Yield Loss in Cereals, Caused by *Fusarium culmorum* and *F. pseudograminearum*, Is Related to Fungal DNA in Soil Prior to Planting, Rainfall, and Cereal Type

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Abstract

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In southeastern Australia, *Fusarium* crown rot, caused by *Fusarium culmorum* or *F. pseudograminearum*, is an increasingly important disease of cereals. Because in-crop control options are limited, it is important for growers to know prior to planting which fields are at risk of yield loss from crown rot. Understanding the relationships between crown rot inoculum and yield loss would assist in assessing the risk of yield loss from crown rot in fields prior to planting. Thirty-five data sets from crown rot management experiments conducted in the states of South Australia and Victoria during the years 2005 to 2010 were examined. Relationships between *Fusarium* spp. DNA concentrations (inoculum) in soil samples taken prior to planting and disease development and grain yield were evaluated in seasons with contrasting seasonal rainfall. *F. culmorum* and *F. pseudograminearum* DNA concentrations in soil prior to planting were found to be positively related to

crown rot expression (stem browning and whiteheads) and negatively related to grain yield of durum wheat, bread wheat, and barley. Losses from crown rot were greatest when rainfall during September and October (crop maturation) was below the long-term average. Losses from crown rot were greater in durum wheat than bread wheat and least in barley. Yield losses from *F. pseudograminearum* were similar to yield losses from *F. culmorum*. Yield loss patterns were consistent across experiments and between states; therefore, it is reasonable to expect that similar relationships will occur over broad geographic areas. This suggests that quantitative polymerase chain reaction technology and soil sampling could be powerful tools for assessing crown rot inoculum concentrations prior to planting and predicting the risk of yield loss from crown rot wherever this disease is an issue.

Fusarium crown rot (FCR), caused predominantly by *Fusarium pseudograminearum* or *F. culmorum*, is a disease of small grain cereals, including bread wheat (*Triticum aestivum*), durum wheat (*T. turgidum*), barley (*Hordeum vulgare*), and oat (*Avena sativa*) (2,4). FCR is an important disease in the eastern Australian grain belt (2,6,10,14), North America (17,24,26), Italy (22), and South Africa (16), among other locations (4).

Annual grain yield losses due to FCR in bread wheat have been estimated to be 2 to 3% in southeastern Australia and 5% in northern Australia, with occasional damage as high as 20 and 89%, respectively, reported in these two regions (10,15,18). In the Pacific Northwest of the United States, Smiley et al. (23) reported average grain yield losses of 10%, with losses as high as 35% observed.

Symptoms of FCR in cereals include brown discoloration of the lower stems (stem browning) and the formation of whiteheads in durum and bread wheat (27). Whitehead incidence and yield loss associated with FCR is exacerbated by moisture stress during grain fill (4,7,10,15,20,23). Hollaway and Exell (10) observed that low September and October rainfall influenced severity of whitehead expression due to FCR in southeastern Australia.

All winter grown cereals, and many grassy weeds, host the FCR pathogens and support inoculum carry over from one season to the next on infested residues (4). Non-grass crops, such as oilseeds and pulses, are regarded as poor hosts (8,9,12,16). The widespread adoption of conservation farming practices—in particular, stubble retention—during the last 20 years has been implicated in the increased prevalence of this disease (4,10).

Managing FCR in-crop is difficult because, currently, there are neither chemical control options nor commercial cereal cultivars with adequate genetic resistance to FCR (4). Therefore, preplanting identification of fields at risk from FCR is critical for reducing short- and long-term yield losses from this disease. Backhouse (1) described a visual method based on disease incidence in and yield of a current cereal which can be used to predict the risk of grain yield loss from FCR in a following cereal crop. However, this method is less useful after a break from cereal because the magnitude of decrease in inoculum due to the break cannot be assessed.

Australian grain growers have access to the PreDicta B testing service which uses quantitative real-time polymerase chain reaction (qPCR) technology to determine DNA concentrations of a range of soilborne pathogens, including *F. culmorum* and *F. pseudograminearum*, prior to planting (19). This technology is used by growers to assess the risk of yield loss from soilborne diseases and is well suited to examining relationships between preplanting *Fusarium* spp. DNA concentrations, disease expression, and yield in cereals.

