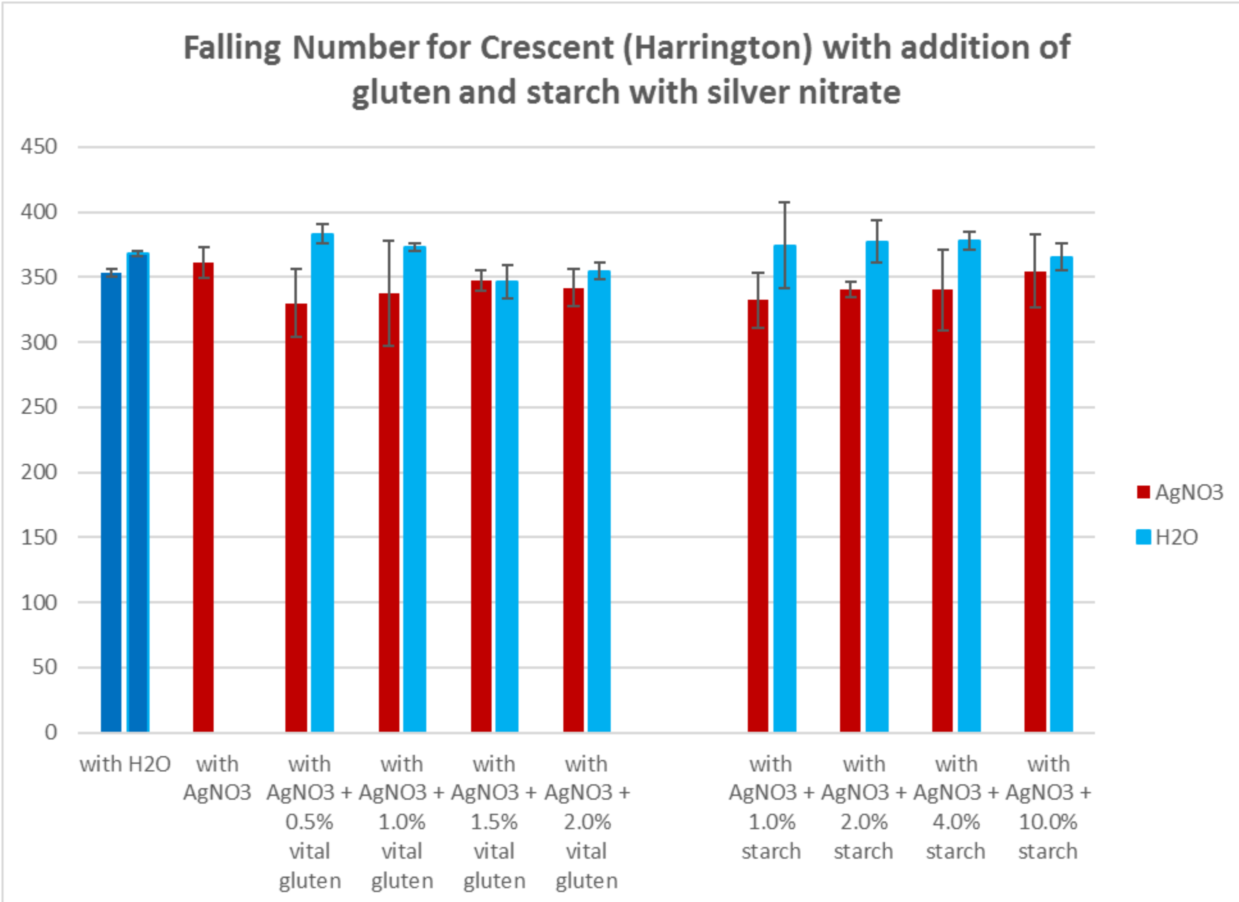
Deliverables: Accurate information as to the effect of PHS vs. LMA on Falling Number and sponge cake quality.

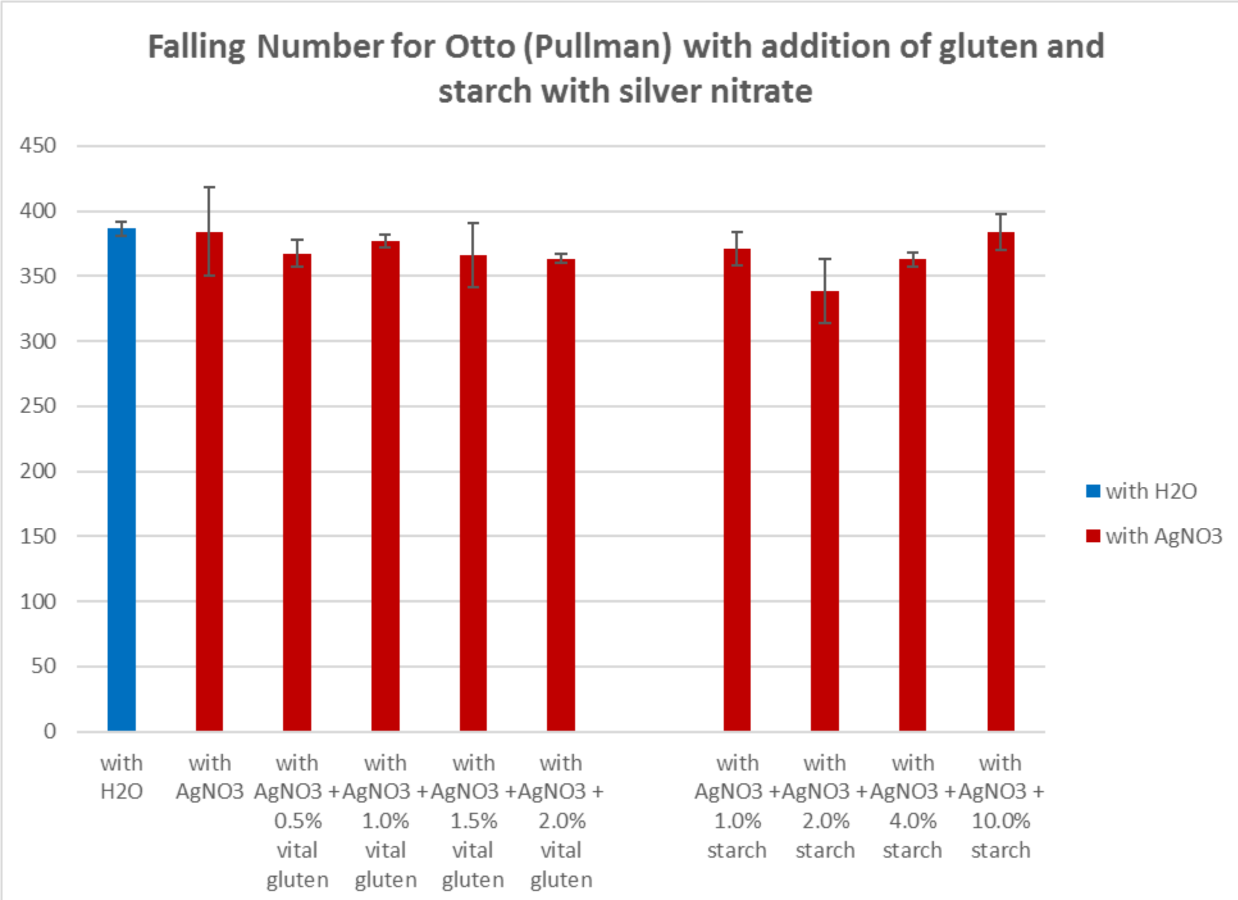
Part 1. Evaluating the effects of silver nitrate ($AgNO_3$) on poisoning the α-amylase produced in pre-harvest sprout (PHS) and late-maturity α-amylase (LMA) samples as measured via Perten Falling Number. Additionally, the effect of a protease inhibitor on the control, PHS, and LMA grain will be measured via Falling Number. Sound Diva grain (Control) and lab-sprouted Diva grain (PHS) were obtained. The Control had a Falling Number of 365 sec, the five PHS samples had Falling Numbers ranging from 93 to 295 sec. The α-amylase levels were also measured in these samples. When the $AgNO_3$ was added, the control was increased to 393 sec. The five PHS samples were increased to 365-424 sec. There was no strong correlation between the original PHS Falling Number and that after addition of $AgNO_3$. All PHS samples had at least an increase of 154 sec, with a maximum of 331 sec increase. See table. Clearly, silver nitrate is an effective laboratory tool to kill α-amylase.

Grain	*Falling Number (sec)*	*FN after AgNO3 (sec)*	*Increase in FN (sec)*
Sound	365	393	28
PHS 1	295	405	110
PHS 2	211	365	154
PHS 3	200	411	211
PHS 4	190	374	184
PHS 5	93	424	331

The lab is in the process of identifying and collecting samples that have been clearly affected by LMA. Additionally, the lab is working on the proper type and concentration of protease inhibitor to achieve the desired effect of poisoning proteases that are being produced during PHS. The lab has also added sprouted grain to control grain in levels of 0.5, 1.0, and 2.0%. The FN has been measured with and without the addition of $AgNO_3$. These data are currently being analyzed.

Part 2. The objective of this part is to study the effects of vital wheat gluten and purified wheat starch addition on Falling Number, along with the addition of AgNO3 to aforementioned samples. Two varieties were chosen for this part of the project: ARS Crescent and Otto. These were chosen as popular varieties grown in the PNW.


Falling Number for Crescent (Harrington) with addition of gluten and starch with silver nitrate
450
400
350
300
250
200
150
100
50
0
with H2O
with AgNO3
with AgNO3 + 0.5% vital gluten
with AgNO3 + 1.0% vital gluten
with AgNO3 + 1.5% vital gluten
with AgNO3 + 2.0% vital gluten
with AgNO3 + 1.0% starch
with AgNO3 + 2.0% starch
with AgNO3 + 4.0% starch
with AgNO3 + 10.0% starch
AgNO3
H2O



The Otto samples are undergoing further evaluation to assess the FN with just the addition of vital wheat gluten and starch (without AgNO3), as is seen for ARS Crescent. In the case of ARS Crescent, the addition of vital wheat gluten and purified wheat starch appeared to increase the FN slightly, but the AgNO3 decreased the FN across the addition of vital wheat gluten and purified wheat starch. The inconsistency of the patterns, however, make drawing stronger conclusions challenging. Part 2. will be completed following the FN tests of Otto with just vital wheat gluten and starch addition.

Part 3. The objective is to bake cakes with the samples outlined in Part 1 and measure cake volume and the Texture Profile Analysis using the TA.XT2 (Texture Technologies). This part of the project is anticipated to begin in early spring of 2019.

Special thanks to Galina Mikhaylenko for sample preparation and analysis.

Washington Grain Commission
Barley Research Final Report

Project #: 3019-3009

Title: Improving Barley Varieties for Feed, Food and Malt

Cooperators: Kevin Murphy, Max Wood, Deven See, Xianming Chen,

Executive summary:

Over the past several years, significant and substantial progress in breeding and varietal development has been achieved within each market class – feed, malting, and food – of barley. A total of five barley varieties have been released: Lyon and Muir in the conventional feed barley class, Survivor in the herbicide tolerant feed barley class, and Havener and Meg's Song in the hulless food barley class. One substantial change has been the successful use of Lyon barley as an all-malt barley type. Here I will briefly summarize these varieties, and begin by introducing the malt barley breeding update.

