Research

Phosphorus Supply Does Not Affect Fusarium Crown Rot of Winter Wheat

C. H. Hagerty^{1,2,†} | K. R. McLaughlin³ | D. R. Kroese¹ | L. K. Lutchter² |

¹ Department of Botany and Plant Pathology, Oregon State University, Columbia Basin Agricultural Research Center, 48037 Tubbs Ranch Road, Adams, OR 97810

² Department of Crop and Soil Science, Oregon State University, Morrow County Extension, 54173 OR-74, Heppner, OR 97836

³ Department of Statistics, Oregon State University, Corvallis, OR 97331

† Corresponding author: C. H. Hagerty; christina.hagerty@oregonstate.edu

Accepted for publication 9 June 2021.

Abstract

Fusarium crown rot (FCR) is a major limitation to the wheat (*Triticum aestivum* L.) industry in the inland Pacific Northwest, United States. Genetic resistance to FCR is poorly understood and major gene resistance is not available in adapted cultivars. Chemical control is ineffective and crop rotations, which disrupt cycles of the disease, are not feasible in the region's precipitation-limited climate. Cultural control methods are the only realistic option for farmers who struggle to minimize the impact of this disease. It is well established that FCR is favored by moisture-limited environments and an oversupply of plant-available nitrogen in soil. Effects of the supply of phosphorus in soil have not been clearly delineated. We conducted a 2-year FCR experiment at two locations in the low-precipitation zone (<30 cm) of north-central Oregon. Phosphorus fertilizer was applied in-furrow with phosphorus (P) at rates of 0, 5, and 15 kg ha⁻¹, to plots planted with either a hard red or soft white winter wheat cultivar. The P at 15 kg ha⁻¹ application rate increased tissue phosphorus concentration, early-season dry matter, and phosphorus uptake at both locations and both years of this study. Phosphorus treatment had no effect on grain yield, protein, or test weight. Phosphorus had no effect on the severity of FCR. This research improved our knowledge of cultural management boundaries as they relate to the control of FCR.

Keywords: disease control and pest management, disease resistance, dryland winter wheat, fungal pathogens, Fusarium crown rot, *Fusarium pseudograminearum*, phosphorus, *Triticum aestivum*

e-Xtra: Supplementary materials are available online.

The author(s) declare no conflict of interest.

Mineral nutrition is a primary component of disease control (Datnoff et al. 2007; Engelhard 1989). Fusarium crown rot (FCR) is a common disease of wheat globally (Bockus et al. 2010). In the Pacific Northwest (PNW), areas in the low-precipitation zone (<30 cm) of east-central and south-central Washington and north-central Oregon experience the greatest FCR disease pressure (Poole et al. 2013; Yin et al. 2020). This zone (1.5 million ha) is an area where deep silt loam soils are common, annual precipitation occurs mostly during winter, summers are dry and warm or hot, and winter

Copyright © 2021 The Author(s). This is an open access article distributed under the CC BY-NC-ND 4.0 International license.

wheat is produced after a preceding year of either tilled or no-till fallow (Hagerty et al. 2019) (Supplementary Table S1).

Winter wheat is a \$2 billion industry in the dryland PNW (USDA-NASS 2017), with 90% of acreage planted to soft white cultivars. Hard red cultivars are produced on the remaining 10% of the region's farmland. The winter wheat production system favors FCR, which can lead to yield loss ranging from 10 to 60% (Smiley et al. 2005). FCR is favored in this production system due to lack of rainfall: *Fusarium* spp. can thrive in drought-stressed conditions and it is well documented that FCR infection is more significant in dry conditions (Chekali et al. 2011).

Fusarium pseudograminearum and *F. culmorum* are the main causal agents of FCR in arid conditions (Bockus et al. 2010). *F. pseudograminearum* is essentially ubiquitous in soils of commercial winter wheat fields of the dryland PNW but severity of the crown rot infection each year is driven by environmental conditions and host susceptibility (Poole et al. 2013; Yin et al. 2020).

