Received: 14 March 2023 | Accepted: 24 June 2023

DOI: 10.1111/ppa.13777

Plant Pathology An International Journal edited by the British Society for Plant Pathology
WILEY

REVIEW ARTICLE

A review on common root rot of wheat and barley in Australia

Yiyi Xiong[1,2] | Cheryl McCarthy[1] | Jacob Humpal[1] | Cassandra Percy[2]

[1]Centre for Agricultural Engineering, University of Southern Queensland, Toowoomba, Queensland, Australia

[2]Centre for Crop Health, University of Southern Queensland, Toowoomba, Queensland, Australia

Correspondence
Cassandra Percy, Centre for Crop Health, University of Southern Queensland, Toowoomba, QLD, Australia.
Email: cassy.percy@usq.edu.au

Funding information
The Department of Agriculture and Fisheries

Abstract

Common root rot (CRR) caused by the soilborne pathogen *Bipolaris sorokiniana* (teleomorph *Cochliobolus sativus*) is becoming increasingly prevalent worldwide. Identification of CRR is difficult and time-consuming for human assessors due to the non-distinctive above-ground symptoms, with browning of subcrown internodes and roots the most distinguishing symptom of infection. CRR disease has been recognized as a significant disease for cereal crops in many countries. In 2009, CRR in Australia was estimated to cause $30 million average annual yield loss for wheat and $13 million for barley. Recent evidence indicates CRR may be more prevalent than expected in Australian wheat cropping areas due to lack of research on this disease. Low levels of *B. sorokiniana* survive in the soil for up to 10 years and attack plants at early stages of growth. Therefore, mitigating CRR in wheat and barley may not be practical at the late stages of infection due to lack of effective methods; however, early detection might be viable to alleviate the impact of this disease. A comprehensive overview of CRR caused by *B. sorokiniana*, including disease background, worldwide economic losses, management methods, potential CRR detection using multispectral and hyperspectral sensors and the research focus over the past 50 years is provided in this article. This review paper is expected to provide thorough supplemental information for current studies about CRR and proposes recommendations for whole-of-field disease scouting methods to farmers, enabling reduced time and cost for CRR management and increasing wheat and barley production worldwide.

KEYWORDS
Bipolaris sorokiniana, common root rot, disease background, management

1 | INTRODUCTION

The most important cereal crops in Australia are bread wheat (*Triticum aestivum*) and barley (*Hordeum vulgare*), which are vulnerable to common root rot (CRR) disease that is becoming increasingly prevalent across winter cereal-growing regions. CRR is caused by the soilborne pathogen *Bipolaris sorokiniana* (teleomorph *Cochliobolus sativus*), causing damage to the roots and subcrown internode of bread wheat and barley (Liueroth et al., 1996; Wildermuth, 1986). Internationally, CRR is also referred to as dryland root rot or foot rot, where it is associated with single fungal species or infection complexes, including *B. sorokiniana* and other *Fusarium* spp. such as *F. culmorum* and *F. graminearum* in wheat and barley worldwide (Wiese, 1987). *B. sorokiniana* can also be responsible for several other diseases including black point (Al-Sadi, 2021), spot blotch (Knight et al., 2010) and Helminthosporium leaf blight (Duveiller et al., 2005).

Globally, scientific papers tend to focus on *B. sorokiniana* in general associated with CRR or spot blotch, as they can be inoculated with the same original isolate. However, notable genetic differences have been observed among isolates obtained from infections of CRR and spot blotch (Horne, 2015; Knight et al., 2010). Specifically, Australian isolates of *B. sorokiniana*, obtained from CRR infections, do not trigger susceptible spot blotch infection responses in barley plants (Knight et al., 2010). In Australia, spot blotch of wheat is infrequent, while CRR is prevalent in both barley and wheat crops (Knight et al., 2010; Murray & Brennan, 2009a, 2009b). *B. sorokiniana* is recognized as the primary causal agent of CRR in Australia, whereas infections caused by *Fusarium* spp. are commonly associated with the development of crown rot. This review focuses on CRR caused by *B. sorokiniana* in Australia, with reference to CRR caused by *B. sorokiniana* in other countries worldwide.

CRR has been reported in every state of mainland Australia since its discovery in the 1920s (Hamblin, 1922; Hynes, 1932) and is a significant problem in dryland cereal farming (Wildermuth, 1986). CRR was widespread in New South Wales during the 1920s and 1930s due to the monoculture wheat practice (Hynes, 1932), yet it was gradually reduced with the introduction of ley farming, which involved using paddocks for pasture or left fallow in between cereal crops (Butler, 1961). CRR was first officially reported in Queensland in 1964 (Simmonds, 1966) and became widespread throughout Australia (Wildermuth et al., 1992). Many economic losses in wheat and barley caused by CRR, directly and indirectly, have been reported worldwide since the 1970s. Evidence will be presented and discussed in detail in the worldwide economic losses section. CRR literature denotes that CRR is a widespread chronic disease frequently overlooked in Australian wheat production systems due to the lack of specific above-ground symptoms (MacLeod et al., 2008; Neate & Vadakattu, 2018). Therefore, CRR is most likely a more significant disease in Australia than previously understood (Neate & Vadakattu, 2018; Purss, 1970). The incidence of CRR has potentially been under-reported and the contribution of CRR to yield loss in wheat and barley is unclear across the Australian grain belt.

Understanding and diagnosing the presence of the CRR pathogen in Australian farming systems is crucial to realizing and reducing the economic losses caused by this disease. Early disease detection and identification with regular monitoring enable management decisions to monitor CRR spread and minimize losses caused by this disease. The two most common disease detection methods in the field are traditional plant disease assessment by experienced personnel and remote sensing technologies using spectral or imaging sensors (Mahlein, 2016). Traditional plant disease assessment for determining and quantifying CRR is time- and labour-intensive and can be impacted by human judgement and observation (Barbedo, 2019). The use of remote sensing in crops enables the acquisition of information about a plant, or a phenomenon of a plant, without physical contact or aggressive manipulation (Gogoi et al., 2018; Mahlein, 2016; Wójtowicz et al., 2016). Disease detection methods will be discussed to provide information on the extent of CRR infestation in the paddocks, which will facilitate whole-farm disease management decisions for growers.

Currently, there is no comprehensive review paper solely focusing on CRR caused by *B. sorokiniana* in general. Nevertheless, four review papers have been published on *B. sorokiniana* pathogen-induced diseases, and it is important to note that these include CRR as a small part and do not specifically address it as the primary focus (Acharya et al., 2011; Al-Sadi, 2021; Ghazvini, 2018; Kumar et al., 2002). The majority of research on CRR in wheat and barley was published worldwide during the 1980s and 1990s. The number of journal papers on CRR in wheat and barley appears to have declined slightly according to the number of publications on Google Scholar (Research focus section). However, its importance and discussion of the disease remain relevant based on the reports from the government, professional organizations and online resources as the distribution and economic losses of CRR remain significant. A new inclusive review is warranted given the continued impact of CRR in wheat and barley with limited understanding in the literature on CRR identification, present and potential economic losses, potential detection and management methods.

This paper provides a comprehensive disease review of CRR caused by *B. sorokiniana*, including morphology, biology and disease cycle, host range, symptomatology, favourable conditions, disease assessment, worldwide economic losses of CRR caused by *B. sorokiniana* in wheat and barley, CRR management practices, potential CRR detection methods and the current research focus. Finally, the conclusion and possible solutions to manage CRR as a re-emerging threat to cereal production systems in Australia are presented. Literature has been reviewed from all over the world with a focus on relevance to Australian cropping systems.

2 | MORPHOLOGY OF *B. SOROKINIANA*

The teleomorph of *B. sorokiniana* is *C. sativus*, which belongs to the Division *Ascomycota*, Subdivision *Loculoascomycete*, Class *Dothideomycetes*, Order *Pleosporales* and Family *Pleosporaceae* (Acharya et al., 2011; Al-Sadi, 2021; Gupta, Vasistha, et al., 2018). The genus *Bipolaris* has brown conidiophores that are several-celled (phragmosporous), elliptical, straight or curved, developing by one germ tube at each end through the apical pore (Acharya et al., 2011; Navathe et al., 2020). *B. sorokiniana* produces olive-brown ovate conidia (Figure 1) with a prominent basal scar and apical cell, and olive-brown conidiophores that are 6–10 ×110–220 μm in size. These olive-brown conidia are 15–28 ×40–120 μm in size and contain 3–9 thick-walled septa with tapered ends, falcate to fusiform in particular (Acharya et al., 2011; Wiese, 1987).

3 | BIOLOGY AND DISEASE CYCLE OF *B. SOROKINIANA*

The CRR fungus *B. sorokiniana* has been reported to occur predominantly in the top 10 cm in soil or infected debris from previous crops (Mathieson et al., 1990). *B. sorokiniana* survives for at least 2 years and may remain viable up to 10 years in the soil (Wildermuth, 1986; Wildermuth & McNamara, 1991). Clarification of the survival of *B. sorokiniana* in current farming systems requires further research.

FIGURE 1 Conidia of *Bipolaris sorokiniana*. [Colour figure can be viewed at wileyonlinelibrary.com]

The sexual reproductive stage is not necessary for the *B. sorokiniana* disease cycle, and it is rarely seen in nature (Bockus et al., 2010; Mathre et al., 2003). Primary *B. sorokiniana* inoculum consists of mycelium from crop residue and infected seed, and conidia in the soil and on the kernel surface (Gupta, Chand, et al., 2018; Murray et al., 1998; Reis, 1990; Wiese, 1987). Conidia can germinate from the susceptible hosts, and the initial infection points are on coleoptiles, subcrown internodes and primary and secondary roots (Bockus et al., 2010). Prior to penetration, appressoria and infection cushions are formed, after which mycelium penetrates the host tissue directly (Apoga et al., 2001; Saad, 2019). Infection spreads from the epidermis to the cortex and endodermis, causing the tissue to disintegrate, and the spread of mycelium leads to the further colonization of plant parts (Mathre, 1997). Repeat infections throughout the growing season can result in the complete decay of the root system. There is insufficient literature regarding the disease cycle of CRR caused only by *B. sorokiniana*, but extensive literature has been presented for the leaf disease, spot blotch, caused by the same fungus.

B. sorokiniana inoculum can be transmitted by wind, rainfall splashes or implements in the soil (Acharya et al., 2011). Moreover, infested seeds can be used to transmit disease over long distances (Mathre, 1997). Disease development below ground is not related to the diffusion of secondary inoculum but provides inoculum for subsequent crops (Murray et al., 1998).

4 | HOST RANGE

B. sorokiniana has been reported to cause CRR in small grain cereals, such as bread wheat (*T. aestivum*), durum wheat (*Triticum turgidum* var. *durum*), barley (*Hordeum vulgare*), rye (*Secale cereale*) and oat (*Avena sativa*), as well as some weeds and grasses, such as crested wheatgrass (*Agropyron pectinatum*), smooth bromegrass (*Bromus inermis*) and various-leaved fescue (*Festuca heterophylla*) (Al-Sadi, 2021; Jones & Clifford, 1983; Kumar et al., 2002). Wheat and barley are the most significant hosts in terms of economic importance (Jones & Clifford, 1983; Kumar et al., 2002). In Australia, genotypic variation in CRR severity has been reported in barley, durum wheat and bread wheat varieties. In Australia, commercial barley varieties are moderately susceptible to susceptible to CRR, whereas commercial bread and durum wheat varieties are ranked from MRMS (moderately resistant—moderately susceptible) to S (susceptible) in the 2022 Queensland winter crop sowing guide (Grains Research and Development Corporation [GRDC], 2021).

5 | SYMPTOMATOLOGY

Most wheat and barley plants are infected by *B. sorokiniana* before the inflorescence emerges (Windels & Wiersma, 1992). The symptoms of CRR first appear on young seedlings from inoculum carried on the seed or from infections caused by conidia in soil close to the seedlings (Jones & Clifford, 1983; Piening, 1997). The above-ground symptoms are not distinctive, but dark brown to black necrosis first appears on the whole or part of the subcrown internode, then it spreads upward into the plant crown, tiller bases and leaf sheaths (Mathre, 1997; Mathre et al., 2003). CRR may be tolerated by the plant and create no above-ground symptoms, as long as sufficient crown roots develop (MacLeod et al., 2008). Therefore, infected plants will survive in most cases, but severely infected seedlings may not emerge (Platz et al., 1999). Infected plants have been reported to be stunted with fewer tillers and kernels per ear (MacLeod et al., 2008; Moore et al., 2005). Whiteheads may develop under severe infection and moisture stress, and severe infections may lead to plant death before heading (MacLeod et al., 2008; Mathre et al., 2003).