Malt barley: ***Our highest programmatic priority at this point is to release a high-quality, high-yielding malt barley variety within the next two years.*** The preceding sentence is a direct quote from the previous progress report submitted in January 2018. We are now in position to release one to two malting barley varieties, including top experimental lines 11WA-107.43 and 12WA-120.14. Each of these have high yields, strong agronomic qualities, and excellent malting quality.

Lyon was also released in 2015, with the high rainfall zone (>20") as its target environment. Across multiple locations over five years (2014-2018), Lyon is consistently (and statistically) among the highest yielding group of barley varieties in the high rainfall locations. Lyon has effectively replaced both Bob and Baronesse in these locations. In addition, in 2018 Lyon was used as a malting barley. It was malted by LINC Malt and beer was brewed by several breweries, including Mountain Lakes Brewery in Spokane, Fremont Brewery in Seattle, Baerlic Brewery in Portland, and Hunga Dunga Brewery and Moscow Brewing Company in Moscow. Demand for Lyon barley malt is increasing, and we anticipate additional breweries utilizing Lyon malt in 2019 and beyond.

Survivor was released in 2017 and in that year was among the highest three yielding varieties topping the high rainfall precipitation zone (4 locations). It is also the only IMI-herbicide tolerant variety available to farmers. We continue to test thousands of herbicide tolerant breeding lines each year to target both the malt and food market classes in addition to the feed barley market class.

Muir was released in 2015 for the <16" rainfall zone. It is resistant to prevalent races of barley stripe rust, and has performed well across the low rainfall zone locations, and quite well in several other locations in the intermediate and high rainfall zones. Muir was intended to replace Bob and Baronesse as the go-to variety in these locations.

Havener, the first hulless food barley released by the WSU Barley Breeding Program which addresses a need for higher yielding hulless varieties with an elevated β-glucan (a heart-healthy soluble dietary fiber) content, has continued to perform well. Developed specifically for human consumption, Havener contains 50 to 75% higher β-glucan than common Washington-grown varieties Lyon, Muir, Champion, Bob and Baronesse.

Released in 2015, Havener has higher yields and test weights across all eastern Washington rainfall zones than the hulless variety Meresse.

Meg's Song was released in 2017, with even higher β-glucan (~7.5%) than Meresse or Havener (~6.0%), and high yields across a broad spectrum of environments. Meg's Song has excellent tolerance to lodging in the field and has attracted the attention of seed dealers and end-users. It has a substantially different cooking and baking profile than Havener, giving them both a solid foothold on the emerging hulless food barley market.

Impact:

Of the earliest varieties released in my program, Lyon, Survivor, Havener, and Meg's Song are beginning to gain traction in the market. They were only recently made available to farmers, so although acreage of each is low, the reception they have received by growers and industry has been positive and should have an upward trend over the next funding period.

The two most pressing issues or constraints to barley production are the decreasing price of barley and the large acreage of Clearfield winter wheat grown in Washington. Price has decreased steadily from $5.53/bushel in 2012, to $4.12/bushel in 2013, $3.54/bushel in 2014, $3.31 in 2015, and $2.90 in 2016 (wagrains.org). Understandably, harvested acreage and total production of barley has decreased over this period. Though it is difficult for my program to have a positive impact on barley price, we are doing so in two meaningful ways. The first is the development of value-added food barley varieties for the emerging market that pays a premium on higher beta-glucan varieties. In addition to releasing two new varieties, Havener (2015) and Meg's Song (2017), with a 50 to 75% increase in beta-glucan content over currently grown hulled feed barley, these new varieties are significantly higher yielding than their hulless predecessors. The second way we are addressing price is through the targeting of malt barley varietal releases, and in particular, that of craft malt. Prices are higher for the malt barley market class and could make a positive difference in the economics of growing barley. We intend to propose for release one to two WSU malting barley varieties in 2019.

To address the impact of Clearfield winter wheat on spring barley production in Washington, in 2017 we released Survivor, a feed variety tolerant to residual herbicide in the soil. Survivor will be first available to growers in 2018, and it too should have a positive impact on barley production in Washington. We have a robust pipeline of imi-tolerant barley lines from the feed, food and malt market classes.

Outputs and Outcomes:

Objective	Deliverable	Progress	Timeline	Communication
Hulled, Feed Barley	Two feed barley varieties, ***Lyon*** and ***Muir***, were released.	Excellent	2015	Talks and presentations at field days; distribution of informative variety rack cards; Wheat Life articles.
Herbicide Tolerant Barley	Our first herbicide tolerant barley variety, ***Survivor***, was released.	Excellent (with continued herbicide tolerant barley varieties across all market classes in development and expected for full release by 2022-2023).	2017	Talks and presentations at field days; distribution of informative variety rack cards; Wheat Life articles.
Hulless, Food Barley	Two new hulless, food barley varieties, ***Havener*** and ***Meg's Song***, with high (>6%) beta glucan, were released.	Excellent (with continued hulless food barley development in progress, particularly for waxy types not represented in Havener or Meg's Song).	2015 (Havener) 2017 (Meg's Song)	a) Talks and presentations at field days; Wheat Life articles; b) Distribution of informative variety rack cards.
Malt Barley	This program was revived from scratch, and we now have 5 to 6 entries in WSU Variety Testing with excellent potential for an upcoming malt barley release.	We have fast-tracked the malt barley program and are now close to releasing the first WSU high-quality malt barley in three decades.	2019-2020	Talks and presentations at field days; 3 years of the annual Know Barley, Know Beer field day; distribution of informative variety rack cards; Wheat Life articles.

Final Progress Report

Project #: 3682

Progress Report Year: 3 of 3

Title: Control of Strawbreaker Foot Rot (Eyespot) and Cephalosporium Stripe in Winter Wheat

Cooperators: **T. D. Murray, Plant Pathologist**
A. Carter, Crop & Soil Sciences, WSU
K. Garland-Campbell, USDA-ARS

Executive summary: Variety trials for eyespot and Cephalosporium stripe were not conducted in 2016-17 due to staff and funding limitations; however, the trials were completed in 2015-16 and 2017-18, and are in progress for 2018-19. A total of 83 new varieties and advanced lines were evaluated for resistance to eyespot and tolerance to Cephalosporium stripe. Data from these plots were used to update disease ratings in the Washington State Crop Improvement Association Seed Buyers Guide and the WSU Extension Small Grains variety selection tool. We streamlined the process used to test varieties by collaborating with the WSU Variety Testing program to identify and test lines that were in their 2nd year of Variety Testing plots and planting head-row plots instead of yield trials. We also solicit advanced lines from WSU Winter Wheat Breeding (including ARS Club-Wheat Breeding) for testing. This approach greatly reduces the space needed for testing, which allows us to test more lines, and reduces labor needed for harvest, but still requires significant labor for destructive sampling and disease rating.

Studies to map disease resistance genes to the eyespot fungi in a population derived from Madsen were conducted to determine whether the same genes control resistance to both pathogens. Although Madsen is one of the first two eyespot resistant varieties released in WA and has been grown for almost 30 years, its resistance to the eyespot pathogens was never mapped because it was not known that there were two different fungal species that caused the disease at the time of Madsen's release. In addition, we know there are differences in the effectiveness of resistance to these fungi in Madsen and other eyespot-resistant varieties. In collaboration with colleagues in China, we also mapped resistance to cereal cyst nematode (CCN) in the same Madsen population and demonstrated that it carries two different genes, one each to *H. avenae* and *H. filipjevi*, both derived from VPM-1, the source of eyespot resistance. Phenotyping and genotyping have been completed and we plan to complete the mapping analysis for eyespot in spring 2019.

Field studies to determine the effectiveness of variety mixtures on eyespot and Cephalosporium stripe were conducted over the past 3 years; the final experiment was planted in September 2018 for disease evaluation and harvest in summer 2019. Disease severity data were collected from all six experiments, but yield data were collected from 4 of 6 experiments due to severe lodging. Data from the first three years (six locations) are being analyzed and conclusions will be presented when all data have been collected and analyzed.

Seed treatment trials for eyespot and Cephalosporium stripe were conducted in 2015-16 and 2016-17; there were no yield or disease control benefits in either year, so the work was not continued. Plots to evaluate foliar fungicides for eyespot were established in 2016 and 2018, but not completed due to a lack of disease and poor stand. We are planning to conduct a trial in spring 2019 in conjunction with a private company if a location with enough disease pressure can be located.

Chemical control of eyespot remains an important option for control and several new products have been registered in the past few years. Some of these contain active ingredients for which we have already screened the eyespot fungi for resistance, but others need to be tested because resistance to them occurs in other plant pathogenic fungi. Due to limitations in funding and labor, we did not make progress on this objective during this funding cycle.

Spore-trapping for the eyespot fungi was conducted over the past three years at the Plant Pathology Farm, Palouse Conservation Field Station, and Spillman Farm to understand the seasonal dynamics of ascospore release, which may contribute to pathogen genetic variation. This study represents more fundamental research to understand the biology of eyespot disease and insure that we have effective control measures going forward, both for stable disease resistance and fungicide sensitivity. Data will be collected through May 2019, summarized and analyzed to conclude this phase of the research.

Impact: Cephalosporium stripe and eyespot continue to be significant yield-limiting diseases for winter wheat production. Nearly all public and private breeding programs in the PNW are addressing these diseases because resistant/tolerant varieties are the most effective way to limit their impact. This project is the only place where all new varieties and advanced breeding lines are evaluated side-by-side for their reaction to eyespot and Cephalosporium stripe. The data we generate are shared with wheat breeders to support variety release and growers at variety testing field tours, online at the WSU Extension Small Grains website, and is used to provide ratings in the WSCIA seed buyer's guide and the WSU Small Grains Variety Selection tool for use by growers in making variety selection decisions.

Currently, the gene present in Madsen is the primary source of resistance in all PNW eyespot-resistant varieties and understanding its genetic control will insure it remains effective. Not all eyespot-resistant varieties are equally effective in limiting disease development. We suspect this may be the result of minor genes that have not been previously identified and/or differences in genes involved in resistance to the two eyespot fungi. Identifying minor genes affecting eyespot resistance and molecular markers for them will allow breeders to develop new varieties with more effective eyespot resistance. Because of the focus on mapping genes in Madsen, we did not screen wild relatives of wheat for eyespot resistance during this grant cycle but continue to believe new sources of resistance are important in the long-run and plan to resume screening in the next cycle.

Publications:

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Bruckner, P.L., J.E. Berg, K.D. Kephart, R.N. Stougaard, G.P. Pradhan, P.F. Lamb, J.H. Miller, S.S. Briar, C. Chen, D.L. Nash, D.L. Holen, J.P. Cook, S. Gale, Y. Jin, J.A. Kolmer, X. Chen, G. Bai, and T.D. Murray. 2017. Registration of 'Loma' Hard Red Winter Wheat. J. Plant Registrations 11:281-284.

Carter, A.H., S.S. Jones, K.A. Balow, G.B. Shelton, A.B. Burke, R.W. Higginbotham, X.M. Chen, D.A. Engle, T.D. Murray, and C.F. Morris. 2017. Registration of 'Jasper" soft white winter wheat. J. Plant Registrations 11:263-268.

