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Fusarium Crown Rot Reduces Water Use and Causes Yield Penalties in Wheat under Adequate and above Average Water Availability

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Abstract: The cereal disease Fusarium crown rot (FCR), caused by the fungal pathogen *Fusarium pseudograminearum*, is a worldwide major constraint to winter cereal production but especially in Australia's northern grain's region (NGR) of NSW and Queensland. Conventionally, FCR induced yield penalties are associated with semi-arid water-limited conditions during flowering and grain-filling. In this study, yield penalties associated with FCR infection were found to be significant under both adequate and above average water conditions which has implication for global wheat production in more favorable environments. This research was conducted to understand the impact of FCR on water availability, yield and grain quality in high protein bread and durum wheat varieties in controlled environment and replicated field experiments across three locations in the NGR over a two-year period. Under controlled conditions, FCR infection significantly decreased water use by 7.5% with an associated yield reduction of 9.5% irrespective of water treatment. Above average rainfall was experienced across all field experimental sites in both 2020 and 2021 growing seasons. The field studies demonstrated a decrease in water use of upwards of 23% at some sites and significant yield penalties across all cultivars of up to 18.4% in natural rainfed scenarios to still 13.2% with further supplementary irrigation.

Keywords: Fusarium crown rot; water use efficiency; wheat; yield gap

Citation: Buster, M.; Simpfendorfer, S.; Guppy, C.; Sissons, M.; Flavel, R.J. Fusarium Crown Rot Reduces Water Use and Causes Yield Penalties in Wheat under Adequate and above Average Water Availability. *Agronomy* **2022**, *12*, 2616. https://doi.org/10.3390/agronomy12112616

Academic Editors: David A Van Sanford and Aiming Qi

Received: 31 August 2022
Accepted: 21 October 2022
Published: 24 October 2022

1. Introduction

Fusarium crown rot (FCR), caused by the fungus *Fusarium pseudograminearum* (Fp), is a major stubble borne disease of wheat in many areas of the world, including Australia [1]. This disease is of emerging concern in regions of Europe with Fp being recorded for the first time in Spain in 2016 [2]. The expression of the disease is regularly linked to water-limited/stressed growing environments particularly during grain-filling, whilst consequences are typically not considered in wetter environments [3,4]. Fungal infection causes a vascular disruption within wheat plants through colonisation of Fp hyphae inside the vascular bundles [5]. It is hypothesised that the congestion of the vascular tissue decreases hydraulic conductivity within infected wheat stems. It is also possible that Fp consumes photosynthates, forcing the plant to expel larger amounts of energy to sustain the fungus as well as supporting plant growth and development. Both these functions are consistent with frequently reported yield and quality penalties in FCR infected wheat crops.

Yield penalties associated with FCR infection have been recorded to be upwards of 89% in some seasons but are more commonly reported to average approximately 10% in Australia [6,7]. Infection of FCR is generally considered significant in dry semi-arid environments, particularly when moisture stress occurs at critical phenological stages during flowering and grain fill [8,9]. This temporal water stress occurrence is often reflected in quality downgrades including increased screenings, low test weight and decreased protein content in Fp infected wheat crops [10].

Understanding the physiological effects of Fp on wheat plants is crucial to understanding the mechanism of yield loss from FCR infection but also for determining potential management strategies. Symptoms in-crop are expressed as basal browning of the sub-crown internode, crown and base of the stem, whilst whiteheads are often observed later in the season where severe infection causes heads to be aborted [11]. Knight and Sutherland [12] quantified the correlation between increases in fungal pathogen biomass to visual browning. As the fungal load increased so did the extent of colonisation of the xylem tissue by Fp. Growth of Fp within the xylem is responsible for yield reductions however the direct mechanism remains in question. The vascular blockage could cause the plant to exert more energy to acquire soil water forcing an increased carbon demand on the plant. Alternately or in addition, the vascular restriction could decrease water available to the plant, inducing drought like symptoms.

This study was conducted to evaluate the effect of Fp infection on high protein potential bread and durum wheat varieties under varying levels of water limitation during grain fill. In this study, we hypothesised that the partial blockage of wheat vascular tissue by Fp hyphal infection could be compensated for by increasing water availability which would in-turn decrease the osmotic strain that must be exerted by infected plants to maintain water status. This study also sought to determine whether vascular restriction caused by Fp infection still result in significant yield reductions in wetter, non-water limited environments.