6 | FAVOURABLE CONDITIONS

Environmental factors, including soil moisture and temperature, pathogen population density in the soil and time of infection, all influence severity and incidence of CRR (Al-Sadi, 2021). During the first 6–8 weeks after planting, warm soil conditions and adequate moisture exacerbate *B. sorokiniana* infection and colonization (Murray et al., 1998). This pathogen can also thrive at temperatures ranging from 16 to 40°C, with ideal soil temperatures of 28 to 32°C (Acharya et al., 2011; Duveiller et al., 2005). Wet conditions are needed to initiate the infection of *B. sorokiniana*, whereas drier conditions near the end of the season result in severe disease (Acharya et al., 2011; Whittle, 1992). CRR has been reported to be more widespread in nitrogen-deficient paddocks (Moore et al., 2005). Despite sufficient nitrogen application, CRR may cause yield loss due to early infection and reduced tiller density if phosphorus and potassium are not applied (Sharma et al., 2006; Singh et al., 2012; Whittle et al., 1991). CRR can also be associated with crown rot caused by *Fusarium pseudograminearum* (Al-Sadi, 2021; Moore et al., 2005; Simpfendorfer et al., 2020).

7 | CRR DISEASE ASSESSMENT

Despite the fact that CRR can affect the subcrown internode, crown, leaf base, coleoptile and roots of infected plants, the standard method for determining the severity of CRR in Australia involves measuring the percentage of dark brown lesion development on the total area of the subcrown internodes of infected plants. This method often includes the use of a rating scale from 1 to 5 (nil to severe) (Verma et al., 1976; Wildermuth, 1986). The rating on subcrown internode discolouration has been directly associated with yield losses (Ledingham et al., 1973; Wildermuth et al., 1992). Presently, rating the percentage of subcrown internode discolouration has been expanded to include an 11-point rating scale (Horne, 2015). Saad et al. (2022) assessed the impact of CRR in the field using plant height, stem number, dry weight of plants and visual discolouration ratings on subcrown internode, main stem, primary stems and secondary stems. Additionally, CRR severity has been calculated by combining the incidence of infection and the extent of discolouration to determine a disease rating, where incidence is the number of subcrown internodes with nonzero severity divided by the total number of plants sampled (Arabi et al., 2015; Mathre et al., 2003).

8 | ECONOMIC LOSSES TO CRR CAUSED BY *B. SOROKINIANA*

8.1 | Worldwide

CRR caused by *B. sorokiniana* is a widespread disease of wheat and barley in warmer and humid regions of the world (Kumar et al., 2002; Mathre et al., 2003). Wheat is generally considered more susceptible to CRR caused by *B. sorokiniana* than barley (Piening et al., 1976). The yield and quality of wheat and barley can be reduced by CRR, making it economically important. The global effect of CRR on crop production varies considerably based on factors such as host cultivars and competitiveness with other microorganisms within the soil (Fernandez et al., 2009; Harba et al., 2020).

CRR caused by *B. sorokiniana* is a significant disease in wheat and barley in the Canadian prairies (Fernandez et al., 2007, 2014; Fernandez & Jefferson, 2004). Surveys from 1969 to 1971 in Canada reported wheat yield losses caused by CRR as high as 28.3%, with an average of 5.7% for Saskatchewan, Manitoba and Alberta provinces (Ledingham et al., 1973). These losses were based on the number of tillers per plant and the number of grains per head in infected and noninfected plants and resulted in approximately 30 million bushels (c.0.8 million tonnes) lost per annum from 1969 to 1971 (Ledingham et al., 1973). Based on the classification of subcrown internode lesions as clean, slight, moderate or severe, the average losses of wheat grain yield at Manitou, Canada were estimated as 30%, 35% and 30% in 1969, 1970 and 1971, respectively (Verma et al., 1976). A survey on CRR in barley in the Alberta, Manitoba and Saskatchewan Canadian prairies indicated CRR costs the industry 54 million bushels (c.1.5 million tonnes) per year, or 10.3% of the crop lost annually from 1970 to 1972 (Piening et al., 1976). In barley, 11.1% yield loss was reported from sowing infested seeds in soil containing low inoculum levels of *B. sorokiniana* in Canada between 1990 and 1993 (Bailey et al., 1997).

In the United States, CRR caused by *B. sorokiniana* dominates the North American prairies (Machacek, 1943; Shrestha et al., 2021). It was reported as pervasive in arid and semiarid regions of the western United States and a primary component of the cereal foot rot complex in Oregon and Washington (Smiley & Patterson, 1996). In a survey of CRR of wheat and barley in south-eastern Idaho (Intermountain West region of the United States) in 2001 and 2002, *B. sorokiniana* was one of the most common pathogens isolated and the most virulent pathogen when tested in greenhouse studies (Strausbaugh et al., 2004). Another survey on CRR from 2008 to 2009 reported that CRR is the most prevalent disease within the Golden Triangle wheat commercial production fields of central Montana in the United States, where CRR was detected in 93% of fields with up to 15% incidence of *B. sorokiniana* isolated from individual tillers (Moya-Elizondo et al., 2011). Samples of spring wheat were collected throughout different commercial fields across North Dakota during 2012, 2013 and 2014 (Shrestha et al., 2021). The results determined that the incidence and severity of CRR were higher in 2012 (a year characterized by warm and dry conditions) compared to the following years 2013 and 2014, based on subcrown internode symptoms (Shrestha et al., 2021). Based on data collected from Canada and the United States, CRR is widely acknowledged to be one of the most significant and prevalent soilborne diseases that affect wheat and barley in North America, including both the Upper Midwest region and Canada.

In China, CRR caused by *B. sorokiniana* has also been documented to impact wheat production. CRR has been found in wheat in the Heilongjiang province of China, in which wheat production was reduced by 25% on the 121,000 ha farm in Hulin County (Zhang et al., 1988). In addition, CRR has also been reported in the Jiangsu province of China with a 69% disease incidence (Li et al., 2011). Both CRR and spot blotch caused by *B. sorokiniana* have been more frequently reported in wheat production areas in north China, where large-scale wheat–maize rotation and straw returning have been used (Su et al., 2021).

Other Mideast Asian countries and Brazil have also reported CRR in wheat and barley growing areas. An average of 40% annual yield loss was documented in three seasons of barley infected by CRR by comparing plots in northern Syria (Van Leur et al., 1997). CRR disease was considered one of the most prevalent diseases in different agro-ecological zones of Syria (Van Leur & Bailey, 2000). In addition, CRR was frequently reported in different parts of the Iranian wheat belt areas, becoming a predominant disease in Iran (Darvishnia et al., 2007; Hajieghrari, 2009). Moreover, CRR in wheat has become an emerging issue in Nepal, Uzbekistan and Cyrus (Bhandari & Shrestha, 2004; Kari, 2001; Turdieva et al., 2020). The estimated wheat yield loss associated with CRR in 17 fields in Rio Grande Sul, Brazil, was up to 23.1% (Diehl et al., 1982).

8.2 | Australia

Generally, CRR was considered to cause approximately 10%–15% yield losses in susceptible varieties in Australia (GRDC, 2016). A survey from 1988 to 1989 in South Australia demonstrated that the average incidence of CRR-infected plants in crops was 60% in wheat and 77% in barley (Whittle, 1992). CRR became a widespread disease in Queensland, with estimated wheat yield losses of 13.9%–23.9% and 6.8%–13.6% between susceptible cultivars and partially resistant cultivars reported in three sites (Wildermuth et al., 1992).

National wheat and barley surveys in 2008 reported that CRR was estimated to cause a $30 million (0.7%) average annual yield loss in wheat and a $13 million (1%) average annual yield loss in barley (Table 1, summarized from Murray & Brennan, 2009a, 2009b). The yield loss caused by CRR was primarily reported in Australia's northern and southern areas, and to a lesser extent, in the western area (Murray & Brennan, 2009a, 2009b). Average annual wheat loss caused by CRR in 1988 and 1998 in the northern region (Queensland Central, NSW North-East/Queensland South-East and NSW North-West/Queensland South-West) were 3.1% and 1.7%, which is much lower than 6.8%–23.9% reported from Queensland by Wildermuth et al. (1992).

Subsequent reports since Murray and Brennan (2009a, 2009b) suggest that CRR is a much more severe disease than previously reported in Australia. CRR symptoms were observed in 20%, 6% and 20% of 40 plants sampled at the maximum biomass stage from the northern, central and southern agricultural regions in Western Australia, respectively, from 2011 to 2013 (DAF, 2015). In central and northern NSW, *B. sorokiniana* was detected in 69% of 248 random paddocks surveyed in 2011, with 16% of paddocks ranked to be at risk of yield loss due to CRR (Simpfendorfer et al., 2011). The most recent report detected CRR in 52%, 31% and 29% of 1774 cereal crops surveyed from 2014 to 2018 in the northern, western and southern regions of Australia, respectively (Simpfendorfer et al., 2020). Medium and high infection levels (>11%) were observed in northern, western and southern areas in 13%, 8% and 5% of the paddocks sampled, respectively (Simpfendorfer et al., 2020). This is much greater than previously reported.

Multiple-pathogen infections of *B. sorokiniana* and other soil/stubble-borne diseases, such as crown rot, are widespread in Australia's northern grain-growing regions, which are expected to result in increased yield loss (Simpfendorfer et al., 2020). Crown rot and CRR have similar symptoms, making them difficult to distinguish without pathogen isolation and identification (Saad et al., 2021). According to a root disease survey conducted in the wet 2016 season at Tamworth, CRR appeared to be a slightly larger yield loss driver than crown rot when both were present (McKay et al., 2018). Therefore, CRR may be misinterpreted as crown rot, and the yield losses of CRR might be higher than reported in previous studies. These reports indicate that the impact of yield loss caused by CRR as defined by Murray and Brennan (2009a, 2009b) could be potentially underestimated, particularly in Australia's northern and western regions. As a result, CRR could be more widespread and frequently overlooked in the Australian wheat cropping areas owing to the lack of distinctive above-ground symptoms and less extensive research on this disease. There is no recent dedicated yield loss trial that has been published. Based on economic loss data and limited yield loss information caused by CRR in Australia and other countries, it is expected that CRR could be considered a national and potentially global concern in wheat and barley production.

9 | MANAGEMENT

Multiple management methods and potential strategies have been proposed to prevent yield loss due to CRR. However, CRR is a chronic disease because *B. sorokiniana* can survive in the soil or as mycelia in host residues and is extremely difficult to manage (Bockus et al., 2010; Wildermuth & McNamara, 1991). Integrated management options involving cultural control such as crop rotation, soil and residue management, sowing of resistant varieties, and biological and chemical control are recommended for CRR caused by *B. sorokiniana* on wheat and barley (Duveiller, 1997; Simpfendorfer et al., 2020).

TABLE 1 Estimated average annual and potential yield loss (%) and cost ($ million) caused by common root rot in wheat and barley in each Grains Research and Development Corporation cropping region of Australia (summarized from Murray & Brennan, 2009a, 2009b).

	Wheat				Barley	
	Present average annual loss (%)				Present average annual loss (%)	
Cropping region	1988	1998	2008	Potential average annual loss (%)	2008	Potential average annual loss (%)
Northern	3.1	1.7	0.8	3.2	1.7	4.7
Southern	0.2	1	1.2	4	1.4	3.7
Western	0.5	0.1	0	0	0	0
Australia	–	–	0.7	2.4	1	2.9
Cost ($ million)	–	–	30	108	13	37

9.1 | Cultural control

9.1.1 | Seed and soil testing

At planting, CRR severity in wheat and barley is highly linked to the *B. sorokiniana* population in the soil (Tinline et al., 1988; Wildermuth & McNamara, 1991). The quantitative DNA-based soil test PREDICTA B provides relative disease risk or population density for a variety of pathogens, which can be used to inform management choices (Simpfendorfer, 2020). Therefore, PREDICTA B testing to determine the DNA concentration of *B. sorokiniana* in the soil before planting is a useful and valuable method for growers to assess the risk of CRR in the paddock (McKay et al., 2018; Simpfendorfer et al., 2011). To prevent disease in wheat and barley, growers should use seeds that are free of any contamination before planting.

9.1.2 | Tillage treatments

Tillage treatments to reduce *B. sorokiniana* in the soil have been experimented with in different countries. In Brazil, fewer *B. sorokiniana* conidia were found in the soil under no-tillage compared to conventional tillage (Reis & Abrao, 1983). In Canada, lower *B. sorokiniana* inoculum density remained in no-tillage than conventional tillage (Bailey & Duczek, 1996), although no consistent effects of tillage treatments on CRR were observed in some years and locations (Bailey & Duczek, 1996; Conner et al., 1987). The no-tillage treatment reduced disease severity and incidence of CRR compared to other types of tillage in Queensland (Wildermuth et al., 1997) and Victoria (De Boer & Kollmorgen, 1988). However, zero tillage is not sufficient to effectively control CRR and should be combined with different crop rotations for optimal results (Bailey & Duczek, 1996). No papers on tillage treatments to reduce CRR have been published since 2000. Therefore, tillage management may be outdated and requires additional research to understand the impact of current farming practices on CRR inoculum levels in soil.

9.1.3 | Seeding depth

Reduced yields caused by CRR were associated with increased seeding depths, because deeper sowing lengthens the subcrown internode, increasing wheat and barley susceptibility to CRR (Duczek & Piening, 1982; Simpfendorfer et al., 2020). Sowing wheat and barley deeper and earlier into warmer soils has been linked to a rising prevalence of CRR across Australia, especially in the northern grain-growing region (Simpfendorfer et al., 2020).