The objective of this study was to assess relationships between preplanting inoculum of *F. pseudograminearum* and *F. culmorum* and yield loss from FCR in bread wheat, durum wheat, and barley in southeastern Australia. This was done using qPCR to measure fungal inoculum DNA concentrations preplanting, followed by in-crop assessment of FCR expression (browning of stem bases and whitehead formation) and cereal yield in seasons with contrasting rainfall in the states of South Australia and Victoria.

Materials and Methods

Thirty-five data sets, obtained from 13 field experiments in nine site-year combinations, were considered in this study (Table 1). Several of the experiments were designed to compare a range of preplanting FCR soilborne inoculum concentrations with grain yield of cereals. Other experiments were established to study aspects of crop sequencing, inter-row planting, and stubble treatments in relation to the management of FCR. The latter experi-

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ments had treatments that enabled comparisons between inoculum concentrations prior to planting and subsequent disease development and grain yield. In all cases, data were only taken from plots with similar histories (other than inoculum concentration) to ensure that comparisons were not confounded by variation in soil water or nutrient levels.

Experimental sites. Experiments were located in the southeastern Australian states of Victoria, at Longerenong (36°40'S, 142°17'E; gray cracking soil) and South Australia, at Cambrai (34°38'S, 139°18'E; sandy loam soil) and Hart (33°46'S, 138°26'E; friable light clay loam over carbonate). In these areas, cereal crops are sown following rain in the period April to June (autumn) and harvested November to December (late spring and early summer).

Sites were selected (using soil sampling and qPCR assays in a manner similar to that described in the next section) to have low or nondetectable concentrations of important soilborne diseases of cereals such as FCR, take-all (*Gaeumannomyces graminis* var. *tritici*), Rhizoctonia root rot (*Rhizoctonia solani*), and cereal cyst nematode (*Heterodera avenae*).

FCR inoculum was introduced to the sites by planting cereal seed inoculated with a macroconidia suspension (10^5 spores/ml) of either *F. pseudograminearum* or *F. culmorum* at a rate of 50 ml per 1 kg of seed (8). The introduction of inoculum to the site occurred from 1 to 5 years prior to the year of study (Table 1).

Treatments imposed to manipulate inoculum densities, the histories, and cereal types for each field experiment are shown in Table 1. Experimental plot sizes were as follows: Longerenong, 8.5 m long by 6 rows wide; Cambrai, 24 m by 6 rows in 2005 and 12 m by 6 rows in 2007; Hart, 14 m by 6 rows. Row spacing was 170 mm at Longerenong, 180 mm at Cambrai, and 250 mm at Hart. Field experiments were direct seeded and managed according to local practice, including the appropriate use of herbicides to control weeds (no residual herbicides were used). All experiments were laid out in randomized blocks replicated six times, except for Hart in 2008 (H5-2008), which had four replicates.

Assessment of preplanting inoculum concentrations. The concentration of DNA of *Fusarium* spp. present in each plot (expressed as picograms of fungal DNA per gram of dry soil) was assessed prior to or at planting. Soil, including plant residues, was sampled using an Accucore sampler (Spurr Soil Probes) to a depth of 100 mm with a diameter of either 10 mm (Longerenong and Hart) or 15 mm (Cambrai). In all, 40 cores were taken from arbitrary points in each plot at Longerenong and Cambrai and 24 per plot at Hart. Within each plot, the samples were taken from the

previous cereal row and included any plant residues that were retained with the sample. Soil from all cores in a plot was combined prior to analysis.

Soil samples were submitted to the Root Disease Testing Service at the South Australian Research and Development Institute (Adelaide) to assay for concentrations of DNA of *F. pseudograminearum* and *F. culmorum*. qPCR assays based on ribosomal DNA (TaqMan) probe sequences specific to *F. pseudograminearum* and *F. culmorum* were applied to the total DNA extracted from the whole oven-dried sample which, in general, weighed approximately 300 to 500 g before processing (18). Results were converted, using quantitative DNA standards, to picograms of *F. pseudograminearum* or *F. culmorum* DNA per gram of dry soil.