F. pseudograminearum overwinters on host debris. In low-humidity conditions, the FCR disease cycle is driven primarily by soilborne inoculum residing in the mulch layer of the soil. *F. pseudograminearum* infects wheat seedling stems and tiller bases. If rapid fungal colonization occurs at the seedling stage, damping-off and seedling mortality can occur. A secondary cycle of splash-dispersed conidia can lead to subsequent infection. A brown discoloration of stem bases, and the coexisting presence of pink, red, or white mycelium, can be observed after wheat plants reach the jointing stage of growth. Stem colonization inhibits flow of water and nutrients to the developing wheat head. The outcome of inhibited flow is prematurely ripe or bleached "whiteheads", compromised grain fill, and pinched or shriveled grain (Bockus et al. 2010).

Genetic resistance to FCR is inadequate in cultivars adapted to the PNW (Graebner and Mundt 2019), and responsible mechanisms of resistance are poorly understood (Smiley et al. 2003). Genetic resistance is complex and controlled by multiple quantitative trait loci with a significant genotype-environment interaction (Pariyar et al. 2020). Foliar fungicides do not control FCR (Moya-Elizondo and Jacobsen 2016) and currently available seed treatments have limited activity on the causal pathogens (Hagerty and Kroese 2021; Moya-Elizondo and Jacobsen 2016).

It is well established that FCR is favored by an oversupply of nitrogen, resulting in excessive aboveground biomass, inefficient depletion of soil moisture, and an increased incidence of disease (Bockus et al. 2010; Davis et al. 2009; Smiley et al. 2005). Plants with excess nitrogen develop robust aboveground biomass that rapidly depletes soil moisture. This can lead to premature drought stress and, thus, FCR is favored (Davis et al. 2009). Phosphorus availability in winter wheat increases root length (Römer et al. 1988), root-to-shoot ratio (Föhse et al. 1988), and root biomass (Liao et al. 2008). However, the effects of the supply of phosphorus in soil on FCR have not been clearly evaluated.

The objective of this field study was to evaluate outcomes from phosphorus fertilization, and the supply of phosphorus in soil, on the incidence and severity of FCR in winter wheat. This work is a contribution to the body of cultural disease management techniques for wheat producers.

MATERIALS AND METHODS

Field and laboratory procedures

Field trials were conducted in north-central Oregon (Morrow County) during the 2017–18 and 2018–19 crop years. Morrow County was selected as the ideal trial location because it is

located in the world's driest rainfed wheat region (Schillinger and Young 2004), with the greatest potential for heavy and uniform FCR disease pressure (Yin et al. 2020). Sites were distinguished by soil type and their location in the county. The north site was a deep (180 cm) Ritzville silt loam located in the central part of the county and 40 km south of the Columbia River. The south site was a shallow (60 cm) Valby silt loam located 32 km from the southwest corner of the region's Blue Mountain Range. These two sites are representative of wheat-producing farms in much of the low-precipitation zone of Oregon and Washington. Winter wheat was planted into no-till fallow at both sites, at a rate of 2 seeds dm^{-2} . We planted a semidwarf soft white winter wheat cultivar (WestBred 528) and a standard-height hard red cultivar (WestBred Arrowhead) because their traits capture the range of cultivars used in the area, thus maximizing the scope of inference of results from this study.

Five replicates of each treatment were planted each year, at each location, in the fall using a no-till plot drill. Plots (1.4 m wide and 15.2 m long) of each cultivar were fertilized with phosphorus (P) at either 0, 5, or 15 kg ha^{-1} . Phosphorus fertilizer was applied in the form of "triple" or "concentrated" super phosphate (0-45-0). Phosphorus was applied in-furrow (with the seed) during planting. Nitrogen application rates were determined from recommendations in the Oregon State University fertilizer guide for winter wheat produced in the low-precipitation zone (Lutcher et al. 2006). Nitrogen fertilizer was applied below and beside the seed during planting. Soil test values for sulfur, potassium, and micronutrients (from soil samples collected and analyzed 2 weeks before planting) were more than adequate for the expected (and harvested) yield of both classes of wheat.

