

Chapter 11

New approaches to crop disease management in conservation agriculture

Steven Simpfendorfer, Alan McKay and Kathy Ophel-Keller

Changes in disease profiles following adoption of CA

Importance of key wheat pathogens in Australia

The economic importance of wheat diseases in Australia was estimated in 1988 (Brennan and Murray 1989), 1998 (Brennan and Murray 1998) and 2008 (Murray and Brennan 2009). The value of wheat and area sown has changed over time, but the expression of yield losses as a percentage of the production enables comparisons between surveys (Table 1). Estimates were made for the northern (central and northern NSW plus Qld), southern (southern NSW, Victoria and SA) and western (WA) grain growing regions of Australia. Five key diseases, reported to increase in prevalence with the adoption of CA, have all steadily risen in their importance across all three regions (Table 1). The cereal root disease Take-all (*Gaeumannomyces tritici*) has generally declined in estimated importance over time. This may reflect the intensification of cropping over this period which has seen a reduction in the area of annual grass-legume pastures. The grass component in ley pastures is known to significantly contribute to elevated levels of take-all in following cereal crops as they serve as an alternate host for the causal pathogen (MacLeod *et al.* 1993).

Table 1. Average potential annual yield loss (%) of key wheat diseases estimated in 1988, 1998 and 2008 by cropping region

Disease	Northern			Southern			Western		
	1988	1998	2008	1988	1998	2008	1988	1998	2008
Yellow spot	3.3	2.0	19.0	1.0	1.6	3.9	5.0	9.3	12.9
Crown rot	3.0	13.0	22.2	0.4	6.6	10.5	0.1	0.3	1.5
Rhizoctonia	0.2	0.1	0.0	3.7	4.7	4.1	0.5	1.4	4.5
RLN <i>Pt</i> ^A	2.8	12.3	11.6	0.0	0.9	2.4	0.0	0.0	0.6
RLN <i>Pn</i> ^B	0.0	1.0	2.4	0.0	2.8	5.6	0.0	0.3	7.8
Take-all	0.8	0.6	0.0	9.5	13.6	3.6	10.0	3.0	1.4

^ARLN = root lesion nematode *Pratylenchus thornei*, ^B*P. neglectus*

Consistent with the trends presented in Chapter 2, Ugalde *et al.* (2007) explored changes in tillage and stubble management practices used by Australian cereal producers between 1995 and 2000. They showed that some form of aggressive tillage was common across nearly all Australian farming systems and regions in 1995, consisting of one, two or multiple cultivations and that there were only isolated pockets of NT or RT in each grain-growing region. However, over the next five years there were substantial shifts in land management with a significant increase in the adoption of conservative tillage practices. The shift was particularly noticeable in the western region where by 2005 more than 85% of the total cropped land was subject to no-till (NT) cropping practice (see Chapter 2).

The changes in tillage practices affected management of cereal stubble. The areas where stubble was incorporated decreased greatly between 1995 and 2000, especially in the northern and southern regions (Ugalde *et al.* 2007). In many parts of the southern region, incorporation was replaced by burning; in the northern and western regions there was a greater tendency to leave the stubble intact.

Changes in practices associated with adoption of CA between 1995 and 2000 are most likely to be key drivers in the prevalence of stubble-borne diseases of wheat between 1998 and 2008 (Table 1). Yellow leaf spot (*Pyrenophora tritici-repentis*) increased significantly over this period in the northern and western regions, but stubble burning in the southern region is likely to have limited infections. Crown

rot (*Fusarium pseudograminearum*) increased significantly in importance between 1998 and 2008, but this was not reflected in the western region (Table 1), even though it had the most adoption of CA (Ugalde *et al.* 2007). This highlights a potential weakness in the approach used by Murray and Brennan (2009) which is based on subjective estimates of incidence, severity and yield loss caused by wheat pathogens by only a limited number (18) of expert pathologists. Differences in the knowledge and awareness of the importance of specific diseases may exist between pathologists which may not reflect the actual disease incidence in a region.

The incidence of crown rot in cereal crops was objectively measured through laboratory plating of 1774 stubble samples collected at harvest across grain-growing regions between 2014-2017. High infection levels (>26%) occurred in 31%, 21% and 15% of paddocks in the northern, western and southern regions respectively (Simpfendorfer, unpublished). This indicates that the importance of crown rot (Murray and Brennan 2009), particularly in the western region, are probably underestimated. Future estimates of the economic importance of crop diseases in Australia would benefit from objective and quantitative data of disease incidence and severity.