Disease assessments. The incidence of stems with stem browning was assessed at plant maturity, except for Cambrai 2005 and Hart in all years, where assessment was at early grain fill. At Longerenong, 30 arbitrarily selected stems were taken from each plot whereas, at Cambrai, 40 and 25 stems were arbitrarily selected in 2005 and 2007, respectively, for assessment. At Hart, stems were sampled from four 0.5-m and four 0.25-m row lengths in 2006 and 2008, respectively. Leaf sheaths were peeled back from each tiller or main stem and the basal node was inspected for the presence or absence of browning symptoms (27). Results were expressed as the percentage of stems with stem browning symptoms per plot.

The incidence of whiteheads was assessed in bread and durum wheat between anthesis (Z60) and maturity (Z91) (6,14,28). Within each plot at Longerenong, three 1-m row lengths of heads were inspected. At Cambrai and Hart, heads were inspected on the plants collected for assessment of the incidence of stem browning as described above. Results were expressed as the percentage of whiteheads per plot.

Grain yield. At plant maturity, using a plot harvester, grain weight was recorded from each plot. Weights were converted to metric tons per hectare prior to analysis.

Rainfall data. Rainfall data for the previous 123 years for Longerenong, Hart (records at Blyth, approximately 10 km away), and Cambrai were obtained from SILO (www.longpaddock.qld.gov.au/silo/), a digest of historic climate data (11). The combined September and October rainfall for each field experiment in the year of study is presented as a percentage of the average long-term combined September and October rainfall for the site.

Statistical analysis. Data sets were excluded from analysis if the site mean yield was less than 0.4 t/ha (i.e., severely drought-

Table 1. Details of Victorian and South Australian field experiments used to assess the relationships of preplanting soil concentrations of DNA of *Fusarium pseudograminearum* (*Fp*) and *F. culmorum* (*Fc*) on crown rot symptom expression and yield of barley, bread wheat, and durum wheat

This study ^a						
Experiment, year	Species	Year	Barley	Bread wheat	Durum wheat	History and methods of establishing <i>Fusarium</i> spp. levels
Cambrai, South Australia						
C1-2005	<i>Fp</i>	2005	–	–	X	2004 canola; 2003 range of crops; 2002 inoculated durum wheat
C2-2007	<i>Fp</i>	2007	–	–	(X)	2006 vetch; 2005 cereal types; 2004–2002 as for experiment C1-2005
Hart, South Australia						
H3-2006	<i>Fp</i>	2006	(X)	X	(X)	2005 ± inoculated durum wheat
H4-2008	<i>Fp</i>	2008	–	–	X	2007 field pea; 2006 cereals; 2005 ± inoculated durum wheat
H5-2008	<i>Fp</i>	2008	–	–	X	2007 field pea; 2006 cereals; 2005 ± inoculated durum wheat
H6-2009	<i>Fp</i>	2009	X	X	X	2008 durum; 2007 field pea; 2006 cereals; 2005 ± inoculated durum wheat
Longerenong, Victoria						
L4-2007	<i>Fc</i>	2007	–	X	X	2006 field pea; 2005 ± inoculated durum wheat
L5-2007	<i>Fp, Fc</i>	2007	–	X	X	2006 field pea; 2005 ± inoculated durum wheat
L7-2009	<i>Fp, Fc</i>	2009	–	X	X	2008 field pea; 2007 ± inoculated durum wheat
L8-2009	<i>Fp, Fc</i>	2009	–	(X)	X	2008 field pea; 2007 ± inoculated durum wheat
L9-2008	<i>Fp, Fc^b</i>	2008	X	X	–	2007 durum wheat sown with 0–100% seed infection
L10-2009	<i>Fp, Fc</i>	2009	X	X	–	2008 durum wheat sown with 0–100% seed infection
L11-2010	<i>Fp</i>	2010	(X)	X	(X)	2009 durum wheat sown with 0–100% seed infection

^a Symbols: – = not present in this experiment, X = data set included in this study, and (X) = data sets excluded from further analysis because preplanting difference of fungal DNA was <50 pg/g of soil between lower and upper quartiles or average site yield was <0.4 t/ha.