Plots were inoculated with *F. pseudograminearum* in the form of infected millet seed. Infected millet inoculum was prepared by growing two individual *F. pseudograminearum* isolates on quarter-strength potato dextrose agar. Colonized agar blocks were then transferred into twice-autoclaved millet seed in autoclavable spawn bags with a 0.2- μm filter patch. Both *F. pseudograminearum* isolates were obtained from collections described by Poole et al. (2013); both isolates were tested for virulence on winter wheat in a glasshouse study in the winter of 2019 to ensure pathogenicity (D. R. Kroese, unpublished data). Inoculum was applied in-furrow (with the seed) with millet at a rate of 50 kg/ha at seeding using a bulk tank on the drill.

Early-season dry matter was collected from each plot in April. Plant samples were obtained from 30 cm of row and at three randomly selected locations at the onset of the "jointing" stage of growth. Plants were pulled, by hand, from loose friable soil that had been direct seeded for many years. Roots were separated from aboveground tissue using heavy-duty, industrial-grade scissors. Roots were discarded. Aboveground tissue was placed in paper sampling bags and transported to a nearby oven-drying facility at Oregon State University's Research Station near Adams, OR. Plants were dried at 60°C for several days; after complete desiccation, early-season dry matter samples were weighed, and the mass of samples was recorded in order to calculate phosphorus uptake. Tissue phosphorus concentration of the subsamples was determined according to protocol B-4.20 from Gavlak et al. (2003) at BestTest Analytical commercial lab in Moses Lake, WA.

Plots were harvested using a small plot combine outfitted with a 1.5-m cutting platform. Chaff was removed from grain (from each plot) using a customized, clipper-type seed cleaner. The mass of harvested grain was used to calculate yield after adjustment to 10% moisture. The 10% adjustment was used because it

is the best approximation of grain moisture contents encountered by regional farmers and elevator operators. Grain test weight and protein content were determined from subsamples analyzed using a Perten Infratec 9200 NIR spectrophotometer (Perten, Waltham, MA, U.S.A.).

FCR ratings

FCR ratings were conducted visually from postharvest stubble and roots. This evaluation was a quantitative assessment (Fig. 1) of the number of plants affected by typical symptomology—symptoms confined mostly to tissue below the second above-ground node. A shovel was used to remove stubble and roots from soil at one randomly selected location in each plot. Sample size for FCR ratings was influenced by location-dependent plant density (stand uniformity) and varied from 7 to 16 plants/plot.

Statistical analysis

Statistix 10 and R programs were used to interpret independent and normally distributed data. The assumption of homogeneity of variance was verified using Bartlett's test. An overall analysis of variance (ANOVA) for each response measurement used a linear mixed-effects model to evaluate the fixed treatment of interest (P rate) and random effects accounting for the experimental setup: trial, variety(trial), and P rate $\times$ trial, where trial is defined to be site-year. Overall treatment responses over

FIGURE 1
Example of Fusarium crown rot incidence rating protocol with plants collected and washed; five plants grouped on the left were asymptomatic and five plants grouped on the right were Fusarium crown rot symptomatic.

site-years were of interest, not results from each site-year. Power calculations for ANOVA *F* tests in mixed-effects models were performed via simulation using the *simr* package in R (Green and MacLeod 2016). Power calculations were performed for the purpose of verifying treatment differences given the number of replications and variance. Treatment means were compared using Tukey's honestly significant difference test ($\alpha = 0.05$) (LeBlanc 2004). A linear regression analysis was used to scrutinize the relationship between grain yield and early-season dry matter across both sites and years.

RESULTS AND DISCUSSION

In the overall model across sites and years, phosphorus rate was found to be significantly associated with tissue phosphorus concentration ($P < 0.0001$), early-season dry matter ($P = 0.0022$), and phosphorus uptake ($P = 0.0009$). There was suggestive evidence for an association between phosphorus rate and test weight ($P = 0.0564$). There was no evidence for association between phosphorus rate and FCR ratings ($P = 0.1908$), grain yield ($P = 0.2566$), or protein content ($P = 0.5794$). However, the power was relatively low for nonsignificant results (0.346 for FCR ratings, 0.380 for grain yield, 0.578 for test weight, and 0.155 for protein content), suggesting that further investigation may be warranted.