Disease incidence in CA systems in Australia

Significant changes in the prevalence of specific plant pathogens are often observed following the adoption of CA. The increased retention of plant residues provides stubble-borne pathogens with an extended opportunity to survive between crops when host plants are absent during both fallow periods and rotations with non-host species (Bockus and Shroyer 1998). Some stubble-borne pathogens can survive multiple years in crop residues. For example, *Fusarium pseudograminearum* (*Fp*), the primary cause of crown rot (CR) in cereals, survives as mycelium for up to three years in infected cereal residues (Summerell and Burgess 1988), and *Bipolaris sorokiniana* (*Bs*), the cause of common root rot (CRR) in cereals, survives on wheat residues at the soil surface for at least two years (Duczek *et al.* 1999). In CT systems, the burial and increased rate of decomposition of crop residues reduces the survival of stubble-borne pathogens (Bockus and Shroyer 1998). Reduced soil disturbance, increased soil moisture and lowering of soil temperatures can also create a more favourable soil environment for many plant pathogens and encourage disease persistence (Bockus and Shroyer 1998). Under favourable climate and soil conditions, CA can increase the prevalence of some diseases and deleterious rhizobacteria (Simpfendorfer *et al.* 2002) while other diseases decrease in the prevalence (Table 2).

Interpretation of disease effects can be complicated by the differential effect of tillage and stubble retention practices on pathogen levels and disease expression. For instance, under a NT system, the incidence of CR (*Fp*) was significantly higher where stubble was retained (32.2%) than where it was removed (4.7%) but under disc tillage, there was no significant difference in disease level between stubble treatments (12-17%) (Wildermuth *et al.* 1997). However, the expression of whiteheads caused by CR was lowest in the NT plots (4.3%) and highest in the RT (19.3%) and CT (disc) (12.2%) stubble-retained treatments. Available soil water (depth of 1.2 m) at sowing and anthesis was highest in the NT plots and lowest in the CT (disc) plots. Moisture stress around anthesis exacerbates the effect of *Fp* necrosis on the vascular system of cereal plants which led to the expression of conspicuous whiteheads (Beddis and Burgess 1992). So, although CA systems can increase the incidence of CR infection, they also favour greater water retention in the soil profile which can reduce plant stress during anthesis and consequently decrease the expression of whiteheads associated with CR infection.

Indirect impacts of CA on plant diseases

Reduced spread of disease The retention of cereal stubble reduces the incidence of some diseases during the pulse phase of crop rotations. Infection of lupin leaves with brown leaf spot (*Pleiochaeta setosa*) in Western Australia was reduced when cereal stubble mulch was retained, compared with stubble removal (Sweetingham *et al.* 1993). The authors proposed that the retention of cereal mulch limited the rain splash of soil-borne *P. setosa* spores into the upper canopy of the lupin crop. The benefit of cereal stubble retention in reducing brown leaf spot in lupins was supported by observations in southern NSW (Simpfendorfer *et al.* 2004).

Table 2. Examples of crop diseases that increase and decrease with CA in Australia