9.1.4 | Stubble management

As *B. sorokiniana* survives in stubble and soil for up to 10 years, stubble management practices have been the focus of CRR management. A recent study reported that moist conditions increased *B. sorokiniana* development within postharvest cereal stubble, and inoculum density may increase if wet weather occurs after harvest (Petronaitis et al., 2020). A reduction of cereal stubble biomass may limit the proliferation of *B. sorokiniana* after harvest, leading to less inoculum carried forward to the following season (Petronaitis et al., 2020). Harvesting at low heights or cutting for hay are possible options, but field validation is required (Petronaitis et al., 2020).

Stubble burning can reduce the carry-over of diseases in subsequent sensitive crops, particularly those fungi that survive in stubble (Scott et al., 2010). Wheat cropping areas in Australia have seen increases in the number of CRR outbreaks associated with stubble retention (Scott et al., 2010). The severity of CRR on wheat was less in the stubble burning or physically removed treatments than in the stubble-retained treatments (Wildermuth et al., 1997). However, stubble burning is not recommended in Australian cropping systems as it causes losses of nitrogen and soil organic carbon, soil erosion, air pollution and turbidity in the waterways compared to stubble-retained systems (Scott et al., 2010). Petronaitis et al. (2022) explored the possibility of using microwave radiation in the laboratory to reduce conidia of *B. sorokiniana* in stubble and soil with significant mortality reported. This was described as a first step and needs to be further investigated in the field.

9.1.5 | Crop rotation

Balanced crop rotation is essential for long-term soil health and reduces the risk of soilborne diseases. As *B. sorokiniana* can survive for at least 2 years on wheat and barley residues at the soil surface, ley farming or a rotation of planting noncereal crops for at least 2 years is highly recommended when *B. sorokiniana* is present (Butler, 1961; Draper et al., 2000; Windels & Wiersma, 1992).

Crop rotation systems are fundamentally affected by the degree of cross-infection between species. Rotation crops like field pea, faba bean, canola, lucerne, mustard, mungbean, sorghum or sunflower are recommended to reduce *B. sorokiniana* levels (Moore et al., 2005; Wildermuth & McNamara, 1991). Specifically, a rotation of durum wheat with *Brassica carinata* contributed to a significant reduction in CRR in seven farms in Sicily (Italy) from 2011 to 2013 (Campanella et al., 2020). In Canada, a rotation that included two or more years of flax (*Linum usitatissimum*) as a break crop in wheat and barley successfully decreased the amount of *B. sorokiniana* inoculum in the soil (Conner et al., 1996). However, proper rotation to nonsusceptible crops or planting partially resistant crops is not always economically viable, although multiple benefits have been reported (Angus et al., 2015). The production of barley or wheat for two or more consecutive seasons is typical in farming in Australia (Fletcher et al., 2016; Windels & Wiersma, 1992). Obtaining maximum benefit is often a more powerful motivator, and we must acknowledge that most farmers' priorities are likely to focus on short-term profitability than environmental concerns (Liu et al., 2018; Morton et al., 2017). Therefore, crop rotation may not be the most effective and practical way to control CRR.

9.1.6 | Resistant varieties

Wheat varietal resistance is related to the severity of CRR (Whittle, 1992). Among all bread and durum wheat varieties in Australia, only one durum wheat genotype that is moderately resistant to moderately susceptible can be considered for cultivation where CRR exists (GRDC, 2021). The availability of CRR resistance in commercial Australian wheat varieties has decreased in recent years. For example, in the last 7 years, the number of commercial cultivars with levels of CRR resistance has reduced from 30% to 0% for bread wheat, and from 100% to less than 20% for durum wheat in Queensland, calculated from the 2014 Queensland Wheat Variety Guide (GRDC & DAFF, 2014) and the 2021 Queensland Winter Crop Sowing Guide (GRDC, 2021). Choosing wheat genotypes with the most resistance is the most effective and direct way to reduce yield losses due to CRR (Arabi et al., 2019; Shrestha et al., 2021). No barley or bread wheat cultivar is resistant to CRR and only one durum wheat variety is currently available to Queensland growers with moderate levels of resistance to CRR (DAFF, 2014; GRDC, 2019, 2021). Although planting CRR-resistant wheat and barley cultivars is an effective method to avoid major losses, there are currently not many options for growers. Therefore, more research and support for the development of CRR-resistant varieties should be encouraged in the future.

9.2 | Genetic resistance to CRR

In general, there are inadequate commercial germplasm resources with resistance to CRR to satisfy worldwide wheat and barley breeding applications because the analysis of complex quantitative trait loci (QTLs) is required (Gupta, Chand, et al., 2018; Lehmensiek et al., 2010; Su et al., 2021). Three papers have been published on genomic studies in barley (Fr926–77/Deuce and Virden/Ellis crosses; Bowman; Delta and Lindwall) to discover QTLs for resistance to CRR using random amplified polymorphic DNA (RAPD) markers (Kutcher, Bailey, Rossnagel, & Franckowiak, 1996; Kutcher, Bailey, Rossnagel, & Legge, 1996; Lehmensiek et al., 2010). The potential of using these barley sources with resistance traits for gene pyramiding to augment resistance levels holds promise. Nonetheless, further investigations involving diverse parent cultivars under different environmental conditions within Australia are essential to ascertain the practicality of this approach, as no subsequent research in this area has been reported to date. The resistance of wheat to *B. sorokiniana* has been primarily related to investigating the transcriptional activation of pathogenesis-related protein genes and the accumulation of reactive oxygen species (Su et al., 2021). A broader range of wheat and barley germplasm must be screened for breeding programmes to identify effective sources of resistance to CRR during both the seedling and adult plant stages (Shrestha et al., 2021).

Morphological and molecular markers are crucial tools for developing genetic diversity strategies and when associated with CRR resistance could significantly enhance the efficiency of identifying resistant germplasm, leading to the transfer of these traits to commercial cultivars (Kutcher, Bailey, Rossnagel, & Franckowiak, 1996; Li et al., 2021; Qalavand et al., 2023). Molecular marker methods, including amplified fragment length polymorphism (AFLP), RAPD, retrotransposon microsatellite amplified polymorphism (REMAP), inter-simple sequence repeat (ISSR) and inter-primer binding site (IPBS), have been effectively employed to detect genetic diversity among *B. sorokiniana* populations across multiple countries (Arabi & Jawhar, 2007; Ghazvini & Tekauz, 2012; Göksel et al., 2020; Knight et al., 2010; Zhong & Steffenson, 2001). To be more precise, Zhong and Steffenson (2001), Knight et al. (2010) and Ghazvini and Tekauz (2012) conducted the research on spot blotch, while Arabi and Jawhar (2007) and Göksel et al. (2020) focused on CRR. The application of these molecular markers offers significant insights into the genetic variations between species, resistance responses and the selection of resistant cultivars.

Understanding the genetic structure of the pathogen population, genetic diversity and germplasm analysis will assist breeders in choosing an appropriate strategy for cultivating resistant varieties. Qalavand et al. (2022) analysed the genetic variability of germplasm and the activities of eight defence-related enzymes to CRR in three known resistant wheat varieties in Iran, with *B. sorokiniana* inoculation at different time points. They found wheat resistance to CRR is primarily related to the increased activity of antioxidant enzymes, although the specific metabolic pathway needs further investigation (Qalavand et al., 2022). Moreover, Qalavand et al. (2023) conducted screening of 33 wheat genotypes for their resistance to *B. sorokiniana*, under greenhouse and field conditions, and performed real-time quantitative PCR analysis on leaves and roots using 10 novel candidate gene markers. The results showed that cv. Alvand had the lowest CRR severity, followed by Baharan and Bam (Qalavand et al., 2023). These findings highlight the potential of defence-related genes and enzymes that could contribute to the development of resistant wheat genotypes in the future.

Investigating and comprehending the mechanisms of necrotrophic effectors on developing genetic interventions could increase plant resistance to pathogens such as *B. sorokiniana* (Shao et al., 2021). Mahdi et al. (2022) demonstrated how the collaboration of the fungal root endophyte *Serendipita vermifera* and the bacterial microbiota can offer synergistic protection against *B. sorokiniana* in barley. This study also demonstrates that there is a modulation of effector expression for both the pathogenic and endophytic fungus. Additional research has unveiled that alternative necrotrophic pathogens generate necrosis-inducing effectors to exploit resistance mechanisms, particularly in regard to other pathogens found in wheat and barley (Friesen et al., 2018; McDonald et al., 2018; Navathe et al., 2020). The detection of a *ToxA*-like gene in the genome of three *B. sorokiniana* isolates responsible for multiple wheat and barley diseases, sharing homology with *PtrToxA* and *SnToxA*, was accomplished through genome analyses (McDonald et al., 2018). Furthermore, isolates carrying *ToxA* genes demonstrated increased virulence on *Tsn1* wheat genotypes based on pathogenicity assays, implying that ToxA from *B. sorokiniana* operates similarly to other ToxA effectors (McDonald et al., 2018). The *ToxA* gene has also been found in the *B. sorokiniana* population of south-central Texas. The prevalence of ToxA sensitivity in winter wheat cultivars in the central and south central regions of the United States suggests that *B. sorokiniana* isolates carrying the *ToxA* gene may have a selective advantage (Friesen et al., 2018). *B. sorokiniana* isolates that carry *ToxA* gene have also been reported to be virulent towards wheat genotypes carrying the *Tsn1* sensitivity gene (Navathe et al., 2020). *ToxA* serves as an illustrative example of a gene that can be acquired by various wheat pathogens to prompt host susceptibility. Elimination of *Tsn1* from wheat may provide a route to improved disease control against *B. sorokiniana* isolates that carry the *ToxA* gene. However, it is important to note that *Tsn1* also provides resistance against other pathogens, so its elimination may increase susceptibility to these pathogens. Mahdi et al. (2022) and McDonald et al. (2018) conducted research on *B. sorokiniana* in general, while Friesen et al. (2018) and Navathe et al. (2020) focused on spot blotch. It can be concluded that further research is needed to determine the role of ToxA in susceptibility to CRR, as no paper has focused on this disease.

Experiments in modified genes in wheat and barley have been conducted. Germplasm derived from crossing *Aegilops ovata* with *T. aestivum*, using Chinese Spring PFT Ib genetic stock and the cultivar Leader, have reported improved resistance to CRR (Bailey et al., 1995). Additionally, the *GmPGIP3*-expressing transgenic wheat lines strongly increased the resistance to CRR in China, offering a promising gene resource for enhancing wheat resistance to CRR (Wang et al., 2015). Transgenic wheat lines expressing *DmAMP1W* in vitro have been developed and also indicated improved resistance to CRR (Su et al., 2020). Another experiment in China indicated that stable transgenic expression of *TaTLP1* (thaumatin-like protein) increased the resistance against CRR in wheat (Cui et al., 2021). Doubled-haploid lines with CRR resistance have been identified by Arabi et al. (2021) in field experiments, which could be used to develop high-yielding barley varieties with defence mechanisms that might work in barley against both CRR and the leaf disease spot blotch based on the results from seven promising resistant doubled-haploid lines within the 40 lines tested. These experiments indicated the resistance is quantitative and requires intensive resources and funding to incorporate these sources of resistance into commercial cultivars.

Resistant cultivars may help limit the growth of *B. sorokiniana* in plant tissue, but it may not completely stop the pathogen from colonizing the plant and therefore may not be used as the sole management tool (Liueroth et al., 1996). Despite this, genetic resistance is still considered one of the most efficient and sustainable ways to help manage root rot diseases (Qalavand et al., 2022). In Australia, there is no primary research involving wheat genetic improvement for CRR resistance. Although the development of transgenic resistance to CRR is a promising approach, breeding CRR-resistant varieties is deemed more viable and cost-effective in Australia, given the limited acceptance of transgenic cultivars.

9.3 | Chemical control

There are currently no fungicide treatments registered for CRR in Australia; however, significant research on chemical control has been conducted internationally. Among the chemical control methods for CRR, seed treatment fungicides are one of the most common methods of application. Presowing seed treatment with fungicides such as mancozeb is an effective way to reduce seedling damage by *B. sorokiniana* (Burlakoti et al., 2013; Giri et al., 2001: Sultana & Rashid, 2012).

Generally, fungicides protect the root system from infection and allow the plant to grow and develop within the protection circle, remaining partially effective against CRR for an extended period (Wei et al., 2020). The systemic fungicides triadimenol and difenoconazole used as seed treatments significantly reduced the incidence of CRR in barley and wheat plants, and increased yield by 7% to 9% in field plots in North Dakota, United States (Stack & McMullen, 1991). Imazalil seed treatment reduced the severity index of CRR in barley from 76 to 66 in large-scale field trials in Idaho, United States, but did not control the disease completely. The fungicide Raxil (Bayer Crop Science) containing tebuconazole was tested on seed in South Dakota, United States, and results indicated that the fungicide increases seed germination and establishment under pressure from *B. sorokiniana* but may not completely inhibit disease development when the seed is contaminated with pathogens (Kaur, 2016). In a 2-year field experiment in Hebei province, China, Wei et al. (2020) found that 82.7% of wheat plants were suppressed against CRR at the seedling stage and 68.5% at the adult stage after seed treatment with fludioxonil + difenoconazole. Seed treatment with demethylation inhibiting (DMI) systemic fungicides partially controlled CRR; however, complete control was difficult to achieve because infection occurs over a long period of the crop lifecycle (Mathre et al., 2001).