2. Materials and Methods

2.1. Controlled Environment Experiment

2.1.1. Soil, Tube Design and FCR Treatments

Polyvinyl chloride (PVC) soil tubes 150 mm diameter × 1200 mm length were used to simulate a field soil profile. The soil used was a Grey Dermosol with a Plant Available Water Capacity (PAWC) of 202 mm/m and starting nitrogen (N) content of 36.4 mg N/kg soil as nitrate and 3.8 mg N/kg soil as ammonium. The upper topsoil (top 260 mm) was packed to a bulk density of 1.1 gcm^{-3} whilst the lower subsoil (bottom 900 mm) was compacted to a bulk density of 1.28 gcm^{-3}. Uninoculated and inoculated FCR treatments were applied. The inoculated treatment contained a 20 mm band of inoculated soil. This was prepared by adding ground Fp colonised wheat seed (0.5–2 mm fraction) evenly mixed throughout the soil band at rates of 1 g inoculum/100 g of soil [11]. The uninoculated treatment had 20 mm of 'clean' soil prepared in a similar manner using ground sterilised wheat seed not colonized by the pathogen. A further 10 mm of soil was then added on top of the inoculated or uninoculated soil layer in both treatments to minimise Fp colonisation across the soil surface during the experiment.

2.1.2. Plant Materials and Growing Conditions

Two bread wheat varieties, LPRB Lancer and LPRB Flanker and two durum wheat varieties, DBA Lillaroi and EGA Bellaroi were grown over a six-month period. Seed was treated with Vibrance® (Syngenta, Basel, Switzerland) and Emerge® (Syngenta, Basel, Switzerland) at rates of 360 mL/100 kg and 240 mL/100 kg, for standard bunt and smut control and early protection against aphids, respectively. Vibrance® seed dressing also ensured no seedling blight in the presence of Fp in inoculation [13]. Five seeds of each cultivar were sown 40 mm below the soil surface (i.e., 10 mm below inoculum layer) and thinned to four plants per tube after establishment. There were five replicates of each cultivar by treatment combination. The experiment was conducted in an air-conditioned polyhouse complex at Tamworth Agricultural Institute (TAI), Tamworth New South Wales with a 25 °C day and external ambient night temperature regime. Soil tubes were individually weighed and watered to field capacity each week until flowering. Post flowering, two separate water regimes were implemented to mimic either 'adequate' or 'high' water availability during grain-filling. The adequate water treatments were managed to 80% of field capacity (−100 kPa average matric potential), whilst the high water treatment maintained the original watering regime of 100% field capacity. Three weeks prior to harvest, soil tubes were not watered for a week to dry the soil column down for core removal and water content was maintained at this level for the remainder of the experiment. Water used by the plants was determined gravimetrically for the entirety of the experiment by weekly weighing and measurement of water applied. At 80 days after sowing, soil tubes were treated with 130 mg/kg of potassium nitrate and 120 mg/kg of urea to equate to 49.4 mg/kg of K and 72.2 mg/kg of N to address deficiency symptoms with application rates based on the top 400 mm of soil.

2.1.3. In-Crop Measurements

Plants were visually scored for the severity of FCR infection based on the extent of browning of stem bases using a 0–3 scale at GS55 and the crown rot index was calculated [14]. This measurement also confirmed that all the FCR inoculated treatments displayed signs of FCR infection and that no infection occurred in the non-inoculated treatment. Immediately prior to harvest counts were taken of plants, tillers, heads, whiteheads and late maturing heads (small spikelet's, less than half the height of the other heads). Heads on the main stem from each plant were removed along with their stems, which were cut 5 mm above soil surface. The remainder of the heads and stems were then collected, keeping the whiteheads and late maturing heads separate. All heads and stems where dried at 40 °C for 72 h prior to weighing to determine dry matter mass.

2.1.4. Harvest Measurements

Grain was threshed from heads on main stems of the four plants in each soil tube. Remaining viable heads, whiteheads and late maturing heads were collected separately and threshed to recover grain. All remaining plant residue was collected and bulked together for plants grown in each soil tube and weighed. Grain weights and counts for main stems, mature heads and white/late maturing heads were taken separately. A crown rot index (%) was calculated from the proportion of 4 main of stem infected tillers multiplied by visual browning (scale of 0–3) [14].