^b Data sets for *F. culmorum* at this site excluded for the reasons given above.

affected site) or the difference from the lower to the upper quartile of the preplanting concentrations of *Fusarium* spp. was DNA at less than 50 pg/g soil. The latter ensured that the range in concentrations of DNA of *Fusarium* spp. was large enough for disease incidence and yield loss relationships to be explored.

Fusarium spp. DNA concentrations were $\ln(x + \text{half the smallest non-zero value})$ transformed, the incidence of stem browning (percent) and whiteheads (percent) were arcsine transformed ($\arcsine\sqrt{(\%/100)}$), and grain yields were square-root transformed to normalize data prior to analysis. Associations between preplanting inoculum concentrations and stem browning, whiteheads, and grain yield were then investigated using linear correlation (Pearson's correlation coefficient) in GenStat (14th edition). One-tailed *t* values were used because it was reasonable to presume that relationships between preplanting inoculum concentrations and stem browning and whiteheads would be positive whereas relationships with grain yield would be negative. No significant relationships appeared to dispute this assumption.

DNA concentrations prior to sowing were compared with relative mean yield (%), where relative mean yield (%) = [(plot yield [t/ha]/average site yield [t/ha]) × 100]. After establishing that these relationships were linear using scatter plots, simple linear regressions in GenStat v14 were used to determine the slopes of these relationships. Significant differences between the slopes were tested for using the *t* test formula $(\beta_1 - \beta_2)/\sqrt{[(\text{s.e. } \beta_1)^2 + (\text{s.e. } \beta_2)^2]}$, where β is the slope of the line and s.e. β is its standard error. Comparisons of slopes between cereal types were only made where the cereal types were present within the same site-season experiment. For regressions and slope comparisons, one-tailed *t* values were used, where appropriate. Yield loss estimates associated with doubling of inoculum concentrations were calculated as

yield loss (%) = 0.301 × the slope of the relationship between preplanting DNA and relative mean yield (%).

Results

Rainfall. Combined September and October (Sep+Oct) rainfall in all site-season combinations (Table 2) was either between 12 and 34% of the long-term average (considerably below average) or between 113 and 200% of the long-term average (above average). Sep+Oct rainfall at Longerenong and Hart was below average in the seasons 2006 to 2008 and above average in the seasons 2009 and 2010. Sep+Oct rainfall at Cambrai was above average in 2008.

***F. culmorum*.** Nine data sets were available for analysis, one for barley and four each for durum wheat and bread wheat (Table 1). Within each of these data sets, preplanting inoculum concentrations in the upper quartile were between three- and sixfold greater than the lower quartile concentrations (Table 2). Three data sets were excluded from further analysis due to insufficient range in the preplanting inoculum concentrations (*data not shown*).

All significant associations between preplanting inoculum concentrations and grain yield were negative and all occurred in seasons with below-average Sep+Oct rainfall (Table 2). All significant associations between preplanting inoculum concentrations and disease expression, as indicated by stem browning and whiteheads, were positive (Table 2). Significant associations for stem browning occurred only in seasons with below-average Sep+Oct rainfall; however, significant associations for whiteheads occurred in seasons with both above- and below-average Sep+Oct rainfall (Table 2). Significant associations between preplanting inoculum concentration and disease expression and significant associations between preplanting inoculum concentration and grain yield were not al-

Table 2. Effects of preplanting soil concentrations of DNA of *Fusarium culmorum* and *F. pseudograminearum* and rainfall on expression of crown rot symptoms (stem browning and whiteheads) and grain yield of barley, durum wheat, and bread wheat in Victoria and South Australia, 2005–2010