Fungicide seed treatments that have been reported to offer some control of CRR in wheat and barley are summarized in Table 2. Multiple fungicide treatment formulations have been registered in the United States and Canada. Different formulations are reported to have varying levels of control of CRR (effective control > suppression of the disease > moderate control). Suppression means consistent control below the optimal level but still offers commercial benefits (Syngenta Canada, 2022). When using products with more than one active ingredient, the effectiveness of all ingredients can be combined for a relatively high level of disease control. In Table 2, both difenoconazole and triticonazole, which belong to the triazole group, are effective ingredients for suppressing CRR in Canada and the United States (McMullen & Bradley, 2007;

TABLE 2 Fungicide seed treatments for wheat and barley to control common root rot (CRR) in the United States, Canada and Australia.

Fungicide common name	Performance listed on the label	Country	References
Carboxin + imazalil + thiabendazole	Suppress CRR, wheat only	USA	Draper et al. (2000), McMullen et al. (2003)
Difenoconazole + mefanoxam	Suppress CRR, for spring and winter wheat only		Draper et al. (2000), Dyer et al. (2007), McMullen and Bradley (2007), McMullen et al. (2003)
Imazalil	Suppress CRR in wheat and barley		Draper et al. (2000), McMullen and Bradley (2007), McMullen et al. (2003)
Tebuconazole	Moderate control of early season CRR		Draper et al. (2000), McMullen and Bradley (2007)
Tebuconazole + thiram			Draper et al. (2000), McMullen et al. (2003)
Triticonazole + thiram			McMullen and Bradley (2007), McMullen et al. (2003)
Triticonazole	Suppress CRR in wheat and barley		McMullen and Bradley (2007)
Tebuconazole + metalaxyl + imazalil	Suppress early CRR in wheat and barley		McMullen and Bradley (2007), McMullen et al. (2003)
Triticonazole	Moderate control of CRR		Peairs et al. (2012)
Metalaxyl + pyraclostrobin + triticonazole	Suppress CRR in wheat and barley		Dyer et al. (2007)
Difenoconazole + metalaxyl-M and S-isomer	Suppress CRR in wheat and barley	Canada	Syngenta Canada (2023)
Difenoconazole + Metalaxyl-M and S-isomer + sedaxane + fludioxonil	Suppress CRR in wheat and barley		Syngenta Canada (2022)
Tebuconazole + metalaxyl	Suppress CRR in wheat and barley	USA and Canada	Bayer Crop Science (2009), Dyer et al. (2007), McMullen and Bradley (2007), McMullen et al. (2003)
Carboxin + thiram	Effective control of CRR for barley seed treatments in laboratory experiments	Australia	Platz et al. (1999)

Syngenta Canada, 2023). While these products are registered for use on wheat and barley in Australia, they are not registered for controlling CRR. Based on the findings of four laboratory barley experiments conducted by Platz et al. (1999), the most effective seed treatments for controlling *B. sorokiniana* at the seedling stage are 50 g thiram and 100 g carboxin per 100 kg barley seed. The National Registration Authority granted an emergency use permit in 1999 (Platz et al., 1999). Nevertheless, there is a lack of further research conducted in either the greenhouse or the field to confirm its effectiveness. Since then, there have been no reported official chemical formulations to address CRR treatment in Australia.

Potential groups of combined fungicides used for CRR treatment were functional and promising in other countries; however, more sound and stable combinations of chemicals need to be explored to meet the standards of chemicals in Australia for wheat and barley. Despite the growing importance of chemical fungicides for controlling CRR, they might disturb the microbial balance, harming beneficial microorganisms and resulting in pathogens that become more resistant to chemicals (Yi et al., 2021). The effectiveness of chemicals is also unpredictably variable and not consistently effective against *B. sorokiniana* (Kumar et al., 2002; Shcherbakova et al., 2018). Thus, a different group of fungicides could be rotated or used in an integrated disease management programme to suppress CRR and avoid chemical resistance.

9.4 | Biological control

The lack of resistant varieties and the concern over environmentally friendly fungicides to combat *B. sorokiniana* has prompted the need and attention for alternative biological strategies (Kumar et al., 2002; Yue et al., 2018). A key to preventing fungal growth and colonization is delaying penetration, achieved by biochemical defence mechanisms (Liueroth et al., 1996). Promising biocontrol techniques have been tested to control CRR in wheat. Multiple antagonistic strains of fungi and bacteria that are found effective in preventing *B. sorokiniana* are presented.

Salehpour et al. (2005) stated that all *Trichoderma* isolates tested increased plant height, fresh and dry weight of roots and shoots of wheat seedlings infected with *B. sorokiniana*. *Trichoderma viride* T112 was the most effective of the *Trichoderma* isolates for controlling mycelial growth of *B. sorokiniana* in wheat grown in the glasshouse. Eken and Yuen (2014) found the bacterial strain *Lysobacter enzymogenes* C3 alone or in combination with the fungal strain *Rhizoctonia*

BNR-8-2 slowed *B. sorokiniana* growth in two wheat varieties grown under greenhouse conditions. These authors concluded that these microbes could potentially be produced as a commercial biological control agent in the future.

Two spring wheat cultivars treated with purified mycelial extracts of a tomato wilt-controlling strain of *Fusarium sambucinum* FS-94 before sowing decreased the incidence of CRR by 30%–40% and the severity by 37%–50% in four growing seasons between 2013 and 2016 (Shcherbakova et al., 2018). *F. sambucinum* FS-94 could act as non-fungitoxic wheat-protecting metabolites (Shcherbakova et al., 2018). The effectiveness of the biological agent actinobacterium *Nocardiopsis dassonvillei* in controlling CRR in wheat was studied by Allali et al. (2019), who demonstrated that the disease severity index in wheat decreased from 90.8% to 27.7%. According to Yue et al. (2018), the biocontrol agent *Chaetomium globosum* 22–10 is a potential antagonist and exhibited growth inhibition of 66.7% in controlling *B. sorokiniana* in wheat seeds on the Petri dish.

Bacteria strains of *Bacillus* species are abundant in soil and offer high potential for biocontrol and development into commercial products. *Bacillus* species have attracted more attention than other genera (Miljaković et al., 2020; Shafi et al., 2017; Yi et al., 2021). Harba et al. (2020) stated that the antagonistic effect of *Bacillus* species could be a significant biological control agent to inhibit radial growth of *B. sorokiniana* in vitro ranging from 59% to 92%, compared to the untreated control. Among the *Bacillus* species, *B. amyloliquefaciens* is known for its capacity to boost plant development and combat various plant-related diseases in different crops (Cheng et al., 2019; Miljaković et al., 2020). Strain XZ34-1 of *B. amyloliquefaciens* demonstrated high biocontrol efficacy of *B. sorokiniana*, inhibiting mycelial growth and spore emergence up to 78.2% in wheat (Yi et al., 2021). *Bacillus halotolerans* Jk-25 also displayed a strong antagonistic effect against *B. sorokiniana* and demonstrated broad-spectrum biocontrol of pathogens under greenhouse conditions (Kang et al., 2023).

More than 100 commercial *Bacillus* formulations have been registered in China for different crops (Cheng et al., 2019). Some effective bacteria have been registered as bacterial pesticides for controlling CRR on barley, for example, *Bacillus subtilis* IPM-215 in Russia and Ukraine, *B. subtilis* BIM B-760D in Belarus and *Pseudomonas fluorescens* 7G, 7G2K, 17-2 in Russia (Gouli et al., 2020). If practical and reliable formulations are readily available in Australia, combined with chemical fungicides, biological agents may be an essential component of controlling *B. sorokiniana* in the future.

10 | DISEASE DETECTION

The elimination of *B. sorokiniana* from a field in a short period of time has not been demonstrated, as low levels of the fungus can survive in the soil and infect plants throughout all growth stages. Currently, there are no effective methods to control CRR at late infection stages. When the crown and root system of the plant is infected with *B. sorokiniana*, the pathogen has the capacity to spread to broad areas, reducing productivity on a large scale and lowering the quantity and quality of wheat and barley products. If early infection can be detected, it might allow growers to make whole-farm decisions about crop variety, fertilizer and water applications, reducing the impact caused by CRR at the early stage. Early detection and assessment of plant diseases are essential for the accurate visual estimation of the incidence, severity and adverse effects of diseases on agricultural produce.

Identifying the non-distinctive symptoms of CRR relies on removing plants from the ground and proper disease rating assessment. The sampling procedures are crucial for the accurate detection and estimation of pathogen levels in a host crop (Bock et al., 2010). Generally, methods for determining and quantifying CRR include traditional visual plant disease assessment, isolation of the pathogen from plant tissues and potential remote sensing disease detection methods. Traditional plant disease assessment and pathogen isolation require personnel with experience and training in detecting plant diseases, which requires extensive time, labour and capital (Mahlein, 2016). Therefore, traditional plant disease detection may not be recommended for large-scale fields. Remote-sensing technologies have been extensively tested for many years for effective disease detection and quantification (Mahlein, 2016). Automated, objective and reproducible detection systems such as RGB imaging, multispectral sensors, thermography and chlorophyll fluorescence have demonstrated their potential for early infection detection and measurement of plant diseases (Devi, 2021; Mahlein, 2016).

Much of the literature on remote sensing is focused on disease detection in visually distinct diseases, such as yellow rust, wheat spike blast disease and powdery mildew, using multispectral and hyperspectral sensors in wheat and barley with high accuracy at mid to late infection stages. Yao et al. (2019) used the handheld line-scanning hyperspectral sensor to achieve 92.1% accuracy in detecting yellow rust of wheat at the asymptomatic and early infection stages in a small laboratory leaf trial. Gongora-Canul et al. (2020) achieved more than 70% accuracy and more than 80% precision in quantification of wheat spike blast (*Magnaporthe oryzae* pathotype *Triticum*) disease severity employing a multispectral camera installed on an unmanned aerial vehicle, based on nongreen pixels from anthesis to late development stages. Behmann et al. (2018) were able to detect powdery mildew (*Podosphaera fusca*) on barley leaves using a handheld Specim IQ hyperspectral camera at mid-late infection with a small greenhouse canopy plot trial. From these articles, visual disease detection can be implemented and analysed with high accuracy.

Unlike visual disease detection, soilborne diseases are more difficult to detect as symptoms are not easily seen by the naked eye at the early infection stage. For soilborne disease detection, Wang et al. (2020) presented an automated approach using MicaSense cameras to distinguish cotton root rot (*Phymatotrichopsis omnivora*) area and healthy plants with a total accuracy of 88.5% based on slight yellowing or bronzing of the leaves and plant wilts.

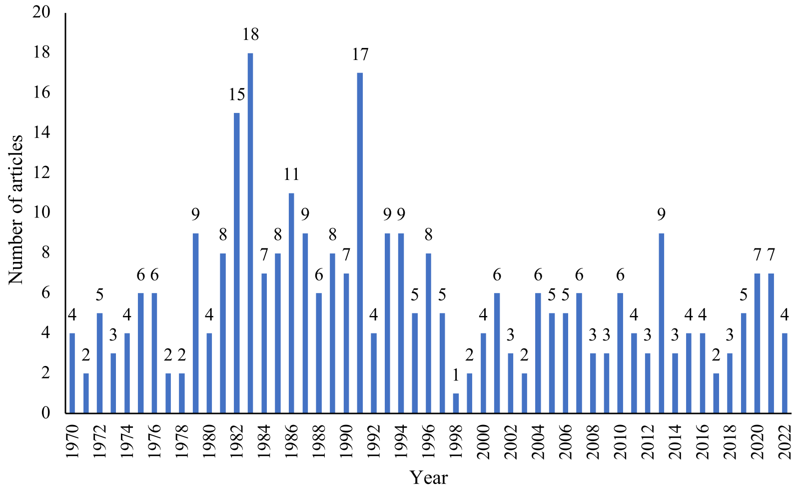
Hyperspectral imaging was used to identify charcoal rot disease (*Macrophomina phaseolina*) with reddish-brown discolouration of the vascular tissue, wilting and chlorosis symptoms at the later growth stage (Nagasubramanian et al., 2019). They achieved a classification accuracy of 95.73% on soybean crops affected with charcoal rot using the hyperspectral sensor (Nagasubramanian et al., 2019). The NIRscan Nano hyperspectral point sensor has been used in three glasshouse and two field trials for early detection of the stubble-borne disease crown rot (*Fusarium pseudograminearum*) in bread wheat with accuracy up to 74% (Humpal et al., 2020). Additionally, Alt et al. (2020) and Gurova et al. (2019) have published papers on the remote sensing detection of *B. sorokiniana* in wheat. Both these papers have been published in non-English journals, and it is not clear if the papers refer to CRR or *B. sorokiniana* infections on leaves. Gurova et al. (2019) reported variety resistance responses on wheat seedlings infected with *B. sorokiniana* by analysing seven different spectral indices from the multispectral spectrum. Alt et al. (2020) demonstrated the use of the Specim IQ, a mobile hyperspectral camera, to study wheat seedlings infected by *B. sorokiniana*. Sensing techniques could be developed that focus on the subtle changes in plants with CRR at the early infection stages, which have the potential to inform farmers how widespread the disease is within a paddock to assist with whole-farm management, alleviating losses to CRR in winter cereals in the future.