2.2. Field Trials

2.2.1. Location and Soil Preparation

Field experiments were conducted across three research stations; Liverpool Plains Research station (LPRS) (31°10′35.9″ S 150°25′12.6″ E), Australian Cotton Research Institute (ACRI) (30°11′37.0″ S 149°36′33.3″ E) and Piallamore (31°10′14.8″ S 151°03′31.2″ E) in north west New South Wales. The experiments were repeated in sequential years across the 2020 and 2021 winter growing seasons. Soil nutritional characteristics at each site were determined prior to sowing in each season through soil sampling at 30 cm increments from surface to 180 cm of depth. The use of 'wet-up' and 'rain exclusion' sites adjacent to the trial area were used to determine drained upper limit (DUL) and plant available water capacity (PAWC) from the top 150 cm of soil. The black vertosol soil at LPRS had PAWC of 282 mm, ACRI a grey vertosol had PAWC of 233 mm and Piallamore a grey dermosol had PAWC 187 mm. Each field site was sown following a long fallow with minimal cereal history in 2019. The second year (2021) a nearby site at each location was used and followed a summer planting of sorghum (Piallamore and ACRI) or mustard (LPRS). The purpose of following the summer grown crop was to ensure a uniform low soil nitrogen and water status across the whole field experimental area. Above average rainfall in both growing seasons filled the soil water profiles prior to planting and higher than average in-crop rainfall was experienced for the duration of the field experiments in both seasons.

2.2.2. Plant Materials and Growing Conditions

Three spring bread wheat varieties, LPRB Lancer, LPRB Hellfire and Suntop and three durum wheat varieties, DBA Lillaroi, DBA Aurora and Jandaroi were grown in each of the two experimental years across each site. Plots were 10 m long by 1.8 m wide sown on 0.25 m row spacings at LPRS and ACRI and 0.33 m row spacing at Piallamore. Sowing rate was adjusted based on grain weight and germination to target establishment of 100 plants m^{-2}. Two water scenarios were created including a natural rainfed treatment and supplementary water to represent a higher rainfall scenario. The higher rainfall scenario used dripper hose at Piallamore and furrow irrigation at LPRS and ACRI. Irrigations took place at GS 61 & GS 69 for all three sites during the 2020 season and Piallamore for 2021. Due to the very wet conditions experienced in 2021 ACRI and LPRS received only one irrigation at GS 61. Each irrigation was approximately 50 mm. Four nitrogen treatments were included in the study to compare upfront and split applications of nitrogen as urea to support yield potential at both a decile 5 and 9 rainfall scenario at each site. Nitrogen responses are not presented in this current study. There were three replicates of each cultivar by treatment combination. In-crop rainfall at Piallamore was 329 mm and 504 mm, LPRS 315 mm and 526 mm, ACRI 184 mm and 394 mm for the 2020 and 2021 seasons, respectively.

2.2.3. Field Measurements

Soil moisture was measured using neutron water meters with permanent access tubes installed into the natural rainfed water treatment at 0–30, 30–60, 60–90, 90–120, 120–150 and 150–180 cm depth intervals. Readings coincided with stem elongation (~GS32), flag leaf emergence (~GS39), flowering (~GS65), grain fill (~GS75) and physiological maturity (~GS99). Due to the large volume of influence of the neutron probe, interaction with air (all sites) and rock bed (Piallamore site only) confounded readings from 0–30 and 150–180 cm depths respectively. As such readings from these depths were not included in statistical analysis across all three sites. At harvest, yield and grain protein levels were measured for each plot using a small plot header and NIR machine (FOSS Infratec™ 1241, FOSS, Hilleroed, Denmark), respectively. Stubble was sampled from two locations within each harvested plot from the three center rows combining to approximately 40 plants to determine FCR incidence and severity [14]. A crown rot index (%) was calculated from the proportion of 25 plants randomly taken from each plot multiplied by visual browning (scale of 0–3) [14].

2.3. Statistical Analysis

The statistical software package R [15] was used to fit linear models to the datasets and ANOVA was performed. Model diagnostics were checked and where necessary, data was transformed to uphold model assumptions. Post hoc multiple comparisons were performed using Tukey's method (package: lsmeans)

3. Results

3.1. Controlled Environment Study

3.1.1. Inoculation Response

Infection severity measured as a crown rot index through visual browning increased from 0–5% in the uninoculated treatments to 50–73% in the inoculated treatments (Supplementary Materials Figure S1) ($p < 0.001$). There was no interation with visual browning and differing water treatments.

3.1.2. Water Use

Wheat water use was reduced by 7.5% (*w*/*w*) across all treatments (p = 0.027) in the FCR inoculated treatment compared to the uninoculated treatment. Average water consumption for the inoculated treatments was 28.5 L/tube (SE 0.71) whilst uninoculated treatments averaged 30.8 L/tube (SE 0.76) (p = 0.027) (Figure 1). No statistical difference was observed between different wheat cultivars or between wheat types (durum or bread wheats), however, inoculated treatments tended to have reduced water use (Figure 1).