Crop	Experiment ^b	DNA (pg/g of soil) ^c	N ^d	Pearson's correlation coefficients ^a			Rainfall (%) ^e	Site mean yield (t/ha)
				Stem browning (arcsine %)	Whiteheads (arcsine %)	Yield (√t/ha)		
<i>F. culmorum</i>								
Barley	L10-2009	5–329	30	–	–	0.11	113	3.21
Durum wheat	L5- 2007	24–328	12	0.74**	0.48§	–0.84***	31	0.77
Durum wheat	L4-2007	52–418	12	0.33	–0.30	–0.88***	31	0.94
Durum wheat	L8-2009	2–69	12	–0.03	–0.14	–0.23	113	2.26
Durum wheat	L7-2009	14–205	12	–	0.55*	–0.23	113	2.59
Bread wheat	L5-2007	8–416	12	0.46§	–0.04	–0.54*	31	1.14
Bread wheat	L4-2007	44–397	12	0.53*	–0.21	–0.82***	31	1.27
Bread wheat	L10-2009	13–282	30	–	0.39*	0.20	113	1.79
Bread wheat	L7-2009	2–66	12	–	0.12	–0.14	113	2.59
<i>F. pseudograminearum</i>								
Barley	L9-2008	1–65	30	0.53**	–	–0.37**	34	1.49
Barley	L10-2009	16–502	30	0.56***	–	0.04	113	3.21
Barley	H6-2009	52–2674	24	–0.09	–	–0.20	130	3.28
Durum wheat	H5-2008	49–176	28	–	–	–0.53**	14	1.37
Durum wheat	H4-2008	28–91	72	0.68***	0.61***	–0.54***	14	1.76
Durum wheat	L5-2007	6–419	11	0.84**	0.22	–0.87***	31	0.69
Durum wheat	L8-2009	3–125	12	0.49§	–0.03	–0.24	113	2.29
Durum wheat	L7-2009	18–476	12	–	0.21	–0.40§	113	2.62
Durum wheat	H6-2009	37–1662	24	0.16	–0.20	–0.44*	130	2.96
Durum wheat	C1-2005	69–381	72	–	0.61***	–0.43***	200	2.94
Bread wheat	H3-2006	9–314	24	0.04	0.10	–0.34§	12	0.41
Bread wheat	L5-2007	23–439	10	0.76**	0.24	–0.94***	31	1.04
Bread wheat	L9-2008	1–129	30	0.67***	0.74***	–0.60***	34	0.64
Bread wheat	L10-2009	10–295	30	0.62***	0.16	–0.13	113	1.64
Bread wheat	L7-2009	11–394	12	–	0.28	0.16	113	2.61
Bread wheat	L11-2010	2–53	36	0.51***	0.34*	–0.15	114	3.71
Bread wheat	H6-2009	89–1630	24	–0.05	0.07	0.05	130	2.94

^a Correlation coefficients (one-tailed) for relationships with preplanting levels of fungal DNA [$\ln(\text{pg/g soil} + \text{half the smallest non-zero value})$]; §, *, **, and *** indicate *P* < 0.1, 0.05, 0.01, and 0.001, respectively; – indicates data not available.

^b Experiment-year. First letter of experiment designation is the site location: C = Cambrai (South Australia), H = Hart (South Australia), and L = Longerenong (Victoria).

^c Lower and upper quartile of preplanting *Fusarium* spp. DNA.

^d Number of field plots within study.

^e Combined September and October rainfall for the experiment presented as a percentage of the long-term September and October rainfall for the site.

ways all present in the same experiments (c.f., durum wheat L4-2007 and bread wheat L10-2009; Table 2).

Grain yield decreased by 9 to 13% in durum wheat and 2 to 8% in bread wheat for each doubling of preplanting inoculum concentration in experiments with below-average Sep+Oct rainfall (Table 3). Comparison of slopes indicated that, for a given concentration of *F. culmorum*, the yield losses were greater for durum wheat than for bread wheat (*t* was significant at $P = 0.004$ in L5-2007 and $P = 0.084$ in L4-2007). For these experiments, the preplanting inoculum concentrations explained more of the variation in relative mean yield for durum wheat (67 to 79%) than for bread wheat (23 to 62%) (Table 3). For experiments with above-average Sep+Oct rainfall, yield losses were very low (around 1%) across all cereal types, and preplanting inoculum concentrations explained none of the variation in relative mean yield (Table 3).