Early detection and precise mapping of the spatial distribution and severity of CRR are vital for growers to minimize the adverse effects of CRR. Remote-sensing technologies using nondestructive imaging or spectral techniques could potentially map and identify existing plant disease caused by *B. sorokiniana*. To make the right decisions at the right time, continuous monitoring of wheat and barley crops is crucial to forecast disease evolution. Further development could assist in developing pathogen/genetic resistance through phenotyping to provide management options for CRR in Australia.

11 | CRR RESEARCH FOCUS

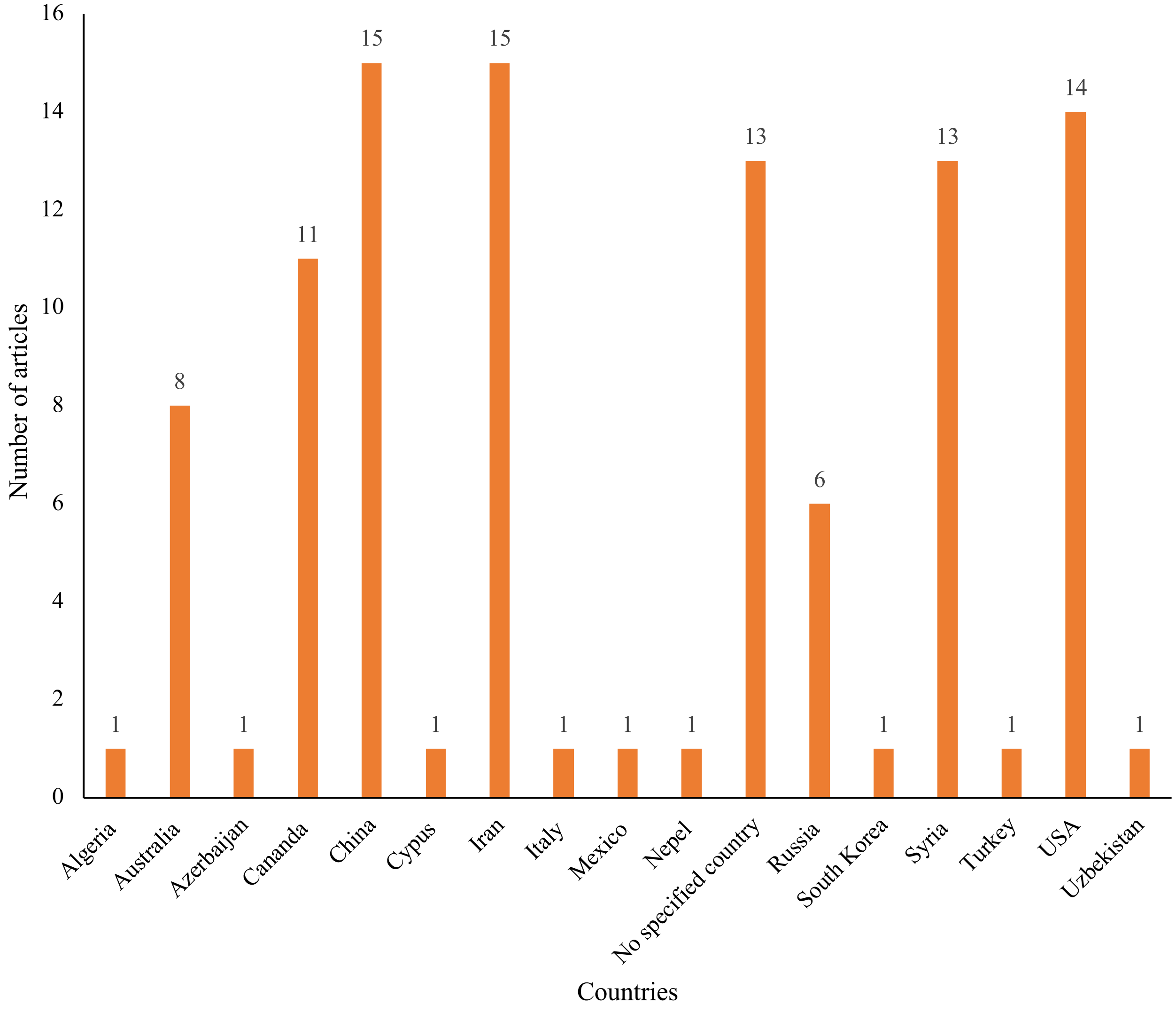
CRR is re-emerging as a significant disease threatening wheat and barley production in Australia and worldwide. Understanding what opportunities are available to the wheat and barley industries to manage and control CRR is significant. Quantities of articles on Google Scholar on the subject of CRR in wheat or barley are presented in Figures 2–4 with a focus on the number of articles from 1970 to 2022, countries conducting the research and the research topics between 2000 and 2022. The data presented in the figures are derived from searching for the terms 'common root rot' in 'wheat' or 'barley' only in the title and English abstract and content from Google Scholar. The journal articles that included CRR caused by *B. sorokiniana* as a section of a paper or those that focused on *B. sorokiniana* as a pathogen of other diseases are not included. Articles and reports in non-English languages from different countries are also not included. Additionally, papers on CRR in other crops, such as oat and rye, are not represented in the data here. Local government documents and media articles from around the world are not included in the data as they are not academic papers in Google Scholar.

Academic papers related to CRR have been published every year between 1970 and 2022, although the numbers fluctuate from year to year (Figure 2). The number of papers published from the 1980s to 1990s was the most frequent, indicating the significance of the disease during this time. Although the numbers of academic publications after 2000 on Google Scholar are less frequent, researchers have consistently been interested in CRR disease-related topics. The decline in publications may indicate reduced funding available for CRR research despite an indication that it is an ongoing issue, as reported in a large number of official reports from local governments, media articles and research papers from different countries (CPN, 2022; DPIRD, 2015; Moore et al., 2005; Murray & Brennan, 2009a, 2009b;



Method: Searched for common root rot in the title of the article, wheat or barley only, English abstract and content only in Google Scholar.

FIGURE 2 Number of articles published on common root rot in wheat and barley from 1970 to 2022. Data source: Google Scholar. [Colour figure can be viewed at wileyonlinelibrary.com]



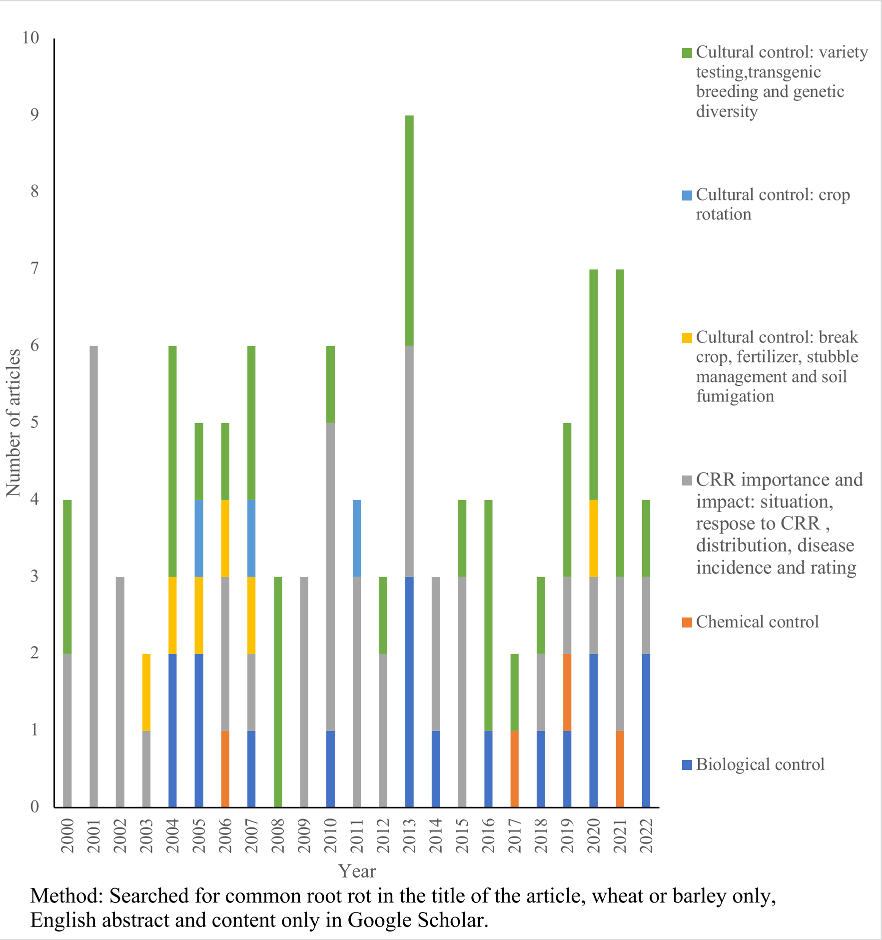
Method: Searched for common root rot in the title of the article, wheat or barley only, English abstract and content only in Google Scholar.

No specified country: not involved with specific resources from a specific country.

FIGURE 3 Number of articles published on common root rot in wheat and barley in different countries from 2000 to 2022. Data source: Google Scholar. [Colour figure can be viewed at wileyonlinelibrary.com]

Syngenta Canada, 2022). This indicates that CRR remains prevalent in wheat and barley paddocks worldwide.

Figure 3 shows that academic articles were published on CRR in 17 countries from around the world between 2000 and 2022, in which China, the United States, Iran, Syria, Canada and Australia have more articles published than other countries. This may correlate to how frequently CRR appears in these countries. More academic papers were published in Australia before 2000 (Conner et al., 1996; Diehl et al., 1982; Piening et al., 1976; Purss, 1970; Van Leur et al., 1997; Wildermuth, 1986; Wildermuth & McNamara, 1991), while more media news and reports from local governments were issued after 2000 (CPN, 2022; DPIRD, 2015; Moore et al., 2005; Murray & Brennan, 2009a, 2009b; Somes, 2018; Syngenta Canada, 2023). Fact sheets about CRR are available and written by GRDC, New South Wales and the Queensland government. At the time of manuscript preparation, the Broad Acre Cropping Initiative (BACI), which is a collaboration between the Queensland government and the University of Southern Queensland (UniSQ), was investing resources into a



Method: Searched for common root rot in the title of the article, wheat or barley only, English abstract and content only in Google Scholar.

FIGURE 4 Numbers of articles published on the importance, impact and management of common root rot in wheat and barley from 2000 to 2022. Data source: Google Scholar. [Colour figure can be viewed at wileyonlinelibrary.com]

project aimed at determining the detection and impact of CRR in Queensland winter cereals. This project was funded in response to the rising levels of CRR detected in Queensland and the lack of information available to growers to control losses to this disease.

Over the past 20 years, more papers on the cultural control strategies for CRR have been published than biological and chemical controls (Figure 4). This may reflect that cultural control strategies are perceived to be effective and applicable for combating CRR. Many papers focus on variety testing and transgenic breeding in the cultural control methods, highlighting the importance of breeding new varieties resistant to CRR as an effective management tool. Additionally, more studies have been conducted on discovering new biological agents in the past decade, indicating biological control is a current research trend. Chemical reactions on CRR seem to be less of a focus for researchers in the past 15 years. The reasons may involve environmental issues, chemical resistance, chemical legislation and financial constraints.

12 | CONCLUSIONS AND RECOMMENDATIONS

When visual CRR symptoms appear in wheat and barley, it is usually too late to stop the disease because the root system is severely damaged. Maintaining a clean field and testing the level of *B. sorokiniana* inoculum in the soil before planting can minimize the risk of CRR. CRR can appear as early as the seedling and tillering stages but becomes more evident after flowering with no distinct paddock symptoms in most years. CRR can be seen to be more prevalent in nitrogen-deficient paddocks; hence, ensuring adequate nitrogen in the soil is vital.

Resistant varieties are not available to Australian growers as a management tool. Therefore, large-scale screening of resistant wheat germplasm is still essential for the development of an effective wheat breeding programme (Su et al., 2021). Transgenic wheat derived from overexpression of pathogenesis-related genes in breeding can be studied for improving resistance (Cui et al., 2021). Developing novel disease management strategies involving host resistance requires a deeper understanding of the signal transduction genes responsible for plant resistance (Alkan et al., 2022). Once resistance genes have been detected and incorporated into wheat and barley lines, several years are needed for the genes to be fixed into the genetic background ready for field trials (Arabi et al., 2021). Consequently, more investment is required as producing resistant varieties requires a high cost in terms of time and capital.