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Berg, J.E., P.F. Lamb, J.H. Miller, D.M. Wichman, K.D. Kephart, R.N. Stougaard, G.P. Pradhan, D.L. Nash, W.E. Grey, D. Gettel, Y. Jin, J.A. Kolmer, X. Chen, G. Bai, T.D. Murray, and P.L. Bruckner. 2016. Registration of 'Northern' Wheat. J. Plant Registrations 10:135-138. dx.doi.org/10.3198/jpr2015.10.0062crc.

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Sexton, Z.F. and T.D. Murray. 2016. Reaction of winter wheat cultivars and breeding lines to eyespot in Washington, 2015. Plant Disease Management Reports 10:CF048.

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Presentations:

Biology and Management of Winter Wheat Diseases. Far West Ag Expo, Kennewick, WA, December 21, 2018.

Biology and Management of Winter Wheat Diseases. Hermiston Farm Fair, Hermiston, OR, November 29, 2018.Stripe rust and other diseases in small grains. WSU Extension, Western Whitman County Field Tour, Dusty, WA, June 7, 2018.

Resistance to Eyespot Disease of Wheat and its Wild Relatives. Chinese Academy of Agricultural Sciences, Institute of Germplasm and Crop Genetic Resources, Beijing, China, September 22, 2017.

Overview of Winter Wheat Disease Research in Washington State, Jilin Agricultural University, Changchun, China, September 20, 2017.

Resistance to Eyespot Disease of Wheat and its Wild Relatives. Brazilian Phytopathological Society, Uberlandia, Brazil, August 22, 2017.

Seasonal Ascospore Release by the Wheat Eyespot Pathogens *Oculimacula yallundae* and *O. acuformis* in the Northwest USA. 12th European Foundation for Plant Pathology meeting, Dunkerque, France, May 30, 2017.

Resistance to Eyespot Disease of Wheat and its Wild Relatives. APS Potomac Division Meeting, Morgantown, WV, March 23, 2017.

Update on Stripe Rust and Eyespot of Wheat. Adams-Lincoln County Conservation Days, Ritzville, WA, January 24, 2017.

Epidemiology and Control of Stripe Rust, Eyespot, and Soilborne Wheat Mosaic. Walla Walla Cereal Grain Seminar, Walla Walla, WA, January 17, 2017.

Update on Stripe Rust and Eyespot of Wheat. Eastern Washing AgExpo, Kennewick, WA, January 3, 2017.

Biology and Control of Eyespot and Stripe Rust of Wheat. Last Chance Pesticide 2016, Asotin County Extension, Clarkston, WA, December 16, 2016.

Epidemiology of Stripe Rust, Eyespot, and Soilborne Wheat Mosaic. WSU Extension Wheat Academy, Pullman, WA, December 13, 2016.

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Outlook for stripe rust and other diseases in small grains. WSU Extension, Western Whitman County Field Tour, Farmington, WA, June 13, 2016.

Outlook for stripe rust and other diseases in small grains. WSU Extension, Western Whitman County Field Tour, Dusty, WA, June 9, 2016.

Outlook for stripe rust and other diseases in small grains. WSU Extension, Variety Testing Field Tour, Ritzville, WA, June 8, 2016.

WGC project number: 3682
WGC project title: Control of Eyespot and Cephalosporium Stripe in Winter Wheat
Project PI(s): T. Murray, A. Carter, K. Garland-Campbell
Project initiation date: July 1, 2016
Project year (X of 3-yr cycle): 3 of 3

Objective	Deliverable	Progress	Timeline	Communication
1. Evaluate mixtures of resistant/tolerant and susceptible varieties in field plots for their impact on eyespot and Cephalosporium stripe.	The potential effectiveness of variety mixtures in controlling eyespot and Cephalosporium stripe will be determined. This is particularly important for Cephalosporium stripe where varieties with highly effective resistance are not available.	**2016:** Field plots were established in Fall 2015 on the Plant Pathology Farm (eyespot) and Palouse Conservation Field Station (Cephalosporium stripe) to determine the effect of mixtures on each disease. Each plot contains two reistant/tolerant and two susceptible varieties planted separately and in all possible combinations. Plots were inoculated in November and disease severity and yield determined in summer 2016. Unfortunately, yield data were not obtained from the eyespot plot due to spring flooding. Data are being analyzed now. **2017:** Data were collected from field plots planted in 2016 and are being analyzed. Field plots were planted again in fall 2017 for data collection in 2018. **2018:** Data for disease severity and yield were collected again and are being analyzed together with data from previous years. Field plots were planted in fall 2018 to complete this study in 2019.	Multiple years of data are needed to confirm the responses of the mixtures being tested, so this work continue each year of the project. Field plots were planted in fall 2018; data from these studies will be analyzed following harvest in 2019 and not be continued.	Results from these plots are presented at field days, variety testing plot tours, and other talks to grower and industry groups, and availble online at the Extension Small Grains Team website. Data will be published in appropriate scientific journals when analysis is complete and presented at scientific meetings.
2. Screen wild wheat relatives for potential new sources of resistance genes	Identify potential new eyespot resistance genes for use by breeders to improve effectiveness of resistant varieties.	**2016:** No activity in 2016. Inoculum is being produced now to screen a Madsen population being mapped for cereal cyst nematode resistance to determine the relationship between these genes. Repeat tests of some wild species is anticipated during 2017 to confirm previous results and identify potential donors for genetic studies. **2017:** A Madsen population was screened for resistance to one (Oy) of the two eyespot pathogens to determine whether the same genes are involved in resistance to both pathogens. This population is also being screened for cereal cyst nematode resistance by colleagues in China. **2018:** Screening of the Madsen population with the second eyespot pathogen (Oa) was completed and data have been summarized. Genotyping data were obtained and mapping of genes involved with resistance will be completed during winter 2019.	**2016:** This work will begin in fall 2016 or spring 2017, but not completed until the end of the project. **2017:** Screening of the Madsen population will continue during the first half of 2018, afterwhich we plan to compelte screening some wheat relatives through 2018 into 2019. **2018:** Screening of the Madsen population for resistance reaction was completed. Data are being analyzed to identify QTL associated with resistance to both pathogens and should be completed by June 2019. Screening of a Cappelle-Desprez x Whetstone population will begin during winter 2019 instead of screening wild relatives.	Results of this research will be shared with breeders, presented at field days, variety testing plot tours, and other talks to grower and industry groups. Data also will be published in appropriate scientific journals.

3. Evaluate eyespot pathogen populations for resistance to new fungicide active ingredients.	Provide data that will help growers and field consultants make decisions about whether and which fungicide to use in controlling eyespot by testing fungicides registered for eyespot control in multiple locations in eastern WA.	**2016:** A field plot was established near Ritzville, WA in spring 2016, but later abandoned due to inadequate eyespot disease and too much dryland foot rot to provide meaningful results. A seed treatment trial was planted in fall 2015, disease evaluated and yield determined in summer 2016. **2017:** No activity on this objective during 2017. **2018:** A field plot was planted in fall 2018 to test fungicides in conjunction with a private company; however, dry conditions resulted in uneven emergence and the plot will not be used. Testing may still occur if a commercial field with eyespot is located in spring 2019.	**2016:** This is the last year of fungicide testing in this funding cycle unless the agchem industry provides support.	Results from these plots will be presented at field days, variety testing plot tours, and other talks to grower and industry groups, and availble online at the Extension Small Grains Team website. Results also will be published in Plant Disease Management Reports so they are available to the larger small grains pathology community.
4. Determine impact of pathogen genetic variation on disease epidemiology, especially the eyespot pathogens, to insure resistance genes remain effective	Develop molecular and microbiological data describing genetic variation in the eyespot and Cephalosporium stripe pathogens and its potential effect on disease control using resistant varieties.	**2016:** Molecular markers were developed for one of the eyespot fungi during 2015. Marker development for the other eyespot fungus and *Cephalosporium gramineum* are in progress, but limited progress was made in the second half of 2016 due to personnel turnover. Spore-traps were established at the Palouse Conservation Field Station and Spillman Farm to understand the seasonal dynamics of ascospore release, which may contribute to pathogen genetic variation. Traps are sampled weekly and evaluated using microscopy and real-time PCR to determine when and relatively how many spores were released. **2017:** Aerial spore-traps were deployed from September through May, with samples collected weekly. Samples from spring have been analyzed; data from fall collections are still being collected and summarized to determine when ascospores of the eyespot fungi are present. No progress was made on development of molecular markers for the eyespot/Cephalosporium stripe fungi. **2018:** Aerial spore-trapping was conducted during spring and fall 2018, and will continue through spring 2019. No progress was made on development of molecular markers for the eyespot/Cephalosporium stripe fungi.	This was a long-term objective and spore-trapping work was conducted each year of the project. Data collection on spore-trapping will end in spring 2019; all data will be combined for analysis and publication.	Results of this research will be shared with breeders, presented at field days, variety testing plot tours, and other talks to grower and industry groups. Results also will be presented at scientific meetings and published in appropriate scientific journals.
	Prepare an article for Wheat Life during the three-year project summarizing results.	**2016:** No progress. **2017:** An article on eyespot and Cephalosporium stripe will be submitted in April 2018. **2018:** An article was published in Wheat Life in May 2018.	An article was published in May 2018.	

5. Evaluate advanced breeding lines and new varieties for resistance to eyespot and Cephalosporium in field plots	Provide unbiased data on the resistance reactions of advanced selections and new varieties to eyespot and Cephalosporium stripe.	**2016:** Forty-four breeding lines and advanced selections were established in field plots and inoculated in fall 2015. Disease evaluation was conducted on both plots in June 2016. Yield data were not taken due to extensive lodging in both plots that was not related to disease resistance and would have led to misleading results. **2017:** Variety screening was not conducted in 2017. Thirty-nine lines were planted and inoculated for both eyespot and Cephalosporium stripe rating in 2018. Data from previous trials was used to provide and update ratings for the WSCIA Seed Buyer's Guide and WSU Small Grains variety selection tool. **2018:** Thirty-nine winter wheat cultivars and breeding lines were evaluated for their resistance/tolerance to eyespot and Cephalosporium in June 2018. Another 39 lines were planted in September for evaluation in 2019.	**2016:** Testing did not occur due to staff and funding limitations. **2017:** Disease testing plots for new varieties were planted in collaboration with the WSU Variety Testing progam in fall 2017 for rating in 2018. **2018:** This was the second year of testing in collaboration with the WSU Variety Testing program and first year with WSU Winter Wheat Breeding. This activity will continue given the nature of variety development.	Results from these plots are presented at field days, variety testing plot tours, and other talks to grower and industry groups, and availble online at the Extension Small Grains Team website. Data are used to update variety ratings in the Washington State Crop Improvement Seed Buyer's Guide, the WSU Extension Small Grains Variety Selection tool, and published online in Plant Disease Management Reports so they are available to the larger wheat research community.

Final Progress Report

Project #: 3675

Progress Report Year: 3 of 3

Title: Enhancing Resistance to Snow Mold Diseases in Winter Wheat

Cooperators: **T. Murray, Plant Pathologist, WSU**
A. Carter, Crop & Soil Sciences, WSU
D. Skinner, USDA-ARS, Pullman, WA
K. Garland-Campbell, USDA-ARS, Pullman, WA
J. Marshall, PSES, University of Idaho

Executive summary: Field plots were established at three locations in WA and one in Tetonia, ID to test advanced breeding lines and three new doubled-haploid populations for snow mold resistance and agronomic performance during this project. We were fortunate to have adequate snow cover at most locations for good disease development that allowed us to collect useful data on disease reaction that allowed us to map QTL for snow mold resistance with a new source of resistance, PI 178384. This material is being used in the WSU Winter Wheat Breeding program now to develop varieties with more effective snow mold resistance. Data from these plots also was used to update variety ratings in the Washington State Crop Improvement Seed Buyer's Guide and the WSU Small Grains Team online Variety Selection tool.