***F. pseudograminearum*.** Seventeen data sets were available for analysis: three data sets for barley and seven each for durum and bread wheat (Table 1). Within each of these data sets, preplanting inoculum concentrations in the upper quartile were twofold and up to sixfold greater than the lower quartile concentrations (Table 2). Three data sets were excluded from further analysis due to insufficient range in preplanting inoculum concentrations, and a further three data sets were excluded due to low site mean yield (*data not shown*).

All significant associations between preplanting inoculum concentrations and grain yield were negative. For barley and bread wheat, significant associations only occurred in seasons with below-average Sep+Oct rainfall (Table 2). For durum wheat, significant negative associations also occurred in all seasons with below-average and most seasons with above-average Sep+Oct rainfall

(Table 2). All significant associations between preplanting inoculum concentrations and disease incidence, as indicated by stem browning and whiteheads, were positive (Table 2). Significant associations between preplanting inoculum and disease expression and significant associations between preplanting inoculum and grain yield were not always present in the same experiments (c.f., bread wheat L11-2010 and L5-2007 and durum wheat H6-2009; Table 2).

Grain yield decreased by 6 to 8% in durum wheat, 2 to 9% in bread wheat, and 1% in barley for each doubling of preplanting inoculum concentration in experiments with below-average Sep+Oct rainfall (Table 3). Where Sep+Oct rainfall was below average, grain yield loss caused by a given concentration of *F. pseudograminearum* was similar in durum wheat and bread wheat (*t* was significant at $P = 0.068$ in L5-2007) and was greater in bread wheat than barley (*t* was significant at $P = 0.01$ in L9-2008). For durum wheat, yield loss caused by a given concentration of *F. pseudograminearum* was greater in seasons with below-average Sep+Oct rainfall than in seasons with above-average Sep+Oct rainfall (*t* was significant at $P < 0.05$). Grain yield decreased minimally (0 to 3%) in all cereal types for each doubling of preplanting inoculum concentration in experiments with above-average Sep+Oct rainfall (Table 3).

For experiments with below-average Sep+Oct rainfall, preplanting inoculum concentrations explained more of the variation in relative mean yield for bread wheat (33 to 85%) and durum wheat (23 to 74%) than for barley (10%) (Table 3). For experiments with above-average Sep+Oct rainfall, little of the variation in relative mean yield was explained by preplanting inoculum for durum wheat (up to 17%) and none of the variation in relative mean yield was explained for bread wheat or barley (Table 3).

Table 3. Effects of preplanting soil concentrations of DNA of *Fusarium culmorum* and *F. pseudograminearum* and rainfall on the magnitude of rates of change in relative mean yield and the implications for comparative yield losses in barley, durum wheat, and bread wheat in Victoria and South Australia