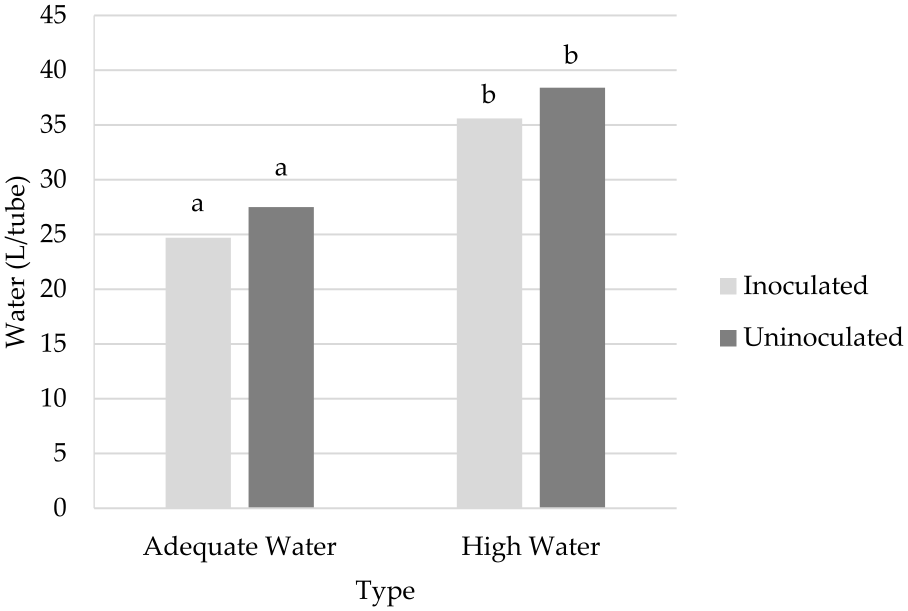

Figure 1. Total gravimetric water use of growth tube (population of four wheat plants) in experiment exploring effect of FCR (Inoculated and Uninoculated) and water (adequate water and high water) on grain yield. Bars with different letters indicate significant differences, $p < 0.05$.

3.1.3. Yield

Fusarium crown rot inoculation reduced yield by an average of 9.5% irrespective of water availability (p = 0.014; Figure 2). A significant reduction in yield was observed in both bread and durum varieties with an average of 9.1% and 10.7%, respectively (Figure 2). The interaction between wheat type and water availability was significant (p = 0.0003). Bread wheat varieties yielded on average 16% more under adequate water compared to high water. Whilst the yield of the durum varieties were not significantly different when compared by water availability (p > 0.05) (Data not shown).

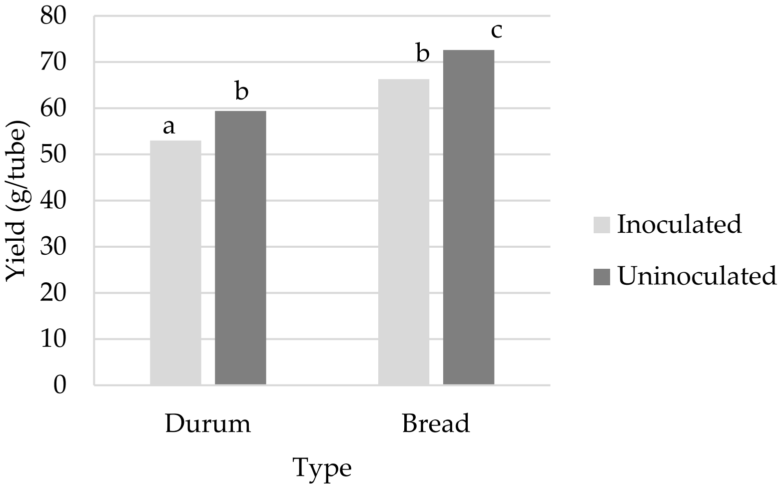

Figure 2. Grain yield per tube of 4 wheat cultivars as summarized by cereal type (two durum varieties: DBA Lillaroi and EGA Bellaroi and two bread varieties: LRPB Lancer and LRPB Flanker) in experiment exploring effect of FCR (inoculated and uninoculated) and variety. Bars with different letters indicate significant differences, $p < 0.05$.

3.2. Field Experimentation

3.2.1. Infection Response In-Crop

Visual severity of FCR infection (crown rot index) assessed in post-harvest stubble samples demonstrated a significant effect of the inoculation treatment at all three sites in the 2020 growing season. Uninoculated treatments had a crown rot index of between 12–28%, whilst inoculated treatments ranged from 35–66% (Figure S5). Both ACRI and LPRS sites had significantly higher FCR severity in the durum compared to the bread wheat varieties when inoculated with Fp. FCR severity was not measured in the 2021 season due to exceedingly wet conditions preventing timely collection of stubble samples after harvest. This delay in sampling under prolonged wet conditions facilitated saprophytic growth of Fp within the standing cereal stubble as well as a range of other saprophytic fungi, such as Alternaria spp., which discoloured the stubble confounding visual FCR severity measurements.