Fructan concentration was measured on field-grown plants to determine its association with snow mold resistance and identify genes involved in its regulation. Methods for analysis of the sugars were revised and problems with equipment used to collect the data arose, which delayed completion of this objective. However, we are now on track to complete this objective in early 2019. We are also conducting another analysis, RNAseq, to help identify the genes involved in fructan production and resistance.

Work to improve growth chamber screening for resistance was put on hold until results of fructan analysis are complete so we can better understand the conditions needed for expression of this trait.

This is the last year of this project. Much progress has been made in understanding the genetics of resistance and new, promising QTL from PI 178384 was identified. Continued development of snow mold resistant varieties will continue under the WSU Winter Wheat Breeding program.

Impact: During this funding cycle, validation of molecular markers for snow mold resistance in a Xerpha x Munstertaler population was completed. A paper was published and the results were presented at one scientific meeting. Another paper describing a Genome-wide association study (GWAS) to identify sources of resistance was submitted for publication. Together, this research lays the foundation for continued development of varieties with effective snow mold resistance.

A new and promising source of resistance for U.S. PNW wheat growers was identified in that should result in more effective resistance to the snow mold diseases than exists now. The material has already been incorporated into the breeding program and lines are under development.

Results of research produced in this project have been and will be communicated to farmers and field consultants at field days, other meetings, and publications such as Wheat Life. Results are communicated to other scientists directly and through publication in appropriate journals.

Publications:

Lozada, D.N., J.G. Godoy, T.D. Murray, and A.H. Carter. 2019. Genetic dissection of snow mold tolerance in US Pacific Northwest winter wheat through genome-wide association study and genomic selection. Frontiers in Plant Science [SUMBITTED January 7, 2019].

Kruse, E.B., S.W. Carle, N. Wen, D.Z. Skinner, T.D. Murray, K.A. Garland-Campbell, and A.H. Carter. 2017. Genomic regions associated with freezing tolerance and snow mold resistance in winter wheat. G3. Genes, Genomes, Genetics 7:775-780. DOI: 10.1534/g3.116.037622.

Presentations:

Update on Snow Mold, Hessian Fly, Eyespot, and Stripe Rust. 2019 Syngenta Cereal & Pulse School, Spokane, WA, February 4, 2019.

Lozada, D.N., J.V. Godoy, T.D. Murray, and A.H. Carter. 2019. Genetic Dissection of Snow Mold Tolerance in US Pacific Northwest Winter Wheat. Proc. International Plant & Animal Genome XXVII Conference, January 12-16, 2019, San Diego, CA.

Murray, T.D. Biology and Management of Winter Wheat Diseases. Far West Ag Expo, Kennewick, WA, December 21, 2018.

Murray, T.D. Biology and Management of Winter Wheat Diseases. Hermiston Farm Fair, Hermiston, OR, November 29, 2018.

Murray, T.D. Pink snow mold of wheat. Moro County Conservation District Field Tour, Moro, OR, May 17, 2017.

Murray, T.D. Kruse, E., S. Carle, T. Murray, D. Skinner, and A. Carter. 2016. QTL analysis of snow mold and cold tolerance in soft white winter wheat cultivar ‘Eltan’. Proc. Plant and Microbe Adaptation to Cold Conference, May 23, 2016, Seattle, WA.

WGC project number: 3675
WGC project title: Enhancing Resistance to Snow Mold Diseases in Winter Wheat
Project PI(s): T.D. Murray, A. Carter, D. Skinner, K. Garland-Campbell, J. Marshall
Project initiation date: July 1, 2016
Project year: 3 of 3

Objective	Deliverable	Progress	Timeline	Communication
1. Field test new doubled-haploid populations to identify resistant lines for breeding program, identify new genes and associated molecular markers.	Data on snow mold resistance of genetic populations that will be used to identify new genes and make selections for the breeding program.	**2016**: Three doubled haploid populations were created in three different backgrounds all using PI173438 as the parent. There are two soft white parents and one hard red parent adapted to the PNW. Populations were planted in Waterville and Mansfield, as well as in Tetonia, ID for snow mold screening. Plots had good stand establishment in the fall, and data was collected in the spring of 2017 for snow mold tolerance. **2017:** The populations were planted again in Waterville and Mansfield, as well as in Tetonia, ID for snow mold screening. Waiting for data collection in spring 2018. **2018:** The plot have had very good snow mold severity in the spring of 2018 and data was collected on these populations one more time. DNA of each line was sent for GBS genotyping and we are awaiting the return of the results. Once returned, the linkage map will be assembled and QTL mapping performed.	Field testing will be conducted in 2017 and 2018. More years of testing may be needed depending on the level of snow mold in each year. One of the three populations will be genotyped in 2018 using GBS and the other two will be used for validation. Once genotypic data is returned, linkage mapping and QTL analysis will be completed.	Results of this work will be presented at field days, variety plot tours, other grower and industry talks, and on the WSU Wheat and Small Grains website.
2. Field test advanced breeding lines and new varieties to determine their reaction to snow mold diseases.	Provide data on snow mold resistance of advanced selections and new varieties. Expand variety ratings in the seed buyer's guide.	**2016:** The winter wheat breeding program planted 246 advanced breeding lines for testing in the spring of 2017 under snow mold conditions. We were able to identify many breeding lines with excellent resistance to snow mold. Many of these have come up through the program with continual selection under snow mold conditions. The establishment of excellent lines with snow mold resistance indicates that selection under natural conditions is an appropriate method for development of new lines. We also evaluated a diversity panel of 480 soft white lines for further genetic understanding of snow mold resistance. **2017:** In the fall of 2017 we planted the diversity panel of 480 lines in both Waterville and Tetonia for evaluation. Our breeding lines were planted in two locations in Waterville. We planted ~300 breeding lines for evaluation. We also planted ~40 populations for early generation selection, and have started including Kim Campbell's club wheat (both early and late generation) in our planting designs to improve club wheat performance to snow mold. **2018:** We have spent the past 5 years directly selecting for snow mold tolerance in our Waterville and Mansfield locations. These selections are now in yield testing after confirmation of snow mold tolerance. The diversity panel of lines was used in a genomic selection validation analysis to see how well they predict the performance of breeding lines. Results indicated good prediction, and we will now use the model to try and make selections in earlier generations before field testing. We have increased the number of club wheat lines tested for Dr. Campbell. We also routinely screen the WSU Variety Testing lines in order to get good data on performance of currently released cultivars.	Field plots will be established in fall 2016 and rated in the spring of 2017 for reaction to snow mold. This will continue each year of the project. We have added additional lines of club wheat and the variety testing program for further analysis.	Results of this work was presented at field days, variety plot tours, other grower and industry talks, and on the WSU Wheat and Small Grains website. Data will be used to provide ratings in the seed buyer's guide. A manuscript has been submitted regarding the genomic selection analysis and validation research.
	Prepare an article for Wheat Life during the three-year project summarizing results to date.	**2017:** No progress. A new schedule was developed for 2018 articles and snow mold was not included.	An article will be submitted in late 2018 near the end of the project.	

3. Measure fructan concentrations in winter wheat crowns of breeding populations and identify genes involved in its production to determine their association with snow mold resistance.	Methods and data that can be used to screen breeding populations efficiently and determine whether fructan accumulation can be used to indirectly select for resistance to snow mold diseases.	**2016:** Samples were collected in 2016 from both field and growth chamber experiments. Sample preparation has been completed, and are now being run to determine fructan concentrations in the different lines. Data should be ready for analysis in early 2017. These lines have also been screened for cold tolerance and snow mold tolerance in order to correlate results. Two populations are being screened. One looking at different levels of cold and snow mold tolerance between lines, and the other is a set of isolines varying for the VRN alleles. **2017:** Samples were collected from field and greenhouse experiments. Work is in progress now to optimize methods for measuring the fructans. The goal is to have all analyses completed by the end of February 2018. **2018:** Due to some problems associated with the machines used to collect the carbohydrate data, we have only just recently collected and analyzed all the data. This data will be summarized for publication in early 2019, as well as additional information from an RNA-Seq analysis which might indicate genes controlling the observed phenotypes	Multiple years of data will be needed to reach conclusions, so this work will be conducted each year of the project. Growth chamber plants were harvested in 2016 and will continue into 2017. Field collections occurred in 2017. Carbohydrate analysis has been completed and we are finalizing RNA-Seq samples.	Results of this work will be presented at field days, variety plot tours, and other grower and industry talks. When completed, results will be published in Wheat Life, scientific journals, and the WSU Wheat and Small Grains website.
4. Establish protocols for screening large numbers of breeding lines for snow mold resistance under controlled environment conditions.	A method of screening for snow mold resistance in growth chambers.	**2016:** Waiting for results from fructan studies to identify critical environmental conditions to identify resistance. **2017:** Growth chamber experiments were conducted in 2017 to collect samples for carbohydrate analyses. These data will be used to develop growth chamber screening methods. **2018:** Growth chamber experiments are on hold until we can finalize objective 3 and better understand conditions needed for trait expression	Growth chamber experiments to measure fructan accumulation will begin in 2016 and continue each year of the project.	Results of this work will be presented at field days, and other grower and industry talks. When completed, results will be published in Wheat Life, scientific journals, and the WSU Wheat and Small Grains website.

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

(Begin 1 page limit)

Project #:3061-7667

Progress Report Year: *_3___of _3___(maximum of 3 year funding cycle)*

Title: **Management of Nematode Diseases with Genetic Resistance**

Scot Hulbert, Kimberly Garland Campbell and Timothy Paulitz

Executive summary:

- To determine the distribution of cereal cyst nematode (CCN) in eastern Washington and the Palouse, we surveyed over 300 fields from 2013-2017. Cysts were identified to species level with DNA techniques developed in previous grants. *H. filipjevi* was only found in southern Whitman County, and *H. avenae* primarily in eastern Whitman County. We also identified fields with high inoculum levels for use in greenhouse testing. A paper has been submitted for publication
- We developed a high throughput greenhouse screening method to identify CCN resistance in wheat. This method assesses roots of young plants grown in cone-tainers containing soil collected from highly infested fields in fall and vernalized at 4 C prior to planting.
- We completed resistance testing of 1209 wheat lines from the programs of Carter, Pumphrey, Campbell, and Morris, regional nurseries, and a Campbell mapping population, all in the greenhouse using above method.
- From above screening, we identified resistance in 10 to 21% of the advanced winter wheat lines, but less than 2% of spring wheat lines.
- We established greenhouse pot cultures of *H. avenae* and *H. filipjevi.* These cultures will be grown in the greenhouse to increase nematode populations and then used for screening
- We developed KASP markers for QTLs for resistance to *H. filipjevi* that were identified in a CIMMYT study and assayed the breeding lines that we evaluated above.
- We tested SSR markers linked to *Cre1, Cre3, Cre5, Cre8, CreX*, and *CreY* genes. These markers may facilitate the understanding of the resistance background of our material.
- We imported differential lines for identification of CCN pathotypes from Turkey, increased the seeds in the greenhouse and did initial experiments, but our pathotypes do not exactly match known ones. .