Crop	Experiment ^b	Relationship of <i>Fusarium</i> spp. DNA with relative mean yield ^a					Loss (%) ^e	Rainfall (%) ^f	Yield (t/ha) ^g
		Slope	s.e. Slope ^c	<i>t</i> Value	df	Variance (%) ^d			
<i>F. culmorum</i>									
Barley	L10-2009	0.94	1.65	0.57	28	0	0	113	3.21
Durum wheat	L5-2007	-24.8***	3.94	-6.2	9	79	9	31	0.77
Durum wheat	L4-2007	-44.3***	9.92	-4.78	10	67	13	31	0.94
Durum wheat	L8-2009	-2.12	2.94	-0.72	10	0	1	113	2.26
Durum wheat	L7-2009	-2.8	3.96	-0.71	10	0	1	113	2.59
Bread wheat	L5-2007	-6.5*	3.13	-2.09	10	23	2	31	1.14
Bread wheat	L4-2007	-26.9***	6.23	-4.32	10	62	8	31	1.27
Bread wheat	L10-2009	2.81	2.73	1.03	28	0	0	113	1.79
Bread wheat	L7-2009	-1.87	4.21	-0.44	10	0	1	113	2.59
<i>F. pseudograminearum</i>									
Barley	L9-2008	-3.2*	1.57	-2.09	28	10	1	34	1.49
Barley	L10-2009	0.28	1.23	0.22	28	0	0	113	3.21
Barley	H6-2009	-1.21	1.22	-0.99	22	0	0	130	3.28
Durum wheat	H5-2008	-24.1**	7.95	-3.03	26	23	7	14	1.37
Durum wheat	H4-2008	-26.4***	4.94	-5.36	70	28	8	14	1.76
Durum wheat	L5-2007	-19.83***	3.65	-5.43	9	74	6	31	0.69
Durum wheat	L8-2009	-1.96	2.5	-0.79	10	0	1	113	2.29
Durum wheat	L7-2009	-3.82	2.81	-1.36	10	7	1	113	2.62
Durum wheat	H6-2009	-4.25*	1.88	-2.26	22	15	1	130	2.96
Durum wheat	C1-2005	-9.5***	2.41	-3.96	69	17	3	200	2.94
Bread wheat	H3-2006	-5.85*	3.69	-1.58	22	6	2	12	0.41
Bread wheat	L5-2007	-28.7***	3.90	-7.36	10	85	9	31	1.04
Bread wheat	L9-2008	-10.7***	2.71	-3.95	28	33	3	34	0.64
Bread wheat	L10-2009	-2.09	2.75	-0.76	28	0	1	113	1.64
Bread wheat	L7-2009	1.55	3.29	0.47	10	0	0	113	2.61
Bread wheat	L11-2010	-2.68	3.27	-0.82	34	0	1	114	3.71
Bread wheat	H6-2009	0.4	1.57	0.28	22	0	0	130	2.94

^a Relative mean yield (%) = (plot mean yield/average yield for the site) × 100. Before regression analysis, data were examined to ensure the relationships were linear. *, **, and *** indicate *P* values < 0.1, 0.05, 0.01, and 0.001, respectively, for a one-tailed test.

^b Experiment-year. First letter of experiment designation is the site location: C = Cambrai (South Australia), H = Hart (South Australia), and L = Longerenong (Victoria).

^c Standard error (s.e.) slope.

^d Variance accounted for.

^e Yield loss if soil DNA doubles.

^f Combined September and October rainfall for the experiment presented as a percentage of the long-term September and October rainfall for the site.

^g Experiment-year mean yield.

***F. culmorum* versus *F. pseudograminearum*.** Associations between preplanting inoculum concentrations and relative mean yield for the two *Fusarium* spp. could be compared in seven of the data sets (Table 3). For six comparisons (barley, L10-2009; durum wheat, L5-2007, L7-2009, and L8-2009; and bread wheat, L7-2009 and L10-2010) the slopes of the relationships were the same for both *Fusarium* spp. (t ns). Of these six comparisons, four data sets had above-average Sep+Oct rainfall, which may have masked differences between the *Fusarium* spp. For bread wheat in experiment L5-2007 (below-average Sep+Oct rainfall), the slope of the relationship was greater for *F. pseudograminearum* than for *F. culmorum* (t was significant at $P < 0.01$), indicating greater losses from *F. pseudograminearum* than from *F. culmorum*.

Discussion

F. pseudograminearum and *F. culmorum* inoculum concentrations in soil prior to sowing, as measured by qPCR, were found to be positively related to FCR expression (stem browning and white-heads) and negatively related to grain yield of durum wheat, bread wheat, and barley. Significant negative relationships between presowing inoculum concentrations and grain yield in bread wheat and barley were observed only in seasons where rainfall received during grain fill (Sep+Oct) was below the long-term average but not in those seasons where it was above average. For durum wheat, significant negative relationships with yield were observed in seasons when Sep+Oct rainfall was both above and below average but yield losses were less where Sep+Oct rainfall was above average. This is the first report in the literature which demonstrates relationships between *Fusarium* spp. DNA concentrations and yield for a range of cereal types.