Stubble burning has been shown to be an effective management tool for CRR. This practice is not recommended for environmental reasons in the future, although stubble management practices remain important to reduce CRR. Fungicides are available internationally, albeit currently not in Australia. Registered fungicides may be incorporated as a seed dressing before planting to improve the overall health of the plant, based on the recommendation by the manufacturer. Additionally, farmers face possibly increasing costs involving fungicides and nutrient treatments to control CRR. Further evaluation and repeated experiments are necessary to determine whether the biological agents effectively manage CRR of wheat, especially in commercial situations.

Understanding the levels of CRR inoculum present in a paddock is crucial. Presowing DNA soil tests can be used to determine the risk of CRR in each season (Simpfendorfer, 2020; Simpfendorfer et al., 2011). Having this information can be of value in determining when to use disease-suppressive chemicals and inoculants in order to achieve maximum effectiveness against CRR. Prevention of high levels of disease is crucial based on empirical studies when the paddock has a history of CRR recorded. In addition, combining cultural methods, chemical control and biological control as an integrated disease management strategy will potentially reduce CRR in wheat and barley. Early disease detection is also emphasized by researchers to assist management of CRR. Due to the speed of data collection and processing in real time, we expect that multispectral and hyperspectral imaging are becoming indispensable aspects of agricultural production. Objective and quantitative trials of remote sensing technologies to analyse the incidence and severity of CRR should be considered in the future.

ACKNOWLEDGEMENTS

This research is funded by The Broadacre Cropping Initiative (BACI), which is a partnership between the University of Southern Queensland and the Queensland Department of Agriculture and Fisheries, in Australia. Y.X. would like to thank UniSQ International Stipend Research Scholarship for supporting the study. Open access publishing facilitated by University of Southern Queensland, as part of the Wiley - University of Southern Queensland agreement via the Council of Australian University Librarians.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable as no new data were generated or analysed.

ORCID

Yiyi Xiong https://orcid.org/0000-0001-9238-6200
Cassandra Percy https://orcid.org/0000-0002-7807-6764

REFERENCES

Acharya, K., Dutta, A.K. & Pradhan, P. (2011) '*Bipolaris sorokiniana*' (Sacc.) Shoem.: the most destructive wheat fungal pathogen in the warmer areas. *Australian Journal of Crop Science*, 5, 1064–1071.

Alkan, M., Bayraktar, H., İmren, M., Özdemir, F., Lahlali, R., Mokrini, F. et al. (2022) Monitoring of host suitability and defense-related genes in wheat to *Bipolaris sorokiniana*. *Journal of Fungi*, 8, 149.

Allali, K., Goudjal, Y., Zamoum, M., Bouznada, K., Sabaou, N. & Zitouni, A. (2019) *Nocardiopsis dassonvillei* strain MB22 from the Algerian Sahara promotes wheat seedlings growth and potentially controls the common root rot pathogen *Bipolaris sorokiniana*. *Journal of Plant Pathology*, 101, 1115–1125.

Al-Sadi, A.M. (2021) *Bipolaris sorokiniana*-induced black point, common root rot, and spot blotch diseases of wheat: a review. *Frontiers in Cellular and Infection Microbiology*, 11, 584899.

Alt, V.V., Gurova, T.A., Elkin, O.V., Klimenko, D.N., Maximov, L.V., Pestunov, I.A. et al. (2020) Ispol'zovaniye giperspektral'noy kamery Specim IQ dlya analiza rasteniy [The use of Specim IQ, a hyperspectral camera, for plant analysis]. *Vavilovskii Zhurnal Genetiki i Selektsii*, 24, 259–266.

Angus, J., Kirkegaard, J., Hunt, J., Ryan, M., Ohlander, L. & Peoples, M. (2015) Break crops and rotations for wheat. *Crop and Pasture Science*, 66, 523–552.

Apoga, D., Jansson, H.-B. & Tunlid, A. (2001) Adhesion of conidia and germlings of the plant pathogenic fungus *Bipolaris sorokiniana* to solid surfaces. *Mycological Research*, 105, 1251–1260.

Arabi, M., Al-Shehadah, E. & Jawhar, M. (2015) A simple approach to assess common root rot severity incidence data in wheat. *Advances in Horticultural Science*, 29, 37–40.

Arabi, M., Al-Shehadah, E. & Jawhar, M. (2019) Diverse responses of old, modern and landraces of Syrian wheat genotypes to common root rot under field conditions. *Hellenic Plant Protection Journal*, 12, 91–96.

Arabi, M., Al-Shehadah, E. & Jawhar, M. (2021) Screening barley doubled haploid lines for spot blotch resistance and its interrelationship with common root rot resistance. *Journal of Stress Physiology & Biochemistry*, 17, 23–31.

Arabi, M. & Jawhar, M. (2007) Molecular and pathogenic variation identified among isolates of *Cochliobolus sativus*. *Australasian Plant Pathology*, 36, 17–21.

Bailey, K. & Duczek, L. (1996) Managing cereal diseases under reduced tillage. *Canadian Journal of Plant Pathology*, 18, 159–167.

Bailey, K., Duczek, L. & Potts, D. (1997) Inoculation of seeds with *Bipolaris sorokiniana* and soil fumigation methods to determine wheat and barley tolerance and yield losses caused by common root rot. *Canadian Journal of Plant Science*, 77, 691–698.

Bailey, K., Harding, H. & Hucl, P. (1995) Four interspecific germplasm lines (302–1, 302–3, 302–5, 302–20) of spring wheat with resistance to common root rot (*Cochliobolus sativus*) derived from *Aegilops ovata*. *Canadian Journal of Plant Science*, 75, 693–694.

Barbedo, J.G.A. (2019) A review on the use of unmanned aerial vehicles and imaging sensors for monitoring and assessing plant stresses. *Drones*, 3, 40.

Bayer Crop Science. (2009) RAXIL® MD Fungicide. Available from: https://www.cropscience.bayer.ca/-/media/Bayer-CropScience/Country-Canada-Internet/Products/Raxil/Raxil-MD-Label-02-09_21_ac.ashx?la=en&hash=46C60EFD2750EA37F4350BACD47338DE24E84169 [Accessed 31st March 2021].

Behmann, J., Acebron, K., Emin, D., Bennertz, S., Matsubara, S., Thomas, S. et al. (2018) Specim IQ: evaluation of a new, miniaturized handheld hyperspectral camera and its application for plant phenotyping and disease detection. *Sensors*, 18, 441.

Bhandari, D. & Shrestha, S.M. (2004) Intensity of common root rot on wheat genotypes. *Nepal Agriculture Research Journal*, 5, 46–48.

Bock, C., Poole, G., Parker, P. & Gottwald, T. (2010) Plant disease severity estimated visually, by digital photography and image analysis, and by hyperspectral imaging. *Critical Reviews in Plant Sciences*, 29, 59–107.

Bockus, W.W., Bowden, R.L., Hunger, R.M., Morrill, W.L., Murray, T.D. & Smiley, R.W. (2010) *Compendium of wheat diseases and pests*. St Paul, MN: American Phytopathological Society.

Burlakoti, R., Shrestha, S. & Sharma, R. (2013) Impact of seed-borne inoculum, irrigation, and cropping pattern on propagation of *Bipolaris sorokiniana* and epidemiology of foliar blight and common root rot in spring wheat. *Journal of Plant Pathology*, 95, 571–578.

Butler, F. (1961) *Root and foot rot diseases of wheat*. Wagga Wagga: Department of Agriculture New South Wales, Science Bulletin No. 77.

Campanella, V., Mandalà, C., Angileri, V. & Miceli, C. (2020) Management of common root rot and *Fusarium* foot rot of wheat using *Brassica carinata* break crop green manure. *Crop Protection*, 130, 105073.

Cheng, X., Ji, X., Ge, Y., Li, J., Qi, W. & Qiao, K. (2019) Characterization of antagonistic *Bacillus methylotrophicus* isolated from rhizosphere and its biocontrol effects on maize stalk rot. *Phytopathology*, 109, 571–581.

Conner, R.L., Duczek, L.J., Kozub, G.C. & Kuzyk, A.D. (1996) Influence of crop rotation on common root rot of wheat and barley. *Canadian Journal of Plant Pathology*, 18, 247–254.

Conner, R.L., Lindwall, C. & Atkinson, T. (1987) Influence of minimum tillage on severity of common root rot in wheat. *Canadian Journal of Plant Pathology*, 9, 56–58.

Crop Protection Network (CPN). (2022) *Common root and foot rot of wheat*. Available from: https://cropprotectionnetwork.org/encyclopedia/common-root-and-foot-rot-of-wheat [Accessed 6th July 2023].

Cui, Z., Liang, F., Zhang, J., Wang, F., Liu, D. & Wang, H. (2021) Transgenic expression of *TaTLP1*, a thaumatin-like protein gene, reduces susceptibility to common root rot and leaf rust in wheat. *The Crop Journal*, 9, 1214–1218.

DAF. (2015) *Focus paddocks benchmarked results summary 2010–14*. Department of Agriculture and Food, Western Australian Agriculture Authority.

DAFF. (2014) *Barley—planting and disease guide 2014 (Queensland and NNSW)*. Sturgess, J. (Ed.). State of Queensland, Department of Agriculture Fisheries and Forestry.

Darvishnia, M., Alizadeh, A., Mohammadi Goltapeh, E. & Zare, R. (2007) Three new *Fusarium* taxa isolated from gramineous plants in Iran. *Rostaniha*, 7, 193–206.

De Boer, R. & Kollmorgen, J. (1988) Effects of cultivation and stubble retention on soil and stubble-born pathogens of wheat in Victoria—an overview. *Plant Protection Quarterly (Australia)*. Available from: http://www.regional.org.au/au/asa/1987/contributed/soil-tillage-water/p-04.htm [Accessed 17th July 2023].

Department of Primary Industries and Regional Development (DPIRD). (2015) *Diagnosing common root rot of cereals*. Perth: Department of Primary Industries and Regional Development, Western Australia.

Devi, M.K.A. (2021) Plant disease identification using the unmanned aerial vehicle images. *Turkish Journal of Computer and Mathematics Education (TURCOMAT)*, 12, 2396–2399.

Diehl, J., Tinline, R.D., Kochhann, R.A., Shipton, P.J. & Rovira, A.D. (1982) The effect of fallow periods on common root rot of wheat in Rio Grande do Sul, Brazil. *Phytopathology*, 72, 1297–1301.

Draper, M.A., Stymiest, C. & Jin, Y. (2000) Common root and crown rot diseases of wheat in South Dakota. *Extension Extra*, Paper 341. Available from: http://openprairie.sdstate.edu/extension_extra/341 [Accessed 6th July 2023].

Duczek, L. & Piening, L. (1982) Effect of seeding depth, seeding date and seed size on common root rot of spring barley. *Canadian Journal of Plant Science*, 62, 885–891.

Duveiller, E. (1997) Helminthosporium blights of wheat: spot blotch and tan spot. *Proceedings of an International Workshop held at CIMMYT*. El Batan: CIMMYT. Available from: http://hdl.handle.net/10883/1229 [Accessed 17th July 2023].

Duveiller, E., Kandel, Y., Sharma, R. & Shrestha, S. (2005) Epidemiology of foliar blights (spot blotch and tan spot) of wheat in the plains bordering the Himalayas. *Phytopathology*, 95, 248–256.

Dyer, A., Johnston, J., Tharp, C., Rupp, J., Lane, T. & Fulbright, J. (2007) *Small grain seed treatment guide*. Bozeman: Montana State University, Extension MontGuide MT199608AG.

Eken, C. & Yuen, G. (2014) Biocontrol of common root rot of wheat with *Lysobacter enzymogenes* and binucleate *Rhizoctonia*. *Romanian Agricultural Research*, 31, 309–314.

Fernandez, M., Fox, S., Hucl, P., Singh, A. & Stevenson, F. (2014) Root rot severity and fungal populations in spring common, durum and spelt wheat, and Kamut grown under organic management in western Canada. *Canadian Journal of Plant Science*, 94, 937–946.

Fernandez, M., Holzgang, G. & Turkington, T. (2009) Common root rot of barley in Saskatchewan and north-Central Alberta. *Canadian Journal of Plant Pathology*, 31, 96–102.

Fernandez, M. & Jefferson, P. (2004) Fungal populations in roots and crowns of common and durum wheat in Saskatchewan. *Canadian Journal of Plant Pathology*, 26, 325–334.

Fernandez, M., Zentner, R., Depauw, R., Gehl, D. & Stevenson, F. (2007) Impacts of crop production factors on common root rot of barley in eastern Saskatchewan. *Crop Science*, 47, 1585–1595.

Fletcher, A., Lawes, R. & Weeks, C. (2016) Crop area increases drive earlier and dry sowing in Western Australia: implications for farming systems. *Crop and Pasture Science*, 67, 1268–1280.