Impact:

- Using the high throughput greenhouse screening system, we can now screen material at an earlier stage and report results to breeders. We identified many good sources of resistance to cereal cyst nematode *H. filipjevi* and *avenae* in the adapted winter wheat and a few in spring wheat breeding lines and varieties. Planting these varieties will reduce the inoculum levels in infested fields.
- We collected all the data needed to identify markers associated with specific *Cre* genes, which should speed up selection and possibly identify new sources of resistance.

- **What measurable impact(s) has your project had in the most recent funding cycle?**

  - Because of the greenhouse techniques that we developed, breeders can now screen more material and are incorporating *Heterodera* resistance into their selections.

Nematode Grant 2016-2018

3061-7667

Management of Nematode Diseases with Genetic Resistance

S. Hulbert, K. Garland-Campbell, and T. Paulitz

3 year summary and final report.

Over the last three years, we have made significant progress on genetic solutions to the management of cereal cyst nematode (CCN, *Heterodera* spp.) for Washington wheat growers. Until 2010, it was considered primarily a problem in NE Oregon, and Dr. Richard Smiley had been investigating it since the mid 1980s. His work documented the losses caused by this nematode, which causes whiteheads, stunting and malformations of the root system, interfering with the uptake of water and nutrients. However, discoveries in 2010 showed that it has spread to the Palouse area of eastern Washington. Given that the first thing in management is defining the problem (where is the pathogen, how much is in a field?), we initiated a series of surveys to find out where the nematode had spread. Over the life of this grant, we surveyed over 300 locations, and have submitted a paper for publication. However, in 2014, we discovered another species in eastern Washington- *H. filipjevi.* Until this discovery, we had assumed that *H. avenae* was the only species. This necessitated developing new techniques that could distinguish the two species, which is almost impossible to do morphologically since the two species look very similar. We developed a DNA technique by sequencing the ITS region of the ribosomal gene, and could extract DNA from a single cyst isolated from the soil and determine its identity. This was then used in subsequent surveys, which found *H. avenae* in 15-25% of the fields in the Palouse region. At the same time, *H. filipjevi* and *H. avenae* have been found in Montana and Idaho.

How can we manage this disease? Like many soilborne pathogens, we have no registered or economical chemical control methods, unlike with foliar pathogens. In higher value crops, like potatoes, some nematicides are registered, but not with wheat. Seed treatments have also been tested by R. Smiley and chemical companies, but nothing has been effective. Crop rotation can provide a limit on the buildup of inoculum, since the CCN only attacks cereals, but not broadleaf crops like peas or chickpeas. However, because the cysts can survive in the soil for many years, they can survive between cereal crops so the pathogen is not eliminated. This leaves genetic resistance as the only economical management technique. Luckily, a number of major resistance genes have been identified to control this disease, called *Cre* genes. These were deployed in Australia over 30 years ago, when this nematode was a major limit on cereal production. Presently, CCN is now a minor problem in Australia. This is what we hope for the PNW.

How to incorporate resistance to CCN into PNW varieties? This can be done by extensive breeding over a long period. But we hypothesized that there may already be resistance in existing adapted varieties, brought in from their pedigrees. This would be the fastest way to proceed. But there were many challenges to screen varieties for resistance to nematodes. Unlike fungi, which can be grown in culture in the laboratory, nematodes require living plants to infect and reproduce. Instead, we looked for fields that already had high populations of the nematodes, that could be planted with lines and then assess the reproduction of the females on the root. We identified a site in Colton, WA and used it for several years in the previous grant cycles. However, we were limited to screen only about 100 lines. Because of the natural variability in the field, we needed replicated small plots, and in each 4 row plot, paired the unknown with 2 rows of a susceptible variety for comparison. We also discovered that we could bring in soil in April, as the nematodes were hatching, and plant in containers in the greenhouse to screen lines. But this was a limited time window. However, we discovered that we could collect soil in the fall, vernalize in the cold room at 4 C for a few months, and then warm up the soil to get the nematodes to hatch and infect plants. With this breakthrough, we were able to increase our capacity to screen lines- not only adapted lines from the winter and spring nurseries and variety testing, but earlier material in the 4 breeding programs at WSU- club, winter, spring and durum. This also expanded our ability to look at both *H. filipjevi* and *H. avenae*. Having two species has further complicated breeding efforts, since resistance to one species may not be effective against the other. But for the first time, breeders could select earlier material.

Because we cannot always depend on field sources of inoculum, we are also developing pot cultures in the greenhouse, for both *H. avenae* and *H. filipjevi.* This involves growing wheat in large containers, harvesting the soil, and replanting for multiple cycles to increase the nematode numbers.

Can we identify the resistance genes we are finding in PNW material, to develop genetic markers to eliminate the costly need to phenotype plants in the greenhouse? This was the next logical step that we have started in this funding cycle. If we could identify DNA markers to the *Cre* genes (or possibly new genes in our PNW material), we could use these to quickly screen material. However, little has been published on *H. filipjevi.* But a recent paper was published on *H. filipjevi* based on Turkish (CIMMY) material, and we developed KASP markers to identify these QTLs in our material. We also tested SSR markers for known *Cre* genes. Finally, to look at the pathogen races (pathotypes) of *H. filipjevi,* we imported differential lines from Turkey and did initial screens with our cyst populations. We also completed a QTL association mapping analysis of a large population, and discovered six QTLs that can be further investigated. This was from the PhD thesis of Yvonne Thompson, who was funded by this research.

In the following few pages, we will address our objective separately and give more details of our results. These were the objectives from last year's proposal.

Objective 1. Screen adapted PNW and US varieties and advanced material in WA breeding programs for resistance to *Heterodera* in infested soil in the greenhouse, identify the *Cre* genes involved, and use markers to incorporate this resistance into breeding programs

We developed a high throughput greenhouse screening method to identify CCN resistance in wheat. This method assesses roots of young plants grown in cone-tainers containing soil collected from highly infested fields in fall and vernalized at 4 C prior to planting. In addition, this soil can be stored in the cold room after vernalization, and be used for up to a year.

We completed resistance testing of 1209 wheat lines from the programs of Carter, Pumphrey, Campbell, and Morris, regional nurseries, and a Campbell mapping population (NEMAX), all in the greenhouse using above method.

From above screening, we identified resistance in 10 to 21% of the advanced winter wheat lines, but less than 2% of spring wheat lines. Named and advanced lines resistant to *filipjevi* in one or more trials include ARS Crescent and Selbu, Cara, Otto, Masami, Madsen, Foote, ORCF-102, Prichett, SY605CL and Steelhead; WA 8235, 8206, 8163, 8194; Svevo and Soft Svevo. Preliminary resistance to *H. avenae* was found in Norwest 553, Jasper, and WA 8227. Chara and WA 8235 showed resistance to both *H. filipjevi* and *H. avenae*. In addition, three HRW and 12 SWW showed resistance.

Objective 2. Use markers to identify the *Cre* genes in our lines, and use markers to incorporate this resistance into breeding programs.

We developed KASP markers for QTLs for resistance to *H. filipjevi* that were identified in a CIMMYT study and assayed the breeding lines that we evaluated above. We were not able to identify the same QTLs in our material, except in the durum Svevo and Soft Svevo. These sources of resistance may be specific to CIMMYT derived material.

We tested SSR markers linked to *Cre1, Cre3, Cre5, Cre8, CreX*, and *CreY* genes. These markers may facilitate the understanding of the resistance background of our material.

We selected a subset of the lines that had been screened in the field and greenhouse. Ten varieties showed a strong resistant response in presence of the nematode in both the greenhouse and field. A genome-wide association study was performed using genotype by sequencing (GBS) markers. Although the panel was not large, a marker trait association (MTA) was discovered on genomes 1D, 3A, 5B, and 6BD; and two putative QTL on genomes 1A and 2B with false discovery rate of $P > 0.05$. QTL on 6B and 6D reveal a novel source of resistance to *H. filipjevi*. The introgression of selected MTAs into wheat cultivars will ultimately provide improved resistance to cereal cyst nematode. This work was part of the PhD thesis of Yvonne Thompson, which was completed in Nov. 2018 and will be published.

Objective 3. Conduct surveys for CCN

From 2013-2017, we surveyed 210 fields for Cereal Cyst Nematodes (CCN) infestation in eastern Washington and the Palouse. In 2016, we surveyed 50 locations in Walla Walla, Garfield, Columbia and western Whitman counties. Cysts were identified to species level with DNA techniques developed in previous. *H. filipjevi* was only found in southern Whitman County, and *H. avenae* in eastern Whitman County. No cysts were found in other locations. In 2017, we concentrated our survey efforts to identify other fields with high levels of *filipjevi* and *avenae* that could be used for greenhouse testing. We identified a field near Colfax for *avenae*, and a field near Colton that may have to be increased for *filipjevi*.

Objective 4. Identify pathotypes of *H. filipjevi*.

A pathotype is like a race of the nematode. Like rusts, CCN has a very specific interaction with the host, which is a gene-for-gene interaction. The nematode produces effectors, which are virulence factors, but can be recognized by the receptors on the plant, leading to a resistance reaction. In order to predict which *Cre* genes are effective, we need to know the pathotype of *H. filipjevi.* This was done with *H. avenae* by R. Smiley in the 1990s, nothing is known about our pathotype of *H. filipjevi*. We imported differential lines for identification of CCN pathotypes from Turkey and increased the seeds in the greenhouse. We conducted initial screens for pathotype identification of our local CCN and results show that our pathotypes are unique, and don't match any of the existing pathotypes.

Deliverables

A growing list of resistant US and PNW varieties and lines, which can be used directly by the growers or incorporated into existing breeding programs.

A greenhouse technique that is optimized for screening more lines for the breeders

Greenhouse pot cultures of *H. avenae* and *H. filipjevi* that can be used for screening of varieties

A beginning knowledge of what *Cre* genes we may have in our backgrounds

A complete understanding of the distribution of *H. avenae* and *H. filipevi* in eastern Washington, including distribution maps.

The first description of the pathotype of *H. filipjevi* in eastern Washington

Refereed papers

Wen, N., Thompson-Manning, Y., Garland-Campbell, K. and Paulitz, T. C. 2018. Distribution of cereal cyst nematodes (*Heterodera avenae* and *H. filipjevi*) in Eastern Washington State. Plant Disease: Submitted.

Manning-Thompson, Y, Thompson, A., Smiley, R., Paulitz, T., Garland-Campbell, K., 2016. Cereal cyst nematode screening in locally adapted spring wheat (*Triticum aestivum* L.) germplasm of the Pacific Northwest, 2015. Plant Dis Manag. Rep. 10:N003

Thompson, AL, Mahoney, AK, Smiley, RW, Paulitz, TC, Hulbert, S, Garland-Campbell, K, 2017. Resistance to multiple soil-borne pathogens of the Pacific Northwest is co-located in a

wheat recombinant inbred line population. G3 (Bethesda). 7(4):1109-1116. doi: 10.1534/g3.116.038604.