The observation of greater losses from FCR in seasons with limited rainfall compared with seasons with above-average rainfall during grain fill was clear in this study and consistent with previous studies (4,10,23,24). Using the data available; it was not possible to determine whether yield losses caused by different presowing concentrations of *Fusarium* spp. inoculum tapers as Sep+Oct rainfall increases or whether there is a sharp cut-off point at which yield loss no longer occurs. Further data sets are required from a wider range of seasons to better define and understand this relationship.

Regression analysis showed that preplanting inoculum concentrations of *Fusarium* spp. explained much of the variation in the yield of durum and bread wheat in seasons conducive to crown rot development. This supports the use of a presowing DNA-based soil test as a method for identifying FCR risk in a field prior to sowing. During seasons conducive to FCR, each doubling in presowing *Fusarium* spp. inoculum concentration reduced the yield of bread wheat, durum wheat, and barley by 2 to 9%, 6 to 13%, and 1% respectively. Within these studies, the low and high preplanting quartiles of fungal DNA generally was 23 to 474 pg/g of soil, representing a fourfold increase, which is consistent with observations from fields in southeastern Australia. This fourfold increase in preplanting inoculum concentrations corresponded to yield losses of 8 to 36% in bread wheat and 24 to 52% in durum wheat in seasons conducive to FCR within these studies. Other studies have reported similar yield loss from FCR (10,15,18,23,25).

These studies showed that durum wheat was more sensitive to yield loss from FCR than bread wheat. Klein et al. (13) also noted the sensitivity of durum wheat to yield loss from FCR. Barley is widely considered less sensitive to FCR than bread wheat, based on general observation rather than on comparative yield data. This study showed barley to be less affected by FCR than bread wheat and suggests that it is probable that barley, under most circumstances, exhibits such small yield losses from FCR that any economic loss would be negligible.

No comparisons of the relative yield losses caused by *F. pseudograminearum* and *F. culmorum* have been reported in the literature. The limited data collected during this study suggest that similar yield losses were caused by both *Fusarium* spp. However, in one case, *F. pseudograminearum* caused higher yield loss than *F.*

culmorum, and the reason for this difference was not clear. Although it seems reasonable to conclude that both *Fusarium* spp. cause similar yield losses, further studies are needed to determine whether the two species in mixed populations in the field interact and can affect cereal yield in a synergistic or antagonist way.

All significant associations between preplanting concentrations of *Fusarium* spp. inoculum and symptoms of FCR (stem browning or white heads) were positive, as to be expected. In seasons conducive to FCR development, significant associations between presowing inoculum concentration and stem browning and presowing inoculum concentration and white head incidence were observed in 80 and 33% of experiments, respectively. This suggests that white-head severity may be a poorer indication of FCR severity in the field and is consistent with the observations of Smiley et al. (23).

The magnitude of potential yield losses associated with higher preplanting *Fusarium* spp. inoculum and the lack of in-crop control options emphasizes the importance of growers being able to assess the inoculum levels in their fields prior to sowing and relate that to the risk of yield loss. Once the risk is known, growers can make informed management decisions. If the risk is high, they can choose to reduce *Fusarium* spp. inoculum by implementing strategies such as rotation to nonhosts (8,9,12,16) or stubble management (5). If the risk is moderate, growers may minimize risk by choosing barley over wheat. However, it must be remembered that barley can still carry over high inoculum loads into the next season (8), thus increasing the FCR risk in a subsequent cereal crop.

The findings from this study indicate that there is merit in cereal growers using a presowing DNA-based test to identify fields at risk of FCR. This is supported by the finding of consistent relationships in a range of environments and seasons in southeastern Australia. Roget (21) in Australia and Bithell et al. (3) in New Zealand have demonstrated that preplanting soil concentrations of DNA of *G. graminis* var. *tritici* can be used in forecasting the risk of disease of take-all in wheat. To further develop relationships between presowing inoculum concentrations and FCR risk, the relationships developed within this study need to be validated across a broader range of environments, seasons, and fields, and this is the subject of current studies.

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