Crop	Disease and causal organism	Selected references
<i>Diseases that increase with CA</i>		
Cereal	Rhizoctonia root rot (<i>Rhizoctonia solani</i>)	de Boer and Kollmorgen (1988), Roget <i>et al.</i> (1996)
	Crown rot (CR; <i>Fusarium</i> spp.)	Dodman and Wildermuth (1989), Wildermuth <i>et al.</i> (1997)
	Yellow spot (<i>Pyrenophora tritici-repentis</i>)	Summerell and Burgess (1989), Bhathal <i>et al.</i> (2003)
	Take-all (<i>Gaeumannomyces graminis</i> var. <i>tritici</i> , Ggt)	Pankhurst <i>et al.</i> (1995a); Roget <i>et al.</i> (1996),
	Eyespot (<i>Oculimacula yullandae</i>)	de Boer <i>et al.</i> (1993), Murray <i>et al.</i> (1991)
	Pythium root rot (<i>Pythium</i> spp.)	Pankhurst <i>et al.</i> (1995b)
	Septoria tritici blotch (<i>Zyloseptoria tritici</i>)	Goodwin (2007)
	Root lesion nematodes (RLN; <i>Pratylenchus</i> spp.)	Rahman <i>et al.</i> (2007); Thompson <i>et al.</i> (2008)
	Net blotch (<i>Pyrenophora teres</i>)	Lehmensiek <i>et al.</i> (2007)
	Septoria nodorum blotch (<i>Parastagonospora nodorum</i>)	Bhathal <i>et al.</i> (2003)
Canola	Blackleg (<i>Leptosphaeria maculans</i>)	Barbetti and Khangura (1999), West <i>et al.</i> (2001)
Pulse	Rhizoctonia bare-patch (<i>Rhizoctonia solani</i>)	Sweetingham (1986)
	Ascochyta blight (<i>Ascochyta</i> spp.)	Davidson <i>et al.</i> (2007)
<i>Disease that decrease with CA</i>		
Cereal	Cereal cyst nematode (CCN; <i>Heterodera avenae</i>)	Rovira 1990, Vanstone <i>et al.</i> (2008)
	Common root rot (CRR; <i>Bipolaris sorokiniana</i>)	Wildermuth <i>et al.</i> (1997), de Boer <i>et al.</i> (1991)
Pulse	Sclerotinia stem rot (<i>Sclerotinia sclerotiorum</i>)	Simpfendorfer <i>et al.</i> (2004)
	Brown leaf spot (<i>Pleiochaeta setosa</i>)	Sweetingham <i>et al.</i> (1993), Simpfendorfer <i>et al.</i> (2004)

Virus incidence in pulse crops also can be reduced by the retention of cereal stubble in CA systems. The final incidence of cucumber mosaic virus (CMV) in narrow-leafed lupins was reduced 25-40% in seven field experiments where cereal stubble was spread on the soil surface (Bwye *et al.* 1999). Inter-row planting into standing wheat stubble halved the incidence of beet western yellows virus (BWYV) in chickpea when compared to the same amount of stubble flattened on the soil surface (Moore *et al.* 2014). The mechanism for these differences is unclear but both CMV and BWYV are spread by aphid vectors and aphid numbers were lower with retained stubble treatments in the lupin study (Bwye *et al.* 1999). Retained cereal stubble can deter the landing of migrant aphid vectors.

A similar association has been found with reduced incidence of barley yellow dwarf virus (BYDV) in wheat and barley in the UK with CA practices. The combined effect of RT plus retention of cereal stubble was shown to provide a 21% yield advantage over CT without stubble. The yield benefit was associated with up to 48% reduction in aphid numbers and 71% decrease in the incidence of BYDV in the RT treatment compared with CT (Kennedy *et al.* 2010).

Earlier sowing opportunities Retention of stubble on the soil surface under CA increases surface moisture at sowing time, and allows an earlier and/or extended sowing window, particularly in dry seasons. Earlier sowing can improve crop water use efficiency and increase wheat yield (Kirkegaard and Hunt 2010) but can increase the incidence of some diseases. Earlier sowing tends to increase the risk of BYDV (McKirdy and Jones 1997) and wheat streak mosaic virus (WSMV) in cereal crops (Coutts *et al.* 2008) due to warmer temperatures in early autumn favouring activity of aphid or mite vectors that transmits these viruses. Earlier planting can also increase levels of stripe rust (*Puccinia striiformis*) at early crop stages due to warmer temperatures in early autumn, favouring rust cycling (Murray *et al.* 2005). Earlier sowing has also been shown to increase ascochyta blight in field peas (McDonald and Peck 2009). However, with the exception of ascochyta blight in field peas, delayed sowing is not generally recommended to reduce risk from these pathogens as the yield penalty associated with later sowing has been shown to generally outweigh the yield benefit from decreased disease severity and growers have options for disease control in early-sown crops.

Deeper planting to access stored soil moisture at sowing Crop yields in the northern region are generally more reliant on stored soil water than in other regions due to the predominance of higher clay content soils with increased plant available water holding capacity and a summer dominant rainfall pattern. However, dry conditions in autumn can limit planting opportunities so growers are often forced

to increase sowing depths with cereals and chickpeas to access deeper soil moisture to establish crops earlier in the planting window. Deeper sowing lengthens the sub-crown internode in cereals which increases susceptibility to CRR (Duczek and Piening 1982). Soil temperatures greater than 20-30°C favour *Bs* infection with yield losses between 7 and 24% reported from CRR in bread wheat (Wildermuth *et al.* 1992). The trend to deeper and earlier sowing of cereals into warmer soils is associated with an increased prevalence of CRR across Australia, especially in the northern region.