Theses

Yvonne Manning. 2018. Identification of Quantitative Trait Loci (QTL) for Resistance to Soil-Borne Pathogens *Fusarium culmorum* and *Heterodera filipjevi* in Wheat (*Triticum aestivum* L). PhD Thesis, Washington State University, Pullman, WA

Abstracts

Paulitz, T. C., Manning-Thompson, Y., Wen, N., Schallter, D., Borneman, J., and Garland-Campbell, K. 2017. Research on Cereal Cyst Nematode in Eastern Washington. 6th International Cereal Nematode Symposium, Agadir, Morocco Sept. 11-15, 2017

Wen, N., Thompson-Manning, Y., Garland-Campbell, K. and Paulitz, T. C. 2019. Distribution of cereal cyst nematodes (*Heterodera avenae* and *H. filipjevi*) in Eastern Washington State. International Plant & Animal Genome XXVII, San Diego, CA, USA Jan 12-16, 2019

Popular Publications

Presentations

Paulitz, T. C. 2016. "Root Disease Research at ARS Pullman-What's New?" Spokane Farm Forum, Ag Expo, Feb. 3, 2016. (presentation).

Paulitz, T. C. 2017. "Root Disease Research at ARS Pullman-What's New?" Spokane Farm Forum, Ag Expo, Feb. 2, 2017. (presentation).

Paulitz, T. C. 2018. "Root Disease Research at ARS Pullman-What's New?" Spokane Farm Forum, Ag Expo, Feb. 7, 2018. (presentation).

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WGC project number: 3061-7667
WGC project title:Management of nematode diseases with genetic resistance
Project PI(s): S. Hulbert, T. Paulitz, K. Campbell
Project initiation date:7/1/2016
Project year 3: 2018-2019

Objective	Deliverable	Progress	Timeline	Communication
Obj. 1. screen adapted PNW and US varieties and advanced material in WA breeding programs for resistance to *Heterodera* in infested soil in the greenhouse identify the *Cre* genes involved, and use markers to incorporate this resistance into breeding programs	List of resistant US and PNW varieties and lines, knowledge of what *Cre* genes we have in our backgrounds	To date have screened over 1000 lines, see 3-year report of project for detailed results	Will continue greenhouse testing next year using vernalized, infested soil in the greenhouse.	See publication list in full report
	Greenhouse pot cultures of *H. filipjevi* and *H. avenae*	Ideally, instead of relying on naturally infested soil collected in the field, we will produce inoculum in the greenhouse. Because the nematode can only reproduce on living plants, this involves infecting plants in large pots, harvesting the soil after two months, and vernalizing it to induce the nematodes to hatch. We have established pot cultures of both species.	Pot cultures will continue to be replanted and cycled to increase the inoculum density	
Objective 2. Use markers to identify the *Cre* genes in our lines, and use markers to incorporate this resistance into breeding programs	Usable markers that can be incorporated in the breeding programs.	See 3-year report. We are currently testing SSR markers linked to Cre1, Cre3, Cre5, Cre8, CreX, and CreY genes. These markers may facilitate the understanding of the resistance background of our material. We also identfied 6 QTLs and will develop markers. We used an NCBI registered Cre sequence to blast against Chinese Spring, and have identified a serial of Cre suspects.We will develop SNP markers linked to these Cre suspects for potential genetic sources of CCN resistance.	Continue to develop and test markers for other identified *Cre* genes	See publication list in full report
Obj. 3. Conduct surveys for CCN	Maps of CCN around **all** of Eastern and Central Washington	From 2013-2015, we surveyed 210 fields in eastern Washton and the Palouse. In 2016, we surveyed 50 locations in Walla Walla, Garfield, Columbia and western Whitman counties. Cysts were identified to species level with DNA techniques developed in previous. *H. filipjevi* was only found in southern Whitman County, and *H. avenae* in eastern Whitman county. No cysts were found in other locations. In 2017, we concentrated our survey efforts to identify other fields with high levels of *filipjevi* and *avenae* that could be used for greenhouse testing. We identified a field near Colfax for *avenae,* and a field near Colton that may have to be increased for *filipjevi.*	The species-specific survey for the Palouse has been completed. A paper has been submitted to Plant Disease	See publication list in full report
Obj. 4. Identify pathotypes of *H. filipjevi*	Knowledge of pathogen diversity in relation to other world populations, to aid in selecting resistance *Cre* genes	Differential lines were imported from Turkey and seed was increased in the greehouse. Initial screening experiments were done, and tentative pathotypes did not match existing ones.	Pathotype testing will continue in the greenhouse in 2019-2020.	see publication list in full report

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

Project # 3019-3685

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**

M. Pumphrey, K. Garland-Campbell, and T. Paulitz

Cooperators: Yvonne Thompson, WSU, Nuan Wen, WSU**,** Arron Carter, WSU; Chris Mundt and Christina Hagerty, OSU

Executive summary:

- A modified method was developed to increase the disease pressure of Fusarium crown rot under greenhouse conditions. This method resulted in less variation and was used to a diverse global spring wheat collection, a set of wheat synthetic lines, a backcross population derived from the spring wheat cultivar Louise and an Iranian land race with multiple root disease resistance and the winter wheat variety trials.
- A genome-wide association study (GWAS) was conducted to determine the genetic architecture of resistance to *F. culmorum* in the global spring wheat collection and QTLs for resistance were identified on chromosomes 1A, 2B, 4D, 5A, 6B, and 7A. Chromosome 2B, 4D, and 7A may reflect novel sources of resistance.
- Resistance was discovered in the set of synthetics. Synthetic wheat is derived from crosses between durum wheat and *Aegilops squarrosa*, the donor of the wheat D genome. Since durum is susceptible, to *Fusarium*, resistance is from the D genome. This germplasm represents potential new sources of resistance and has been crossed with winter wheat breeding lines from the USDA and WSU breeding programs.
- We evaluated the Louise/IWA860877 (AUS285451) backcross population in the field for resistance to *Fusarium.* The results were skewed towards susceptibility as would be expected from a backcross population but some resistant lines were identified. We are following up to identify the loci responsible for this resistance using QTL analysis.

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
-The first QTLs for resistance to *F. culmorum* have been identified.

WGC project number: 3019-3685
WGC project title: Fusarium Crown Rot on Wheat: Prebreeding and Development of Tools for Genetic Disease Management
Project PI(s): M. Pumphrey, K. Garland-Campbell, and T. Paulitz
Project initiation date: 7/1/2018
Project year: Year 1 2018-2019

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.	We have screened almost 500 lines from regional nurseries and variety testing for resistance to *F. culmorum* , and are identifying the most resistant and susceptible. We have further optimized our greenhouse testing protocol to maximize disease and reduce variability by using a cold vernalization period followed by a water stress treatment at the end. Using this protocol we have screened the following: 2018 Winter Variety Trials- 97 entries in 3 replications, 291 cones total Cara Xerpha- 128 entries in 3 replications, 384 cones total DNAM tauschii- 8 entries in 3 replications, 24 cones total DNAM RIL- 54 entries in 4 replications, 216 cones total CIMMYT Synthetics- 20 entries in 4 replications, 80 cones total	Greenhouse screening will continue with optimized methods in 2019-2020	Yvonne Manning. 2018. Identification of Quantitative Trait Loci (QTL) for Resistance to Soil-Borne Pathogens *Fusarium culmorum* and *Heterodera filipjevi* in Wheat (*Triticum aestivum* L). PhD Thesis, Washington State University, Pullman, WA
Objective 2. Select for QTLs associated with resistance in segregating populations	Resistant sources that can be used for variety development.	A mini-core collectionof 600 lines was developed for the spring core collection. Phenotyping and screening of mapping population in the greenhouse has been completed.We conducted 6 replications of this populations for a total of 3600 conetainers screened. The student has completed the analysis and written the PhD thesis. QTLs were identified on chromosomes 1A, 2B, 4D, 5A, 6B, and 7A. Chromosome 2B, 4D, and 7A may reflect novel sources of resistance.	Verification of QTLs will continue in 2019-2020	Yvonne Manning. 2018. Identification of Quantitative Trait Loci (QTL) for Resistance to Soil-Borne Pathogens *Fusarium culmorum* and *Heterodera filipjevi* in Wheat (*Triticum aestivum* L). PhD Thesis, Washington State University, Pullman, WA.
Objective 3. Look for new sources of resistance in a new set of synthetic wheat that was developed by CIMMYT in Turkey.	Resistant sources that can be used for variety development.	Resistance was discovered in the set of synthetics. Synthetic wheat is derived from crosses between durum wheat and *Aegilops squarrosa,* the donor of the wheat D genome. Since durum is susceptible, to *Fusarium* , resistance is from the D genome. This germplasm represents potential new sources of resistance and has been crossed with winter wheat breeding lines from the USDA and WSU breeding programs.	Greenhouse screening of synthetics will continue in 2019-2020.	

Objective 4. Screen the population of AUS28451 X Louise in the greenhouse for tolerance to *Fusarium,* to identify new possible sources of resistance.	Resistant sources that can be used for variety development.	We evaluated the Louise/IWA860877 (AUS285451) backcross population in the field for resistance to *Fusarium.* The results were skewed towards susceptibility as would be expected from a backcross population but some resistant lines were identified. We are following up to identify the loci responsible for this resistance using QTL analysis.	We will conduct another round of greenhouse screening for resistance to *Fusarium* and identify QTLs associated with disease resistance	

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Washington Grain Commission

Wheat and Barley Research Annual Progress Reports and Final Reports

Project #: **3019 3574**

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, Nilsa A. Bosque-Pérez, 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 2018. 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.

Impact:

Spring wheat production has averaged ~30 million bushels in WA in recent years. A conservative state-wide 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, and hard red spring wheat varieties 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: 3574
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: 2018
Project year: 1 of 3

Objective	Deliverable	Progress	Timeline	Communication
Screen WSU Spring Wheat 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 80 spring wheat lines, 40 winter wheat varieties, numerous spring wheat breeding populations, and new entries into the WSU Wheat Variety Testing Program were screened in 2018.	Annually	Progress will be presented by M. Pumphrey at field days, plot tours, at Wheat Research Reviews for individual states. Presentations will be made to the Washington Wheat Commission and WAWG conferences upon invitation. Progress will be reported in Wheat Life magazine and data will be recorded with nursery data.
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 populations were self pollinated, selected for Hessian fly resistance, and Doubled-haploid progeny were developed from resistant plants. Also, JD and Melba were used to introduce four new resistance sources through backcrossing with phenotypic selection.	Annually	

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

Project #: 3667

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, Craig F. Morris, Doug Engle*

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 the USDA-ARS Western Wheat Quality Laboratory. 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 exporters 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:
Otto, Puma, Jasper, Sequoia, Glee, JD, Louise, Sprinter, Chet, Alum, Seahawk, Melba, Tekoa, Ryan, Whit, Babe, Dayn and Diva are examples of top-performing WSU variety releases that are widely grown 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 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. Landmark varieties like Louise and Xerpha, are being replaced by better end-use quality replacements with higher yields, better agronomics, and stable performance. This short, medium, and long-term impact is of paramount importance to the Washington grain industry.