3.2.2. Water Use

A 21% increase in PAW remaining was seen in the inoculated treatment compared to the uninoculated treatment at Piallamore in 2020 in the durum as early as GS32 ($p < 0.05$) (Figure 3). This trend continued throughout the duration of the growing season with an 18% reduction in water use in FCR infected plots still observed at harvest ($p < 0.05$) (Figure 3). A similar trend was also observed in the bread wheat varieties, however, the separation between inoculated and uninoculated treatments was not significant until harvest where FCR infection increased PAW remaining by 23% ($p < 0.05$).

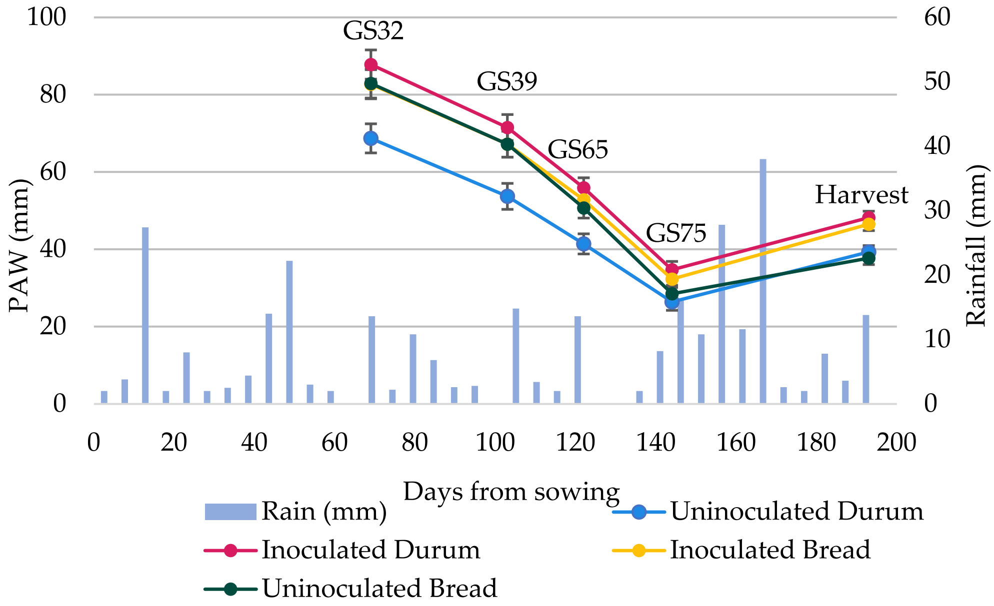

Figure 3. Plant available water (PAW) at Piallamore trial site (2020) measured through neutron probes between 30–150 cm depth indicated by lines of three bread (LRPB Lancer, Suntop and LRPB Hellfire) and three durum (DBA Lillaroi, Jandaroi and DBA Aurora) wheat varieties under both inoculated and uninoculated Fusarium crown rot treatments. Error bars indicate standard error. Rainfall (>2 mm) indicated by columns. Piallamore trial site 2020.

In 2021 at the Piallamore site, the bread wheat varieties used 23% less water in comparison to the durum varieties at GS65 and at harvest ($p < 0.05$) (Figure 4). No significant separation between Fp inoculation treatments was observed at this site in 2021.

Water use at the ACRI and LPRS sites was less consistent and often showed no differences between treatments (Figures S2–S4). However, during the 2020 season at the LPRS site the durum varieties consistently used less water at each growth stage in comparison to the bread wheat varieties (non significant) (Figure S2). Similar observations were made between the bread and durum wheat varieties at harvest at ACRI in 2020 (Figure S3).