The phosphorus application rate of P at 15 kg ha⁻¹ increased tissue phosphorus concentration, as compared with lower rates (Table 1; Fig. 2). Tissue phosphorus concentrations observed in this study fall within the acceptable range for wheat, and soil test phosphorus was also in the acceptable range (Table 1; Fig. 2). Rates of P at 5 and 15 kg ha⁻¹ had a positive effect on early-season dry matter and phosphorus uptake (Table 1; Fig. 2). This outcome, which was unexpected because corresponding soil test phosphorus concentrations were relatively high (Table 2), may be a consequence of a localized frost that occurred early in the spring during the second year of the study (Gusta et al. 1999; Willemot 1975). Rate-induced increases in early-season dry matter were thought to be a potential problem, because production of greater-than-average biomass, in a moisture-limited environment, could reduce water-use efficiency and exacerbate colonization of plants by crown rot pathogens (Bockus et al. 2010). Data from this experiment, however, showed that phosphorus fertilization applied in-furrow at planting had no effect on postharvest crown rot ratings (Table 1).

Grain yield was unaffected by phosphorus application in this study (Table 1). Early-season dry matter accumulation and grain yield were positive and significantly correlated in this study ($R^2 = 0.12$) (Fig. 3). However, information about early-season dry matter, and its relationship to grain yield (Fig. 3), is an indication that the optimum phosphorus application rate may have been less than the maximum rate used in this experiment. The

TABLE 1

In-furrow phosphorus rate effects on tissue phosphorus concentration, early-season dry matter production, phosphorus uptake, Fusarium crown rot rating, grain yield, test weight, and grain protein in a dryland winter wheat trial conducted in Morrow County, OR²

Phosphorus rate (kg ha ⁻¹)	Tissue phosphorus concentration (mg g ⁻¹)	Early-season dry matter production (g m ⁻¹ row)	Phosphorus uptake (mg m ⁻¹ row)	Fusarium crown rot rating (incidence)	Grain yield (kg ha ⁻¹)	Test weight (kg hl ⁻¹)	Grain protein (g kg ⁻¹)
0	2.4 a	31.4 a	75.4 a	0.46 a	2,980 a	61.6 a	11.1 a
5	2.5 a	41.2 b	103.0 b	0.49 a	3,118 a	61.3 a	11.1 a
15	2.9 b	51.1 c	148.2 c	0.53 a	3,207 a	61.2 a	10.8 a

² Letters indicate results of a posthoc Tukey's honestly significant difference ($\alpha = 0.05$) test. Treatments with the same letter are not significantly different.

FIGURE 2 Boxplot matrix of study year (2017–18 and 2018–19) and study location (north site and south site) to visualize the relationship between in-furrow phosphorus rate (P at 0, 5, or 15 kg ha⁻¹) and response variables (tissue phosphorus concentration, early-season dry matter, and phosphorus uptake) of a dryland winter wheat field study conducted in Morrow County, OR.

TABLE 2

Preplant soil test phosphorus, soil pH (pH), and soil organic carbon by site and year in field sites in Morrow County, OR

Year	Soil depth (cm)	Soil test phosphorus (mg kg ⁻¹)		pH		Organic carbon (g kg ⁻¹)	
		North site	South site	North site	South site	North site	South site
2017–18	0–30	15	15	6.8	7.2	3.5	9.3
2018–19	0–30	25	17	7.2	6.0	5.2	6.9

FIGURE 3 Linear regression model with early-season dry matter as a predictor and grain yield of winter wheat as a response variable in an in-furrow phosphorus trial in Morrow County, OR. The gray boundary around the linear regression represents the 95% confidence band of the linear fit.

grain yield response may be attributed to differences in the concentration of zinc in soil or the plant's ability to acquire zinc from the rhizosphere. Interactions between phosphorus and zinc are well documented, with phosphorus increasing zinc availability (Barben et al. 2010; Hafeez et al. 2013; Zhu et al. 2001). Previous work shows that zinc-deficient plants are more easily colonized by the pathogen compared with plants with adequate zinc supply (Grewal et al. 1996; Sparrow and Graham 1988).