Outputs and Outcomes: File attached

WGC project number: 3667
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-17
Project year (X of 3-yr cycle): 3of 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 1500 breeding samples were analyzed by numerous milling and baking quality tests each year in recent years. This is a substantial increase over previous years and has allowed enhanced selection of advanced breeding lines with good quality. **Two new wheat varieties were released in part due to this project and data in 2018.**	The economic return for this work will manifest itself each breeding cycle with superior quality varieties and germplasm.	Progress will be summarized and discussed at numerous field days (>10 per year), grower meetings (~10 per year), the annual Research Review, through WSCIA meetings, Wheat Life, Variety Release Meetings, and direct communication with the WGC every year. Arron Carter participates in mulitple US Wheat trade tours and we hosted many trade teams in 2018.
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.	A hard red spring wheat bi-parental popualtion was milled and baked to map breadmaking quality traits in 2017. Milling and baking analysis of a bi-parental winter wheat mapping population has also been completed. A genetic map of hard red spring wheat quality QTL was generated, and thiss work presented at the PNW Wheat Quality Council	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 3676**
Progress Report Year:	*_3___ of __3__ (maximum of 3 year funding cycle)*
Title:	**Improving Spring Wheat Varieties for the Pacific Northwest**
Cooperators:	Mike Pumphrey, John Kuehner, Vic DeMacon, Sheri Rynearson, Wycliffe Nyongesa

Executive summary:

The WSU spring wheat breeding program's elite material and recently released varieties continue to be the top performers is statewide variety trials and for growers. *A new 2-gene Clearfield hard red spring wheat is planned for release in 2019*. Foundation and registered seed of Ryan, Seahawk, Tekoa, Alum, Chet, and Glee spring wheats and JD and Melba spring club wheats was produced and sold in 2018. 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 80% of certified soft white spring wheat production acres in Washington in 2018*. Our newest 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 rapidly adopted by seed dealers and growers as seed stocks are multiplied. Glee has been the leading dryland hard red spring wheat variety in the state the past five years, while Chet has been widely adopted in lower rainfall areas and Alum is rapidly increasing in acreage. WSU hard red spring wheat varieties were planted on 28% of the certified hard red spring wheat production acres in Washington in 2018. 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.

Impact:

The WSU spring wheat breeding program is in a unique position to focus on grower opportunities and challenges, large and 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 and yield protection. Our latest releases package excellent yields with superior quality and key yield protection traits. Our newer releases are poised to lead acreages planted in the future due to improved potential profitability for growers, and rapid industry adoption. Public wheat breeding programs at WSU and across the country payback consistently on research dollars invested. With 50% or more of the spring wheat acres in Washington planted to WSU spring wheat varieties, growers continue to realize a substantial return on research dollars invested in this program.

Outputs and Outcomes: File attached

WGC project number: 3019 3676
WGC project title: Improving Spring Wheat Varieties for the Pacific Northwest
Project PI(s): Mike Pumphrey
Project initiation date: 2016
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 Seahawk, Glee, Alum, Chet, Tekoa, Melba, and Ryan continued to lead yield trials in their classes in 2018, and have widespread seed availability. Significant positive economic impact for PNW growers is generated by higher-yielding varieties. We had very good test plots across regions in 2018. Good data quality is fundamental to making solid selections. Our 2-gene Clearfield breeding efforts have fully matured, and we plan to release our first hard red spring wheat in 2019. Our attention to stable falling numbers over the past five years has resulted in selection of superior lines for this trait.	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 2018. A primary focus in 2018 was backcrossing Fusarium head blight resistance into hard red spring wheat germplasm. Extensive crossing blocks for irrigated hard red spring wheat germplasm development were also completed. A large fall-seeded spring wheat trial was established in October 2018 with irrigation. Backcrossing of the AXigen trait for CoAXium wheat production system was intitated in 2018. We are backcrossing 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 association mapping, 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 2018 to help long term breeding efforts. Scientific products of our efforts through multiple projects in 2018 include nine 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, association mapping, 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 #: **3677**

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, Vic DeMacon, Sheri Rynearson, Wycliffe Nyongesa

Executive summary:

This project is an integral component of the Spring Wheat Breeding program. This project provides 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 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 substantial, and these outputs shape our overall breeding efforts.

Impact:

This project is critical to the spring wheat breeding program and with project 3676, establishes our core breeding efforts. Program efficiency is significantly increased, by evaluating early generation lines for quality and eliminating those with poor quality characteristics before further field testing. This allows for increased testing of superior material in the field program and protects resources from being used to further test lines that are inferior in terms of quality, lack of adequate pest resistance, and numerous other DNA-marker selectable traits. Spring wheat varieties with complex stripe rust resistance, Hessian fly resistance, aluminum tolerance, superior end-use quality, and broad adaptation are critical for Washington wheat producers by adding millions of dollars of annual return. Over the past four years, we have released Chet, Alum, Seahawk, Tekoa, Ryan, and Melba. They have been rapidly adopted by seed dealers and growers as seed stocks are multiplied, and are top-volume sellers through the Washington State Crop Improvement Association. 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. A new release, proposed as Net Cl+, in spring 2019, will provide growers a much needed top-performing two-gene Clearfield spring wheat variety.

Outputs and Outcomes: File attached

WGC project number: 3019 3677
WGC project title:Greenhouse and laboratory efforts for spring wheat variety development
Project PI(s): Mike Pumphrey
Project initiation date: 2017
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.	The Clearfield breeding efforts are progressing nicely, with new 2 gene lines entering advanced yield trials each year. One Wheat Life article was written/contributed in 2018, as well as supporting other articles. Axigen trait introgression began in 2018, and we have made BC1 maerials with this new herbicide tolerance to date. Nineteen DNA markers were applied to elite selections, crossing parents, and early generation lines for selection. Four hessian fly resistance genes have been backcrossed into elite germplasm to the BC3 or BC4 stage.	Activities recur annually. The two-gene Clearfield™ breeding progress is good, and a hard red spring wheat is proposed for release in Feb 2019. Activities are cyclical and occur annually throughout the normal breeding cycles.	Pumphrey attended/presented at numerous WSU field days, workshops/meetings, PNW wheat Quality Council, WSCIA Annual Meeting (presentation), WSCIA Board Meetings, WA Grain Commission meetings, industry tours.
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.	By January 2019, we completed evaluation of ~3200 headrow selections for several end-use quality traits. Over half of selections without superior quality related values were discarded, ensuring very high quality lines are advanced. These have been advanced to a greenhouse generation advance and will be evaluated as F5:6 lines in 2019.	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.	
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 have continued to successfully develop and advanced hundreds of crosses for selection in breeding populations. The primary focus in 2018 was Hessian fly resistance selection in club wheat, and introgresssion of new Hessian fly resistance genes,	Greenhouse multiplication and crossing is completed annually, including two large crossing blocks and thousands of early generation lines tested for stripe rust and herbicide tolerance.	

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

Project #: 13C-3019-3687

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 (CSS) , Kim Garland-Campbell (USDA/ARS; CSS), Xiao Zhang (WSU, Tri-cities, CEB), Timothy Paulitz (USDA/ARS; Plant Path)*

Executive summary: Lignin content and accumulation in stems, leaves and roots has been linked with different stress tolerances in crop plants. Lignin confers rigidity to plant cell walls, and increases in response to drought, heavy metals, salinity, and pathogen attack. Therefore, managing overall lignin content, as well as its proportion in the roots versus shoots of crop plants is important for improved stress tolerance. Few studies have investigated the role of lignin in grass root systems at present. Reports on maize and wheat showed that lignin content in the root was higher than in the shoot, and that these levels varied depending on genotype. In wheat, lignin concentration was shown to decrease in seedlings and roots when exposed to mineral deficiencies and increase in response to toxic minerals. Given these findings, our preliminary results, there is a need to further investigate the role of lignin in roots. The overall goal of the project is to determine the role of lignin in wheat roots for drought tolerance and disease resistance and to develop a high-throughput method for lignin analysis is wheat roots and straw. We have worked on processing stem and root tissues for overall lignin content using two independent assays as well as sending pulverized stem and root tissues for analysis of monomers to the Zhang lab at WSU-TC. We had good success with lignin extraction in stems, but are still working on lignin extraction from root tissues. We have also begun to implement drought studies using the Phenospex drought spotter in the wheat greenhouse. In the next two years, we will refine the methodology and complete the analyses on the Lou/Au backcross populations in terms of lignin content, drought performance, and disease resistance for soil-borne pathogens.

Impact: In addition to stress tolerance, lignin has important implications for the rhizosphere and agricultural soils, particularly since it is a stable component of soil organic matter (SOM). There is evidence that lignin slows down the mineralization of nutrients from crop residues. For example, the ratio of lignin to nitrogen is used as an indicator for litter degradation. Studies have shown that lignin negatively affects short-term nitrogen release from different types of green manures that differ in lignin content and that time is a key factor in the lignin/nitrogen equation. Since SOM contains roughly two-thirds of global terrestrial carbon storage and lignin is an important component of SOM, lignified biomass represents a promising source of sustainable fertilizer, which is a concern for Washington state farmers and globally. Our research has shown the lignin monomer content and not total lignin content in winter wheat stems is important for residue breakdown and thus management. Long-term our data will shed light on the role of lignin in rhizosphere processes as well—such as soil-borne pathogen management and improving overall plant responses to abiotic stresses like drought, salinity, changes in pH, and cold.

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, Xiao Zhang, Timothy Paulitz
Project initiation date: 7/1/18
Project year (X of 3-yr cycle): year 1 of 3

Objective	Deliverable	Progress	Timeline	Communication
1. Quantification of lignin content in roots	A robust and reliable method to accurately determine lignin content in root samples in a high-throughput manner is the main deliverable of this objective.	The first rounds of lignin extractions were performed with the parental lines: AUS28451 and Louise in 2018 both for total lignin and for lignin monomers. Following optimization of the protocols for root extractions, the Lou/Au BC1F6 populaitons will be analylzed in 2019-2020.	The quantification of lignin and optimization of the extraction metnods will be performed in the first part of year 1 so that by the end of year 1 all of the BC1F6 populations will be analyzed	An article was published in the Aug/Sept 2018 issue of Wheat Life on drought and roots. If a robust and high-throughput method proves successful, a methods protocol will be published.
2. Assessment of the role of lignin in drought	If lignin in roots is associated with drought, this can then be a desirable trait and selected/screened for in breeding populations.	The parental lines have been assessed and protocols established for the greenhouse trial in year 1 so the selected BC lines with low, intermediate and high lignin content can be assessed in years 2 and 3.	Assessment of the parental lines were completed in 2018 and will be followed by two rounds of greenhouse trials with the backcross lines in years 2 and 3.	The findings and protocols will be reported at field days and in peer-reviewed publications. We published two abstracts in the Lind Field Day Abstract book in 2018 and Sanguinet also presented on roots at the Wheat Academy in Dec. 2018
3. Root lignin and soil-borne disease	If lignin in roots is associated with disease reisistance as hyprothesized, this can then be selected/screened for in breeding populations.	Previous work has indicated that the landrace AUS28451 is resistant to soil-borne nematodes and Rhizoctonia. Both parental and BC lines with varing degrees of root lignin content have been assessed for disease resistance in a greenhouse screen with conetainers.	Assessment of disease resistance will be repeated in 2019-20.	The findings and protocols will be reported at field days and in peer-reviewed publications.