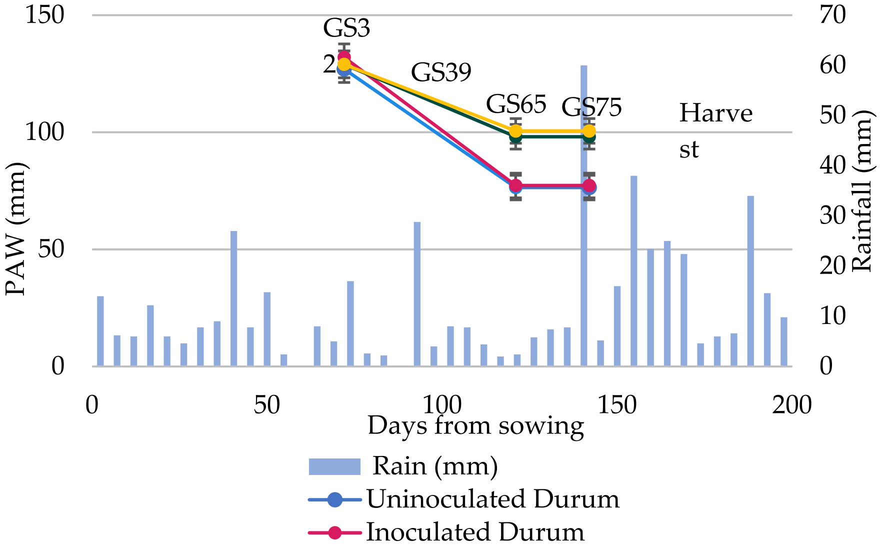

Figure 4. Plant available water (PAW) Piallamore trial site (2021) measured through neutron probes between 30–150 cm depth indicated by lines of three bread (LRPB Lancer, Suntop and LRPB Hell-

fire) and three durum (DBA Lillaroi, Jandaroi and DBA Aurora) wheat varieties under both inoculated and uninoculated Fusarium crown rot treatments. Error bars indicate standard error. Rainfall (>2 mm) indicated by columns.

3.2.3. Yield and Screenings

2020. Growing Season

Grain yield was reduced due to FCR inoculation by between 6.4 to 18.4% across all three sites in both water scenarios in the 2020 growing season except for the supplementary irrigation treatment at Piallamore, ($p < 0.05$) (Table 1). The largest yield penalty associated with FCR inoculation (18.4%) was observed at Piallamore in the natural rainfed scenario (Table 1). Average yield loss associated with FCR inoculation was lower (14%) in the bread wheat than in the durum varieties (25%) (data not shown). Both Piallamore and LPRS recorded significantly lower yield in the natural rainfed scenario compared to the supplementary irrigation treatment ($p < 0.05$) (Table 1). The same trend in yield was not observed at ACRI ($p > 0.05$). The supplementary irrigation treatment consistently reduced small grains (screenings) levels across all three sites in comparison to the natural rainfed treatment (Table 1). FCR inoculation increased the level of screenings at all three sites during the 2020 growing season in the natural rainfed treatment only ($p < 0.05$) (Table 1).

Table 1. Grain yield and screenings of three bread (LRPB Lancer, Suntop and LRPB Hellfire) and three durum (DBA Lillaroi, Jandaroi and DBA Aurora) wheat varieties when inoculated or uninoculated with Fusarium crown rot under natural rainfed and supplementary irrigation scenarios across three trial sites; Australian Cotton Research Institute (ACRI), Liverpool Plains Research Site (LPRS) and Piallamore, in 2020. Values within a site followed by the same letter are not significantly difference at the 95% confidence interval.

		Grain Yield (Kg/ha)		**Screenings %**	
Site	**Rainfall**	**Inoculated**	**Uninoculated**	**Inoculated**	**Uninoculated**
ACRI	Natural Rainfed	5872 bc	6628 a	6.64 c	5.78 b
	Supplementary Irrigation	5517 c	6358 ab	4.38 a	4.18 a
LPRS	Natural Rainfed	4769 c	5202 b	6.64 c	5.78 b
	Supplementary Irrigation	5054 bc	5397 a	4.38 a	4.18 a
Piallamore	Natural Rainfed	3475 c	4257 b	9.26 c	5.95 b
	Supplementary Irrigation	4550 ab	4729 a	2.67 a	2.38 a

2021 Growing Season

In the 2021 growing season, there was no significant effect of FCR inoculation on yield across all three sites (Table 2). A 12% yield increase was recorded at LPRS with the application of supplementary irrigation compared to the natural rainfed scenario. Piallamore and ACRI observed no significant difference in yield between water treatments in 2021. The supplementary irrigation treatment reduced screening levels at the ACRI and LPFS sites in comparison to the natural rainfed treatment ($p < 0.05$) (Table 2). FCR had no significant effect on screenings at all three sites during the 2021 growing season except for in the supplementary irrigation treatment at Piallamore where FCR inoculation caused a slight increase in screening levels ($p < 0.05$) (Table 2).

Table 2. Grain yield and screenings of three bread (LRPB Lancer, Suntop and LRPB Hellfire) and three durum (DBA Lillaroi, Jandaroi and DBA Aurora) wheat varieties when inoculated or uninoculated with Fusarium crown rot under natural rainfed and supplementary irrigation scenarios across three trial sites; Australian Cotton Research Institue (ACRI), Liverpool Plains Research Site

(LPRS) and Piallamore, in 2021. Values within a site followed by the same letter are not significantly difference at the 95% confidence interval.