Friesen, T., Holmes, D., Bowden, R. & Faris, J. (2018) ToxA is present in the US *Bipolaris sorokiniana* population and is a significant virulence factor on wheat harboring *Tsn1*. *Plant Disease*, 102, 2446–2452.

Ghazvini, H. (2018) The host–pathogen interaction between barley and casual agent of spot blotch (*Bipolaris sorokiniana*) disease: a review. *Crop Breeding Journal*, 8, 1–15.

Ghazvini, H. & Tekauz, A. (2012) Molecular diversity in the barley pathogen *Bipolaris sorokiniana* (*Cochliobolus sativus*). *Australasian Plant Pathology*, 41, 283–293.

Giri, G., Gade, R. & Patil, C. (2001) Seed borne *Bipolaris sorokiniana* in wheat and its chemical control. *Journal of Soils and Crops*, 11, 109–112.

Gogoi, N., Deka, B. & Bora, L. (2018) Remote sensing and its use in detection and monitoring plant diseases: a review. *Agricultural Reviews*, 39, 307–313.

Göksel, Ö., İmren, M., Alkan, M., Paulitz, T.C., Bayraktar, H., Palagioğlu, G. et al. (2020) Molecular and pathogenic characterization of *Cochliobolus* anamorphs associated with common root rot of wheat in Azerbaijan. *Phytopathologia Mediterranea*, 59, 147–158.

Gongora-Canul, C., Salgado, J., Singh, D., Cruz, A.P., Cotrozzi, L., Couture, J. et al. (2020) Temporal dynamics of wheat blast epidemics and disease measurements using multispectral imagery. *Phytopathology*, 110, 393–405.

Gouli, V.V., Marcelino, J.A. & Gouli, S.Y. (2020) Microbial formulations for control of noxious organisms. In: Gouli, V.V., Marcelino, J.A. & Gouli, S.Y. (Eds.) *Microbial pesticides: biological resources, production and application*. London: Academic Press, pp. 193–247.

Grains Research and Development Corporation (GRDC). (2016) *GROWNOTES wheat section 9 diseases*.

Grains Research and Development Corporation (GRDC). (2019) *2020 Queensland winter crop sowing guide*.

Grains Research and Development Corporation (GRDC). (2021) *2022 Queensland winter crop sowing guide*.

Grains Research and Development Corporation (GRDC) and Queensland Department of Agriculture, Fisheries and Forestry (DAFF). (2014) *2014 wheat varieties*.

Gupta, P., Chand, R., Vasistha, N., Pandey, S.P., Kumar, U., Mishra, V.K. et al. (2018) Spot blotch disease of wheat: the current status of research on genetics and breeding. *Plant Pathology*, 67, 508–531.

Gupta, P.K., Vasistha, N.K., Aggarwal, R. & Joshi, A.K. (2018) Biology of *B. sorokiniana* (syn. *Cochliobolus sativus*) in genomics era. *Journal of Plant Biochemistry and Biotechnology*, 27, 123–138.

Gurova, T., Klimenko, D. & Lugovskaya, O. (2019) [Spectral characteristics of wheat varieties under biotic stress]. *Dostizheniya Nauki i Tekhniki APK*, 33, 71–75.

Hajieghrari, B. (2009) Wheat crown and root rotting fungi in Moghan area, northwest of Iran. *African Journal of Biotechnology*, 8, 6214–6219.

Hamblin, C. (1922) "Foot rot" of wheat caused by the fungus *Helminthosporium*. *The Agricultural Gazette of New South Wales*, 33, 13.

Harba, M., Jawhar, M. & Arabi, M. (2020) In vitro antagonistic activity of diverse *Bacillus* species against *Cochliobolus sativus* (common root rot) of barley. *Acta Phytopathologica et Entomologica Hungarica*, 55, 35–42.

Horne, M. (2015) *Inter-relationships between Bipolaris sorokiniana isolates involved in spot blotch, common root rot and black point in winter cereals*. Thesis. Brisbane: University of Southern Queensland.

Humpal, J., McCarthy, C., Percy, C. & Thomasson, J.A. (2020) Detection of crown rot in wheat utilising near-infrared spectroscopy: towards remote and robotic sensing. In: *Proceedings of the Autonomous Air and Ground Sensing Systems for Agricultural Optimization and Phenotyping V, 2020*. International Society for Optics and Photonics, 11414.

Hynes, H. (1932) Foot rot of cereals. Observations on the disease in New South Wales. *The Agricultural Gazette of New South Wales*, 43, 107–115.

Jones, D.G. & Clifford, B.C. (1983) *Cereal diseases, their pathology and control*. Hoboken, NJ: John Wiley & Sons.

Kang, K., Niu, Z., Zhang, W., Wei, S., Lv, Y. & Hu, Y. (2023) Antagonistic strain *Bacillus halotolerans* Jk-25 mediates the biocontrol of wheat common root rot caused by *Bipolaris sorokiniana*. *Plants*, 12, 828.

Kari, A. (2001) *Disease incidence of common root and foot-rot on durum wheat in semi-arid conditions in Cyprus*. Technical Bulletin. Cyprus Agricultural Research Institute, publications.ari.gov.cy

Kaur, N. (2016) *Root rot pathogens of wheat in South Dakota and their affect on seed germination and seedling blight in spring wheat cultivars*. Thesis. Brookings: South Dakota State University.

Knight, N., Platz, G., Lehmensiek, A. & Sutherland, M. (2010) An investigation of genetic variation among Australian isolates of *Bipolaris sorokiniana* from different cereal tissues and comparison of their abilities to cause spot blotch on barley. *Australasian Plant Pathology*, 39, 207–216.

Kumar, J., Schäfer, P., Hückelhoven, R., Langen, G., Baltruschat, H., Stein, E. et al. (2002) *Bipolaris sorokiniana*, a cereal pathogen of global concern: cytological and molecular approaches towards better control. *Molecular Plant Pathology*, 3, 185–195.

Kutcher, H., Bailey, K., Rossnagel, B. & Franckowiak, J. (1996) Linked morphological and molecular markers associated with common root rot reaction in barley. *Canadian Journal of Plant Science*, 76, 879–883.

Kutcher, H., Bailey, K., Rossnagel, B. & Legge, W. (1996) Identification of RAPD markers for common root rot and spot blotch (*Cochliobolus sativus*) resistance in barley. *Genome*, 39, 206–215.

Ledingham, R., Atkinson, T., Horricks, J., Mills, J., Piening, L. & Tinline, R. (1973) Wheat losses due to common root rot in the prairie provinces of Canada, 1969–71. *Canadian Plant Disease Survey*, 53, 113–122.

Lehmensiek, A., Bovill, J., Sutherland, M. & McNamara, R. (2010) Genomic regions associated with common root rot resistance in the barley variety Delta. *Australasian Plant Pathology*, 39, 241–246.

Li, Q., Gao, C., Xu, K., Jiang, Y., Niu, J., Yin, G. et al. (2021) Transcriptome-based analysis of resistance mechanism to black point caused by *Bipolaris sorokiniana* in wheat. *Scientific Reports*, 11, 6911.

Li, W., Chen, Y., Zhang, X., Zhang, B., Yu, H. & Chen, H. (2011) Pathogenic fungi of wheat brown foot rot and their pathogenicity in China. *Journal of Triticeae Crops*, 31, 170–175.

Liu, T., Bruins, R.J. & Heberling, M.T. (2018) Factors influencing farmers' adoption of best management practices: a review and synthesis. *Sustainability*, 10, 432.

Liueroth, E., Franzon-Almgren, I. & Gunnarsson, T. (1996) Root colonization by *Bipolaris sorokiniana* in different cereals and relations to lesion development and natural root cortical cell death. *Journal of Phytopathology*, 144, 301–307.

Machacek, J.E. (1943) An estimate of loss in Manitoba from common root rot in wheat. *Scientific Agriculture*, 24, 70–77.

MacLeod, B., Vanstone, V., Khangura, R. & Beard, C. (2008) *Root disease under intensive cereal production systems*. Perth: Department of Primary Industries and Regional Development.

Mahdi, L.K., Miyauchi, S., Uhlmann, C., Garrido-Oter, R., Langen, G., Wawra, S. et al. (2022) The fungal root endophyte *Serendipita vermifera* displays inter-kingdom synergistic beneficial effects with the microbiota in *Arabidopsis thaliana* and barley. *The ISME Journal*, 16, 876–889.

Mahlein, A.-K. (2016) Plant disease detection by imaging sensors—parallels and specific demands for precision agriculture and plant phenotyping. *Plant Disease*, 100, 241–251.

Mathieson, J., Rush, C., Bordovsky, D., Clark, L. & Jones, O. (1990) Effects of tillage on common root rot of wheat in Texas. *Plant Disease*, 74, 1006–1008.

Mathre, D.E. (1997) *Compendium of barley diseases*. St Paul, MN: American Phytopathological Society Press.

Mathre, D.E., Johnston, R. & Grey, W. (2001) Small grain cereal seed treatment. *The Plant Health Instructor*. Available from: https://www.apsnet.org/edcenter/disimpactmngmnt/topc/Pages/Small-Grain-Cereal-Seed-Treatment.aspx [Accessed 15th June 2022].

Mathre, D.E., Johnston, R. & Grey, W. (2003) Diagnosis of common root rot of wheat and barley. *Plant Health Progress*, 4, 11.

McDonald, M.C., Ahren, D., Simpfendorfer, S., Milgate, A. & Solomon, P.S. (2018) The discovery of the virulence gene *ToxA* in the wheat and barley pathogen *Bipolaris sorokiniana*. *Molecular Plant Pathology*, 19, 432–439.

McKay, A., Simpfendorfer, S., Vadakattu, G., Bithell, S., Moore, K., Daniel, R. et al. (2018) PREDICTA® B update and new tests for 2018. *GRDC update papers*. Canberra: Grains Research and Development Corporation.

McMullen, M., Jin, Y., Watkins, J. & Hein, G. (2003) *Pest management strategic plan for northern wheat*. Brookings: USDA. Available from: Wheat Diseases (psu.edu) [Accessed 6th July 2023].

McMullen, M.P. & Bradley, C.A. (2007) *2007 North Dakota field crop fungicide guide*. Fargo, ND: North Dakota State University.

Miljaković, D., Marinković, J. & Balešević-Tubić, S. (2020) The significance of *Bacillus* spp. in disease suppression and growth promotion of field and vegetable crops. *Microorganisms*, 8, 1037.

Moore, K., Manning, B., Steven, S. & Verrell, A. (2005) *Root and crown diseases of wheat and barley in northern NSW*. Tamworth: NSW Department of Primary Industries.

Morton, L.W., McGuire, J.M. & Cast, A.D. (2017) A good farmer pays attention to the weather. *Climate Risk Management*, 15, 18–31.

Moya-Elizondo, E.A., Rew, L.J., Jacobsen, B.J., Hogg, A.C. & Dyer, A.T. (2011) Distribution and prevalence of *Fusarium* crown rot and common root rot pathogens of wheat in Montana. *Plant Disease*, 95, 1099–1108.

Murray, G.M. & Brennan, J.P. (2009a) *The current and potential costs from diseases of barley in Australia*. Barton: Grains Research and Development Corporation.

Murray, G.M. & Brennan, J.P. (2009b) *The current and potential costs from diseases of wheat in Australia*. Canberra: Grains Research and Development Corporation.

Murray, T.D., Parry, D.W. & Cattlin, N.D. (1998) *A color handbook of diseases of small grain cereal crops*. London: Manson Publishing.

Nagasubramanian, K., Jones, S., Singh, A.K., Sarkar, S., Singh, A. & Ganapathysubramanian, B. (2019) Plant disease identification using explainable 3D deep learning on hyperspectral images. *Plant Methods*, 15, 98.

Navathe, S., Yadav, P.S., Chand, R., Mishra, V.K., Vasistha, N.K., Meher, P.K. et al. (2020) *ToxA–Tsn1* interaction for spot blotch susceptibility in Indian wheat: an example of inverse gene-for-gene relationship. *Plant Disease*, 104, 71–81.

Neate, S. & Vadakattu, G. (2018) Pre-breeding solutions for resistance and tolerance to Rhizoctonia root rot, takeall and common root rot diseases of wheat. In: Gupta, V.V.S.R., Barnett, S. & Kroker, S. (Eds.) *Proceedings of the 10th Australasian Soilborne Disease Symposium, September 2018*. Adelaide: APPS, pp. 22–23.

Peairs, F., DeWolf, E., McCornack, B., Hunger, R., Edwards, J., Armstrong, J. et al. (2012) *Pest management strategic plan for winter wheat in the southern Great Plains*. El Reno, OK: USDA.

Petronaitis, T., Forknall, C., Brodie, G., Simpfendorfer, S. & Backhouse, D. (2022) "Killer joules": spores of *Bipolaris sorokiniana* and *Fusarium* species are susceptible to microwave radiation. *Australasian Plant Pathology*, 51, 433–440.