FCR increases the incidence of pinched grain (in prematurely ripe whiteheads) and reduces grain test weight (Smiley et al.

2005). Test weight data (Table 1) provide additional, indirect evidence that phosphorus application had no effect on the severity of disease. Phosphorus application had no effect on the protein content of grain (Table 1). Although phosphorus addition did increase plant biomass, phosphorus likely did not influence FCR because biomass was not beyond what soil moisture could support in the years in which this study was conducted.

CONCLUSIONS

Within the scope of inference of this study, results from the experiment described here provide direct and indirect evidence that phosphorus fertilizer application, at rates normally utilized in the low-precipitation zone of the inland PNW, does not affect postharvest, aboveground symptomology associated with FCR.

Effect of phosphorus supply on grain yield, and the wheat plant's tolerance to FCR, may be influenced by the soil test zinc level in soil. Additional work on the interactive effect of both nutrients is warranted and ongoing.

ACKNOWLEDGMENTS

We thank the wheat producers of Morrow County for hosting our on-farm trials and all Columbia Basin Agricultural Research Center personnel.

LITERATURE CITED

Barben, S. A., Hopkins, B. G., Jolley, V. D., Webb, B. L., and Nichols, B. A. 2010. Phosphorus and zinc interactions in chelator-buffered solution grown Russet Burbank potato. *J. Plant Nutr.* 33:587-601.