Site	Rainfall	Grain Yield (Kg/ha) Inoculated	Grain Yield (Kg/ha) Uninoculated	Screenings % Inoculated	Screenings % Uninoculated
ACRI	Natural Rainfed	4972 a	4826 a	2.41 b	2.53 b
	Supplementary Irrigation	4914 a	5071 a	1.36 a	1.53 a
LPRS	Natural Rainfed	5496 c	5412 c	2.18 bc	2.22 c
	Supplementary Irrigation	6199 ab	6220 a	1.88 a	1.92 ab
Piallamore	Natural Rainfed	7745 a	7925 a	2.35 ab	2.24 ab
	Supplementary Irrigation	7885 a	7954 a	2.36 b	2.15 a

4. Discussion

4.1. Water Use

The FCR pathogen (Fp) causes a partial blockage to the vascular tissue at the base of stems in infected wheat plants [16]. In theory, FCR infection would therefore be expected to result in a reduction in the plant transpiration and ultimately water use. To the best of the authors knowledge, this is the first comprehensive study to support preliminary findings by Graham et al. [10]. Observations were made first in the controlled environment study where FCR infection reduced water use by 7.5%. Field experiments at the Piallamore site (2020) further confirmed this observation with increased PAW remaining in inoculated treatment, indicating reduced crop water use of over 20% at differing growth stages throughout the growing season. At Piallamore in 2021, more in-crop rainfall occurred (504 mm) compared to the previous 2020 season (329 mm). This likely resulted in diminished separation in water use between inoculated and uninoculated treatments in 2021 (Figure 4) compared with 2020. These observations can likely be explained through the continually wet conditions removing the differences in PAW measured and causing greater runoff in wetter plots and replenishing the dryer ones.

Furthermore, there was a trend for the durum varieties to use less water than the bread wheat varieties by approximately 20% in the controlled environment study and ranging in the field from 5% to 22%. However, significance of these findings in the field was not consistent across seasons and experimental sites. The increased susceptibility of durum varieties to FCR relative to bread wheat [17] appeared to result in greater suppression of water use.

Unsurprisingly, the results from field experiments were less consistent than those generated under controlled conditions. We expect there are multiple factors contributing to these observations. Firstly, both growing seasons experienced above average rainfall at all three sites. This reduced the magnitude of differences in water treatments as the PAW was frequently increased by regular rainfall events. Secondly, concerning the LPRS and ACRI experimental sites the soil types were deep heavy clays which have a high-water holding capacity (282 mm and 233 mm, respectively). This resulted in a higher moisture buffering capacity for the plants and again reduced the separation of water use with generally higher PAW. Finally, Piallamore had a less frequent history of wheat plantings in the past five years resulting in the background inoculum levels being lower than that of the other trials sites. These differences are thought to explain the lower separation between FCR treatments at LPRS and ACRI compared to the Piallamore site.

Implications of changes in water use not only allow greater understanding of the effect of FCR infection on wheat physiology but may also allow opportunity for remote detection based on changes in transpiration status of plants through technologies such as thermal imagery detection of canopy temperature. However, this could be confounded by other environmental factors. Spatially quantified severity of FCR infection through remote detection could potentially facilitate growers to spatially manage this disease either through cultural, such as nitrogen rates, or chemical practices such as preventative fungicide applications in following crops. Furthermore, early detection based on the differences in water use (and transpiration rate or canopy temperature) may allow potential for novel screening methods to be developed for FCR, increasing the rate of genetic selection when breeding for resistance and/or tolerance to this disease.

4.2. Yield and Grain Quality

Yield is the most significant factor contributing to financial returns from cereal production. Yield is strongly driven by nitrogen and rainfall and can be partially buffered through stored soil moisture [18,19]. However, if the plant is unable to utilise the total available moisture it undergoes an FCR-imposed constraint on water transport ultimately reducing yield as well as quality through an increase in the number of small grains (screenings). The vascular restriction of the plant's xylem by FCR appears to induce a restriction on water and solute transfer [16]. Results from the controlled environment study indicate that even when the plant has abundant and non-limiting water supply, there is still a 9.5% yield reduction associated with FCR infection. This result was further confirmed under field conditions at three sites in 2020 where an 8.3% to 18.4% reduction in yield was recorded with above average rainfall (Natural) and from 6.4% to 13.2% yield loss still occurred with further supplementary irrigation for two of the three sites. Therefore, it is not only in dry seasons that FCR management is crucial to minimise yield loss but wet seasons as well. Furthermore, screenings were observed to have increased under FCR infection due to the restriction on the vascular conductivity during grain fill. Results were amplified in the natural rainfed system in the 2020 season, whilst effects were rarely demonstrated in the supplementary irrigation treatment. These results provide an indication that higher rainfall environments, such as southern regions of Australia and many regions in Europe, might be experiencing lower but still significant yield and quality loss due to FCR which is potentially going unnoticed due to lower expression of the disease. Given the lack of particularly effective chemical control strategies, cultural methods such as rotation and other integrated management strategies remain the most viable solution [20,21]. As a relatively new arrival to European farming systems this might be a disease to watch with caution [2]. Based on the numbers from [1] and assuming a conservative European wheat production of ~150 Mt this could mean a reduction in yield of approximately 15 Mt in just the top European growing nations and worse under warmer drier conditions.