Petronaitis, T., Forknall, C.R., Simpfendorfer, S. & Backhouse, D. (2020) Stubble olympics: the cereal pathogen 10 cm sprint–growth patterns of fungi causing crown rot, common root rot and yellow leaf spot in post-harvest cereal stubble. *GRDC Update*. Grains Research and Development Corporation. Available from: https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2020/08/stubble-olympics-the-cereal-pathogen-10cm-sprint [Accessed 6th July 2023].

Piening, L. (1997) Common root rot and seedling blight. In: Mathre, D. (Ed.) *Compendium of barley diseases*. St Paul, MN: American Phytopathological Society, pp. 10–13.

Piening, L., Atkinson, T., Horricks, J., Ledingham, R., Mills, J. & Tinline, R. (1976) Barley losses due to common root rot in the prairie provinces of Canada, 1970–72. *Canadian Plant Disease Survey*, 56, 41–45.

Platz, G., Meldrum, S. & Webb, N. (1999) Chemical control of seed borne diseases of barley. In: *Proceedings of the Proceedings of 9th Australian Barley Technical Symposium*. Melbourne: ABTS, pp. 1–2.21.

Purss, G. (1970) Resistance to common root rot (*Cochliobolus sativus*) in wheat in Queensland. *Australian Journal of Experimental Agriculture*, 10, 497–501.

Qalavand, F., Esfahani, M.N., Vatandoost, J. & Azarm, D.A. (2022) Enzyme activity and population genetic structure analysis in wheat associated with resistance to *Bipolaris sorokiniana*-common root rot diseases. *Phytochemistry*, 200, 113208.

Qalavand, F., Nasr-Esfahani, M., Vatandoost, J. & Azarm, D.A. (2023) Transcriptome-based analysis of resistance mechanisms to *Bipolaris sorokiniana*, a common wheat root-rot disease. *Plant Biology*, 25, 119–130.

Reis, E. (1990) Integrated disease management: the changing concepts of controlling head blight and spot blotch. In: Saunders, D.A. (Ed.) *Proceedings of the Third International Conference on Wheat for the Nontraditional Warm Areas*, Foz do Iguacu (Brazil), 29 Jul–3 Aug 1990. CIMMYT: Mexico, pp. 165–177.

Reis, E. & Abrao, J. (1983) Effect of tillage and wheat residue management on the vertical distribution and inoculum density of *Cochliobolus sativus* in soil. *Plant Disease*, 67, 1088–1089.

Saad, A. (2019) *Range of winter cereal reactions to root and crown rot pathogens*. Toowoomba: University of Southern Queensland.

Saad, A., Macdonald, B., Martin, A., Knight, N.L. & Percy, C. (2021) Comparison of disease severity caused by four soil-borne pathogens in winter cereal seedlings. *Crop and Pasture Science*, 72, 325–334.

Saad, A., Macdonald, B., Martin, A., Knight, N.L. & Percy, C. (2022) Winter cereal reactions to common root rot and crown rot pathogens in the field. *Agronomy*, 12, 2571.

Salehpour, M., Etebarian, H., Roustaei, A., Khodakaramian, G. & Aminian, H. (2005) Biological control of common root rot of wheat (*Bipolaris sorokiniana*) by *Trichoderma* isolates. *Plant Pathology Journal*, 4, 85–90.

Scott, B., Eberbach, P., Evans, J. & Wade, L. (2010) *Stubble retention in cropping systems in southern Australia: benefits and challenges*. Wagga Wagga, NSW: EH Graham Centre for Agricultural Innovation. Monograph No. 1.

Shafi, J., Tian, H. & Ji, M. (2017) *Bacillus* species as versatile weapons for plant pathogens: a review. *Biotechnology & Biotechnological Equipment*, 31, 446–459.

Shao, D., Smith, D.L., Kabbage, M. & Roth, M.G. (2021) Effectors of plant necrotrophic fungi. *Frontiers in Plant Science*, 12, 687713.

Sharma, P., Duveiller, E. & Sharma, R.C. (2006) Effect of mineral nutrients on spot blotch severity in wheat, and associated increases in grain yield. *Field Crops Research*, 95, 426–430.

Shcherbakova, L.A., Nazarova, T.A., Mikityuk, O.D., Istomina, E.A. & Odintsova, T.I. (2018) An extract purified from the mycelium of a tomato wilt-controlling strain of *Fusarium sambucinum* can protect wheat against *Fusarium* and common root rots. *Pathogens*, 7, 61.

Shrestha, S., Poudel, R.S. & Zhong, S. (2021) Identification of fungal species associated with crown and root rots of wheat and evaluation of plant reactions to the pathogens in North Dakota. *Plant Disease*, 105, 3564–3572.

Simmonds, J.H. (1966) *Host index of plant diseases in Queensland*. Brisbane: Queensland Department of Primary Industries.

Simpfendorfer, S. (2020) *Implications of continuing dry conditions on cereal disease management*. Wagga Wagga, NSW: Grains Research and Development Corporation.

Simpfendorfer, S., Alston, A., McKay, A. & Poole, G. (2011) *Cereal pathogen survey of Central and Northern NSW - 2011*. Available from https://www.dpi.nsw.gov.au/__data/assets/pdf_file/0003/431265/Cereal-pathogen-survey.pdf [Accessed 6th July 2023].

Simpfendorfer, S., McKay, A. & Ophel-Keller, K. (2020) New approaches to crop disease management in conservation agriculture. In: Pratley, J. & Kirkegaard, J. (Eds.) *Australian agriculture in 2020: From conservation to automation*. Wagga Wagga, NSW: Agronomy Australia and Charles Sturt University, pp. 173–188.

Singh, S., Gupta, V., Razdan, V., Singh, V. & Gupta, V. (2012) Effect of fertilizers on severity of spot blotch caused by *Bipolaris sorokiniana* and yield of wheat. *Annals of Plant Protection Sciences*, 20, 411–413.

Smiley, R.W. & Patterson, L.-M. (1996) Pathogenic fungi associated with Fusarium foot rot of winter wheat in the semiarid Pacific northwest. *Plant Disease*, 80, 944–949.

Somes, T. (2018) *First common root rot yield loss trials in 20 years on the Darling Downs*. Wagga Wagga, NSW: Grains Research and Development Corporation.

Stack, R. & McMullen, M. (1991) Effect of fungicidal seed treatments on common root rot of spring wheat and barley. *North Dakota Farm Research*, 49, 13–16.

Strausbaugh, C.A., Bradley, C.A., Koehn, A.C. & Forster, R.L. (2004) Survey of root diseases of wheat and barley in southeastern Idaho. *Canadian Journal of Plant Pathology*, 26, 167–176.

Su, J., Zhao, J., Zhao, S., Li, M., Pang, S., Kang, Z. et al. (2021) Genetics of resistance to common root rot (spot blotch), Fusarium crown rot, and sharp eyespot in wheat. *Frontiers in Genetics*, 12, 1008.

Su, Q., Wang, K. & Zhang, Z. (2020) Ecotopic expression of the antimicrobial peptide DmAMP1W improves resistance of transgenic wheat to two diseases: sharp eyespot and common root rot. *International Journal of Molecular Sciences*, 21, 647.

Sultana, A. & Rashid, A. (2012) Impact of seed transmission of *Bipolaris sorokiniana* on the planting value of wheat seeds. *Journal of Environmental Science and Natural Resources*, 5, 75–78.

Syngenta Canada. (2022) *VIBRANCE® QUATTRO Fungicide*. Available from: https://assets.syngenta.ca/pdf/ca/labels/VIBRANCE_QUATTRO_31408_en_pamphlet.pdf [Accessed 5th July 2022].

Syngenta Canada. (2023) *DIVIDEND EXTREME® Fungicide*. Available from: https://assets.syngenta.ca/pdf/ca/labels/DIVIDEND_EXTREME_29490_en_pamphlet.pdf [Accessed 5th July 2022].

Tinline, R., Wildermuth, G. & Spurr, D. (1988) Inoculum density of *Cochliobolus sativus* in soil and common root rot of wheat cultivars in Queensland. *Australian Journal of Agricultural Research*, 39, 569–577.

Turdieva, D., Aznabakieva, D., Lukmonova, M. & Alijonova, S. (2020) Common root and fuzarium foot rot of winter wheat in Uzbekisistan. *Akademicheskaya Publitsistika*, 3, 36–39.

Van Leur, J., Alamdar, M. & Khawatmi, S. (1997) Effect of common root rot (*Cochliobolus sativus*) on yields of barley under experimental conditions in northern Syria. *Australian Journal of Agricultural Research*, 48, 351–358.

Van Leur, J. & Bailey, K. (2000) The occurrence of barley root diseases in different agri-ecological zones of Syria. *Canadian Journal of Plant Pathology*, 22, 61–69.

Verma, P., Morrall, R. & Tinline, R. (1976) The epidemiology of common root rot in Manitou wheat. IV. Appraisal of biomass and grain yield in naturally infected crops. *Canadian Journal of Botany*, 54, 1656–1665.

Wang, A., Wei, X., Rong, W., Dang, L., Du, L.-P., Qi, L. et al. (2015) *GmPGIP3* enhanced resistance to both take-all and common root rot diseases in transgenic wheat. *Functional & Integrative Genomics*, 15, 375–381.

Wang, T., Thomasson, J.A., Yang, C., Isakeit, T. & Nichols, R.L. (2020) Automatic classification of cotton root rot disease based on UAV remote sensing. *Remote Sensing*, 12, 1310.

Wei, X., Xu, Z., Zhang, N., Yang, W., Liu, D. & Ma, L. (2020) Synergistic action of commercially available fungicides for protecting wheat from common root rot caused by *Bipolaris sorokiniana* in China. *Plant Disease*, 105, 667–674.

Whittle, P., Rathjen, A., Dubé, A. & Frensham, A. (1991) Common root rot in wheat and barley in South Australia: its distribution and relationship with yield. In: Tinline, R.D., Bailey, K.L., Duczek, L.J. & Harding, H. (Eds.) *Proceedings of the First International Workshop on Common Root Rot of Cereals*. Saskatoon: Canadian Department of Agriculture, pp. 6–13.

Whittle, P.J.L. (1992) *Studies on common root rot and Bipolaris sorokiniana in wheat and barley in South Australia*. Thesis. University of Adelaide.

Wiese, M.V. (1987) *Compendium of wheat diseases*. St Paul, MN: American Phytopathological Society.

Wildermuth, G. (1986) Geographic distribution of common root rot and *Bipolaris sorokiniana* in Queensland wheat soils. *Australian Journal of Experimental Agriculture*, 26, 601–606.

Wildermuth, G. & McNamara, R. (1991) Effect of cropping history on soil populations of *Bipolaris sorokiniana* and common root rot of wheat. *Australian Journal of Agricultural Research*, 42, 779–790.

Wildermuth, G., Thomas, G., Radford, B., McNamara, R. & Kelly, A. (1997) Crown rot and common root rot in wheat grown under different tillage and stubble treatments in southern Queensland, Australia. *Soil and Tillage Research*, 44, 211–224.

Wildermuth, G., Tinline, R. & McNamara, R. (1992) Assessment of yield loss caused by common root rot in wheat cultivars in Queensland. *Australian Journal of Agricultural Research*, 43, 43–58.

Windels, C.E. & Wiersma, J.V. (1992) Incidence of *Bipolaris* and *Fusarium* on subcrown internodes of spring barley and wheat grown in continuous conservation tillage. *Phytopathology*, 82, 699–705.

Wójtowicz, M., Wójtowicz, A. & Piekarczyk, J. (2016) Application of remote sensing methods in agriculture. *Communications in Biometry and Crop Science*, 11, 31–50.

Yao, Z., Lei, Y. & He, D. (2019) Early visual detection of wheat stripe rust using visible/near-infrared hyperspectral imaging. *Sensors*, 19, 952.

Yi, Y., Shan, Y., Liu, S., Yang, Y., Liu, Y., Yin, Y. et al. (2021) Antagonistic strain *Bacillus amyloliquefaciens* XZ34-1 for controlling *Bipolaris sorokiniana* and promoting growth in wheat. *Pathogens*, 10, 1526.

Yue, H.-M., Wang, M., Gong, W.-F. & Zhang, L.-Q. (2018) The screening and identification of the biological control fungi *Chaetomium* spp. against wheat common root rot. *FEMS Microbiology Letters*, 365, fny242.

Zhang, J., Zhu, X., Liu, Y. & Li, H. (1988) Xiǎomài gēn fǔ bìng de yánjiū I bìngyuánjùn zhǒnglèi hé xīn zhǒng de xíngtài tèzhēng [Studies on the root rot of wheat]. *Journal of Natural Science of Heilongjiang University*, 2, 68–74.

Zhong, S. & Steffenson, B.J. (2001) Virulence and molecular diversity in *Cochliobolus sativus*. *Phytopathology*, 91, 469–476.

How to cite this article: Xiong, Y., McCarthy, C., Humpal, J. & Percy, C. (2023) A review on common root rot of wheat and barley in Australia. *Plant Pathology*, 72, 1347–1364. Available from: https://doi.org/10.1111/ppa.13777