Washington Grain Commission
Wheat and Barley Research Annual Progress Report

Project #: 3690
Progress Report Year: *_1__ of _3__ (maximum of 3 year funding cycle)*

Title: Developing Washington Wheat with Stable Falling Numbers (FN) through Resistance to Preharvest Sprouting and LMA.
PIs: Camille M. Steber, Michael O. Pumphrey, Arron H. Carter, and Kimberly Garland Campbell
Cooperators: Deven See, Craig Morris, Aaron Esser, and Drew Lyon

Executive summary: The goal of this project is to breed for stable Falling Numbers (FN) in Washington wheat through selection for genetic resistance to preharvest sprouting and late maturity alpha-amylase (LMA). The project identified cultivars with low FN problems through evaluation of the WSU cereal variety trials, and with sprouting and LMA problems through greenhouse and field testing. We have identified molecular markers linked to PHS resistance and are in the process of identifying molecular markers linked to LMA resistance loci to allow selection in as many as 5000 early breeding lines per year. We are improving field and greenhouse testing for use in screening elite breeding lines.
Objective 1. Identify varieties with stable FN by performing FN tests and statistical analysis of variety trials in environments that have preharvest sprouting and/or LMA
FN data from the soft white winter WSU variety trials was analyzed using five statistical methods designed to examine how traits are impacted both by genetics and the environment. FN is difficult to analyze due to the fact that it impacted by multiple environmental factors leading to preharvest sprouting or to LMA. The factor analytic model seemed to provide the best approach to compare both how well a variety performs for falling number and how stable that falling number is over changing environments.
Objective 2. Screen winter and spring wheat breeding lines for preharvest sprouting and/or LMA. In 2018, 1,335 lines were screen for LMA susceptibility using in the field, and 708 lines were screened for preharvest sprouting susceptibility by spike-wetting test.
Objective 3. Identify molecular markers linked to LMA susceptibility in northwest wheat.
a. We have completed three greenhouse and two field experiments screening the 250 lines of the spring TCAP population for LMA. b. Based on one greenhouse experiment, 3 of 10 spring RIL populations and 3 of 20 winter RIL populations were chosen as good candidates for LMA mapping.
Objective 4. Develop molecular markers for selection of PHS resistance in northwest wheat. A preliminary genome-wide association mapping was conducted. Some loci linked to good seedling emergence did not correspond to loci for preharvest sprouting resistance, suggesting that we may be able to select preharvest sprouting resistant without compromising seedling emergence. Molecular markers associated with preharvest sprouting resistance will be confirmed using spike-wetting tests of 461 doubled haploids descended from parents in the original association mapping study.

Impact: Wheat in all market classes is dramatically discounted for low falling numbers (below 300s). Moreover, a consistent problem with low FN could damage the reputation of Washington wheat in foreign markets. Screening for low FN, LMA, and sprout-susceptibility will the selection of new varieties with more stable FN. Posting of FN data on the WSU small grains website and the PNW FN website makes this data available to farmers and to breeders.

WGC project number: 3690
WGC project title: Developing Washington Wheat with Stable Falling Numbers (FN) through resistance to preharvest sprouting and LMA
Project PI(s): Camille M. Steber, Michael O. Pumphrey, Arron H. Carter, and Kimberly Garland Campbell
Project initiation date: July 1, 2018
Project year (X of 3-yr cycle): This is year 1 of 3 of the funding cycle.

Objective	**Deliverable**	**Progress**	**Timeline**	**Communication**
1. Identify varieties with stable FN by performing FN tests and statistical analysis of variety trials in environments that have PHS and/or LMA.	**1.** FN testing results posted on the PNW FN website (steberlab.org). **2.** Development of statistical methods to compare varieties for performance and stability of FN. **3.** A new FN comparison tool.	**1.** FN testing of susceptible spring and winter varieties has been completed for all variety trial locations. **2.** FN data from the WSU soft white winter variety testing in 2013, 2014, and 2016 has been analyzed using five different statistical approaches. A first article about the statistical analysis of falling number data has been submitted to Crop Science. Ongoing research using a factor-analytic model in AMSREML appears to provide the best tool for comparing both how well a variety performs for falling number, and how stable the falling number is over changing environments. **3.** We used half-seed assays to examine whether of subset of variety trial samples with FN below 300 seconds had alpha-amylase distribution consistent with LMA or preharvest sprouting. We had some samples that had FN below 300 that did not have elevated alpha-amylase enzyme levels. These results are just anecdotal. But it appears that this phenomenon of low FN without alpha-amylase was associated with low protein of around 6%. This supports a previous report by Andrew Ross of Oregon State University saying that low protein can cause a lower FN.	**1.** Annually. FN testing of susceptible varieties will be used to determine which WSU Cereal Variety locations will be subject to FN testing. **2.** In 2018 and 2019, compare various methods for ranking varieties for FN. **3.** In 2019, complete statistical analysis of soft white winter FN data from 2013, 2014, and 2016. **4.** In 2020, select a method for annual analysis of variety trial FN data.	Results of annual FN testing will be made available on the PNW FN website and on the WSU small grains website. Information will be published in peer-reviewed journals, summarized in a Wheat Life article, presented during field days, and presented at the annual Wheat Review.
2. Screen winter and spring wheat breeding lines for PHS and LMA susceptibility.	Data obtained will allow selection for increased resistance to LMA and preharvest sproutng in winter and spring wheat breeding programs at WSU. This should indirectly lead to release of variaties with increased resistance to low FN.	**1.** The LMA field-testing method was used to induce LMA in a total of 1,335 lines. This included 72 spring wheat breeding lines, 168 winter wheat breeding lines, 185 variety trial and parental lines, 426 TCAP spring wheat mapping plots, and 484 QAM winter wheat mapping lines. FN testing of this material is still in progress. **2.** Preharvest sprouting resistance was tested using greenhouse spike-wetting tests of spikes harvested at physiological maturity from the field. Testing results were obtained for 495 soft white winter and 213 spring wheat lines. **3.** Experiments were performed to optimize the temperature, humidity, and developmental timing of LMA induction. The goal of using the Chemwell-T robot to optimize alpha-amylase enzyme assays (Megazyme SD assay) met with serious problems in 2018. The programming of the robot does not allow it to maintain a consistent 5 minute reaction time, making results inconsistent. This meant that over 1000 samples had to be repeated using the Phadebas enzyme assay.	**1.** Perform field LMA testing annually of about 1000 lines annually for breeding and mapping. **2.** Perform spike-wetting tests annually. **3.** Continue improving methods to increase efficiency.	Information will be published in peer-reviewed journals, summarized in a Wheat Life article, presented during field days, and presented at the annual Wheat Review.

3. Identify molecular markers linked to LMA susceptibility in northwest wheat.	**1.** Molecular markers linked to LMA resistance allowing selection in earlier generation breeding lines. **2.** Mapped LMA genes/loci linked to LMA resistance and susceptibility in the soft white spring TCAP population. **3.** Mapped LMA genes/loci linked to LMA resistance and susceptibility in recombinant inbred line populations.	**1.** We have completed 3 greenhouse and two field LMA testing experiments for the spring TCAP population. Only the third greenhouse experiment showed good LMA induction due to optimized conditions. We will need to repeat the greenhouse screening one more time to obtain publication-worthy data. Preliminary genome-wide association mapping is in progress. **2.** The parents for 10 spring RIL populations were screened for LMA in a single greenhouse experiment. Of these 3 populations, AVS*2xJD, UI-Platinum x LCS Star, and UI-Platinum x LCS Atomo, are likely to show clear segregation of LMA resistant and susceptible lines. The parents of 20 winter RIL population have been screened in a single greenhouse LMA experiment. Of these, three look promising for LMA mapping including, Xerpha x Munstertaler, Cara x Xerpha, and Finch x Eltan. Analysis of additional samples from the 2018 field season are still in progress, and will be used to confirm identification of useful populations for LMA testing. Promising populations have been and will be planted for the 2019 field season.	**1.** The goal to complete TCAP LMA screening in 2018 must be extended into 2019. **2.** Genome-wide association mapping in the TCAP will be performed in 2019. **3.** RIL populations for LMA mapping will be identified by 2019, and LMA screening initiated in 2019 and 2020.	Information will be published in peer-reviewed journals, summarized in a Wheat Life article, presented during field days, and presented at the annual Wheat Review.
4. Develop molecular markers for selection of preharvest sprouting resistance in northwest wheat.	**1.** Molecular markers that can be used to select for resistance to preharvest sprouting. **2.** Identify markers that can select for sprouting resistance without compromising field emergence.	**1**. Mapping results for preharvest sprouting were based on FN and sprouting scores from spike-wetting tests. Mapping was also preformed for emergence based on field emergence and coleoptile/seedling elongation. Comparison found that there were some strong genes/loci lined to emergence that were not linked to preharvest sprouting susceptibility. This is a preliminary result, but suggests that this mapping approach may be used successfully in soft white winter wheat populations. **2.** Spike-wetting tests were performed for 461 doubled-haploid winter wheat breeding lines derived from parents in the QAM and SNP winter wheat mapping populations. These data can be used to confirm marker-trait associations for molecular markers.	**1.** In 2018, GWAS was performed in a second population to confirm marker-trait associations. **2.** In 2018, spike-wetting tests were performed on winter doubled haploid populations. **3.** In 2019 and 2020, we will develop a genomic prediction model.	Information will be published in peer-reviewed journals, summarized in a Wheat Life article, presented during field days, and presented at the annual Wheat Review. The goal in to summarize these markers on the PNW fallng number website to make it easier for wheat breeders to access this information.

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. Arron H. Carter, and Dr. Kimberly Campbell*

Executive summary: *We update two software package and published two articles partially under support of this project in this fiscal year. The two software package are GAPIT (Genome Association and Prediction Integrated Tool) and iPat (integrated Prediction and Association Tool). Both of the packages can be used to conduct GWAS (Genome Wide Association Study) and GS (Genomic Selection). GAPIT is R Package for users with programming skills in R language. Analyses can be programmed to process large amount of analyses with same settings. iPat has graphic user interface. Breeders can simplify use any computer pointing device to drag their datasets into the interface and then click on the graphical icons for analyses. Bot of these packages implemented the two new methods we published in 2018 by Wang and et al. (Heredity, 121, 648–662). We also publish an article on Wheat Life in November of 2018 entitled "Empowering breeders for success".*

Impact: *Our collabrative research positions WSU/USDA-ARS research team as one of the 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 benefit Washington, but will also benefit the entire world through the dissemination of knowledge. In short term, breeders can conduct most of data analyses without frustration on data formating and selecting different analytical functions. They have more oppertunities to find the casative 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, and Kimberly Campbell*

Project initiation date: 1-Jul-18

Project year: 1 of 3

Objective	Deliverable	Progress	Timeline	Communication
1) Develop a sophisticated, single-step method that combines MAS and GS to boost prediction accuracy	Two peer reviewed paper was published (Wang and Et. Al., Heredity, 121, 648–662, 2018; and Chen and Zhang, Bioinformatics, Volume 34, Issue 11, 1 June 2018, Pages 1925–1927). The paper describes two newly developed methods which have been implemented in GAPIT and iPat.	The manuscript is in progress for implementation of the methods to combine GWAS (genome wide association study) and GS (genomic selection).	December 31, 2018: investigate multiple variable linear regression methods. Published one peer reviewed paper; June 30, 2019: published one peer reviewed paper to describe methods to combine GWAS (genome wide association study) and GS (genomic selection).	1) One article published bt Wheat Life (November 2018); 2) One presentation to WGC meeting; 3) One presentation at international conference of plant and animal genome; and 4) two papers on academic journal (Wang and et. Al., Heredity, 121, 648–662, 2018; and Chen and Zhang, Bioinformatics, Volume 34, Issue 11, 1 June 2018, Pages 1925–1927).