Results for the 2021 season did not measure any significant effect of FCR infection on yield and marginal effects on screenings. This was not surprising given the significant amount of rainfall received in-crop. These results indicate that although the controlled environment water treatments and 2020 season supplementary irrigation treatment still experienced significant yield and quality losses associated with FCR infection there may be a higher threshold where exceedingly wet conditions limit disease impacts. Transient waterlogging and associated anaerobic soil conditions experienced in 2021 across sites may have limited growth of Fp but was not examined in detail in this study.

5. Conclusions

These findings should increase awareness and concern of potential yield and quality losses (elevated screenings) from FCR in wetter environments where Fp is present but this disease is traditionally not considered an issue. For example, in Europe where Fp was first recorded in 2016 [2]. Historically FCR has only been a concern under water-limited conditions. However, yield penalties were demonstrated in both field and controlled environmental conditions under non-water limited environments (except for exceedingly wet conditions) which suggests FCR is not restricted to causing yield loss only under water-limited situations. The impact of Fp on water transport and usage within the plant also presents an opportunity for early detection with remote sensing technologies and possible mechanisms for screening plants in breeding programs for resistance. It also demonstrates a potential link between Fp resistance and water transport mechanisms within the plant.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy12112616/s1, Figure S1: Crown Rot Index (0–100%) of two bread (LRPB Lancer, LRPB Flanker) and two durum (DBA Lillaroi, and DBA Bellaroi) wheat varieties under both inoculated and uninoculated Fusarium crown rot treatments. Results from controlled environment study exploring water use and yield loss from FCR inoculation. Error bars indicate standard error. Figure S2: Plant available water measured through neutron probes between 30–150 cm depth indicated by lines of three bread (LRPB Lancer, Suntop and LRPB Hellfire) and three durum (DBA Lillaroi, Jandaroi and DBA Aurora) wheat varieties under both inoculated and uninoculated Fusarium crown rot treatments. Error bars indicate standard error. Rainfall (>2 mm) indicated by columns. LPRS trial site 2020. Figure S3: Plant available water measured through neutron probes between 30–150 cm depth indicated by lines of three bread (LRPB Lancer, Suntop and LRPB Hellfire) and three durum (DBA Lillaroi, Jandaroi and DBA Aurora) wheat varieties under both inoculated and uninoculated Fusarium crown rot treatments. Error bars indicate standard error. Rainfall (>2 mm) indicated by columns. ACRI site 2020. Figure S4: Plant available water measured through neutron probes between 30–150 cm depth indicated by lines of three bread (LRPB Lancer, Suntop and LRPB Hellfire) and three durum (DBA Lillaroi, Jandaroi and DBA Aurora) wheat varieties under both inoculated and uninoculated Fusarium crown rot treatments. Error bars indicate standard error. Rainfall (>2 mm) indicated by columns. ACRI site 2021. Figure S5: Crown Rot Index (0–100) of three bread (LRPB Lancer, Suntop and LRPB Hellfire) and three durum (DBA Lillaroi, Jandaroi and DBA Aurora) wheat varieties under both inoculated and uninoculated Fusarium crown rot treatments. Results from 2020 growing season across three trial sites (ACRI, LPRS and Piallamore). Error bars indicate standard error.

Author Contributions: Conceptualization, M.B., R.J.F. and S.S.; methodology, M.B., R.J.F. and S.S.; software, M.B. and R.J.F.; validation, M.B.; formal analysis, M.B. and R.J.F.; investigation, M.B.; resources, M.B.; data curation, M.B.; writing—original draft preparation, M.B.; writing—review and editing, M.B., R.J.F., M.S., C.G. and S.S.; visualization, M.B.; supervision, R.J.F., M.S., C.G. and S.S.; project administration, R.J.F. and S.S.; funding acquisition, R.J.F., M.S., C.G. and S.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded under the Grains Agronomy and Pathology Partnership between New South Wales Department of Primary Industries and Grains Research and Development Corporation, project code DAN00213.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Please contact the corresponding author with requests for data

Acknowledgments: Would like to acknowledge the contributions of technical staff at New South Wales Department of Primary Industries for their technical support of the project.

Conflicts of Interest: The authors declare no conflict of interest.

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