- Bockus, W. W., Bowden, R. L., Hunger, R. M., Morrill, W. L., Murray, T. D., and Smiley, R. W. 2010. Compendium of Wheat Diseases and Pests, 3rd Ed. American Phytopathological Society, St. Paul, MN, U.S.A.
- Chekali, S., Gargouri, S., Paulitz, T., Nicol, J. M., Rezgui, M., and Nasraoui, B. 2011. Effects of *Fusarium culmorum* and water stress on durum wheat in Tunisia. *Crop Prot.* 30:718-725.
- Datnoff, L. E., Elmer, W. H., and Huber, D. M., eds. 2007. Mineral Nutrition and Plant Disease. American Phytopathological Society, St. Paul, MN, U.S.A.
- Davis, R. A., Huggins, D. R., Cook, J. R., and Paulitz, T. C. 2009. Nitrogen and crop rotation effects on Fusarium crown rot in no-till spring wheat. *Can. J. Plant Pathol.* 31:456-467.
- Engelhard, A. W. 1989. Soilborne Plant Pathogens: Management of Diseases with Macro- and Microelements. American Phytopathological Society, St. Paul, MN, U.S.A.
- Föhse, D., Claassen, N., and Jungk, A. 1988. Phosphorus efficiency of plants. *Plant Soil* 110:101-109.
- Gavlak, R., Horneck, D., Miller, R. O., and Kotuby-Amacher, J. 2003. Soil, Plant and Water Reference Methods for the Western Region. WCC-103 Publication, Fort Collins, CO, U.S.A.
- Graebner, R. C., and Mundt, C. C. 2019. 2019 Oregon soft winter elite yield trials—Disease notes. https://agsci.oregonstate.edu/sites/agscid7/files/crop-soil/2019_disease_summary_oweyt.pdf
- Green, P., and MacLeod, C. J. 2016. Simr: An R package for power analysis of generalised linear mixed models by simulation. *Methods Ecol. Evol.* 7: 493-498.
- Grewal, H. S., Graham, R. D., and Rengel, Z. 1996. Genotypic variation in zinc efficiency and resistance to crown rot disease (*Fusarium graminearum* Schw. group 1) in wheat. *Plant Soil* 186:219-226.
- Gusta, L. V., O'Connor, B. J., and Lafond, G. L. 1999. Phosphorus and nitrogen effects on the freezing tolerance of Norstar winter wheat. *Can. J. Plant Pathol.* 79:191-195.
- Hafeez, B., Khanif, Y. M., and Saleem, M. 2013. Role of zinc in plant nutrition-a review. *J. Exp. Agric. Int.* 3:374-391.
- Hagerty, C. H., Fickas, K. C., and Wysocki, D. 2019. Agronomic Zones of the Dryland Pacific Northwest. PNW 354. PNW Extension Press, Corvallis, OR, U.S.A.
- Hagerty, C. H., and Kroese, D. R. 2021. Winter wheat seed treatments challenged by Fusarium crown rot inoculation, 2018/19 in Oregon, USA. *Plant Dis. Manage. Rep.* 15:CF161.
- LeBlanc, D. C. 2004. Tukey's honestly significant difference test. Pages 261-262 in: *Statistics: Concepts and Applications for Science*. Jones Bartlett, Sudbury, MA, U.S.A.
- Liao, M., Hocking, P. J., Dong, B., Delhaize, E., Richardson, A. E., and Ryan, P. R. 2008. Variation in early phosphorus-uptake efficiency among wheat genotypes grown on two contrasting Australian soils. *Aust. J. Agric. Res.* 59:157-166.
- Lutcher, L. K., Horneck, D. A., Wysocki, D. J., Hart, J. M., Petrie, S. E., and Christensen, N. W. 2006. Winter Wheat in Summer-Fallow Systems (Low Precipitation Zone). Oregon State University Extension Service, Corvallis, OR, U.S.A.
- Moya-Elizondo, E. A., and Jacobsen, B. J. 2016. Integrated management of Fusarium crown rot of wheat using fungicide seed treatment, cultivar resistance, and induction of systemic acquired resistance (SAR). *BioControl* 92:153-163.
- Pariyar, S. R., Erginbas-Orakci, G., Dadshani, S., Chijioke, O. B., Léon, J., Dababat, A. A., and Grundler, F. M. 2020. Dissecting the genetic complexity of Fusarium crown rot resistance in wheat. *Sci. Rep.* 10:3200.
- Poole, G. J., Smiley, R. W., Walker, C., Huggins, D., Rupp, R., Abatzoglou, J., Garland-Campbell, K., and Paulitz, T. C. 2013. Effect of climate on the distribution of *Fusarium* spp. causing crown rot of wheat in the Pacific Northwest of the United States. *Phytopathology* 103:1130-1140.
- Römer, W., Augstin, J., and Schilling, G. 1988. The relationship between phosphate absorption and root length in nine wheat cultivars. *Plant Soil* 111:199-201.
- Schillinger, W. F., and Young, D. L. 2004. Cropping systems research in the world's driest rainfed wheat region. *Agric. J.* 96:1182-1187.
- Smiley, R., Whittaker, R., Gourlie, J., Easley, S., Rhinhart, K., Jacobsen, E., Peterson, J., Kidwell, K., and Campbell, K. 2003. Genetic tolerance to Fusarium crown rot of wheat. Pages 40-52 in: 2003 Columbia Basin Agriculture Research Center Annual Report. Agricultural Experiment Station, Oregon State University, Corvallis, OR, U.S.A.
- Smiley, R. W., Gourlie, J. A., Easley, S. A., Patterson, L.-M., and Whittaker, R. G. 2005. Crop Damage Estimates for Crown Rot of Wheat and Barley in the Pacific Northwest. *Plant Dis.* 89:595-604.
- Sparrow, D. H., and Graham, R. D. 1988. Susceptibility of zinc-deficient wheat plants to colonization by *Fusarium graminearum* Schw. Group 1. *Plant Soil* 112:261-266.
- USDA-NASS. 2017. QuickStats Wheat Value 2017. United States Department of Agriculture—National Agriculture Statistics Service. <https://quickstats.nass.usda.gov/results/B05C556C-D51C-3450-8A40-2C2D6FEC7723>
- Willemot, C. 1975. Stimulation of phospholipid biosynthesis during frost hardening of winter wheat. *Plant Physiol.* 55:356-359.
- Yin, C., McLaughlin, K., Paulitz, T. C., Kroese, D. R., and Hagerty, C. 2020. Population dynamics of wheat root pathogens under different tillage systems in NE Oregon. *Plant Dis.* 104:2649-2657.
- Zhu, Y.-G., Smith, S. E., and Smith, F. A. 2001. Zinc (Zn)-phosphorus (P) interactions in two cultivars of spring wheat (*Triticum aestivum* L.) differing in P uptake efficiency. *Ann. Bot.* 88:941-945.