Bipolaris sorokiniana was recovered from 52%, 31% and 29% of 1774 cereal crops surveyed in the northern, western and the southern region respectively between 2014 and 2018. Medium to high (>11%) infection levels occurred in 13%, 8% and 5% of paddocks in the northern, western and southern region respectively (Simpfendorfer, unpublished). Consideration of integrated management options for CRR appears to be an increasing priority for Australian cereal growers. Importance is heightened by potential interaction between *Bs* and other soil- or stubble-borne diseases such as CR which can exacerbate yield loss (Simpfendorfer 2016a).

New management approaches for crop disease control in CA systems

Although the adoption of CA is associated with an increased incidence of some diseases, Australian researchers have been developing a range of innovative strategies to assist growers to minimise losses. These include pre-plant testing to determine levels of pathogen risk, technology and engineering innovations at sowing, breeding tolerant varieties and improving fungicide efficacy. Novel approaches, such as the potential of microwave radiation to reduce the survival of stubble-borne pathogens, are also currently being explored in Australia.

Value of PREDICTA® B to determine disease risk prior to sowing

A quantitative DNA-based soil testing service, PREDICTA® B, is available in Australia to assist grain growers to predict the likely risk of soil-borne diseases by measuring pathogen levels prior to planting. Growers have the option of changing cultivars or modifying cropping programs in situations where the risk of crop loss is high. The service was launched in 1997 with the initial focus on soil-borne pathogens of wheat and barley. Since then the range of pathogens covered has grown steadily and has expanded to include stubble-borne pathogens and cover a broader range of crops including pulses and oilseeds (Ophel-Keller *et al.* 2008). PREDICTA B has provided growers with a transformational change in their ability to quantify the risk of various diseases within their farming systems.

The key advantage of these DNA based assays is their ability to quantify a broad range of soil- and stubble-borne pathogens affecting cereals and pulses in a single soil sample. PREDICTA B results compiled and mapped to the nearest town highlight higher risk cropping areas for different diseases prior to sowing, and this can be used to inform industry (Figure 1).

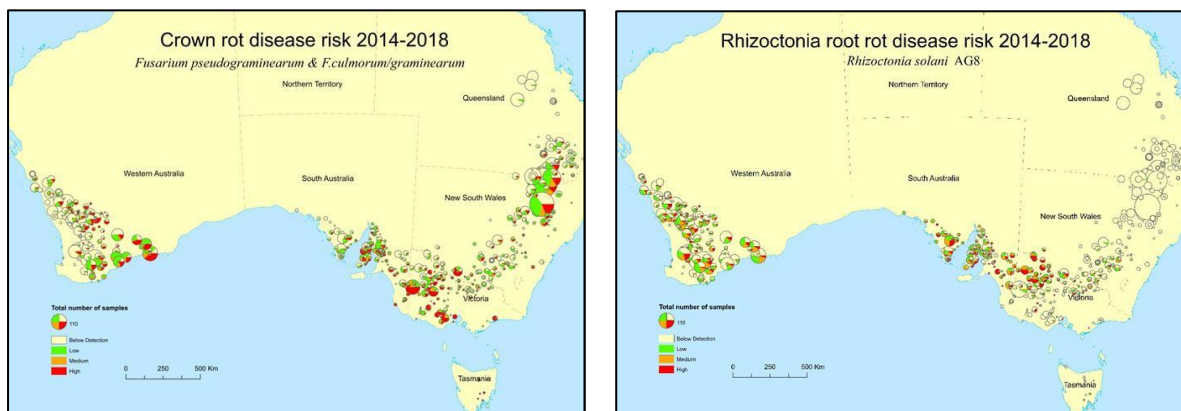


Figure 1. Distribution and levels of *Fusarium spp.* associated with causing crown rot (left) and *Rhizoctonia solani* (AG8; right) detected by PREDICTA B in grower paddocks and NVT sites prior to seeding 2014-2018 (N.B. the size of each pie chart is proportional to the number of samples mapped to the town and the numbers of low, medium and high disease risk samples are presented as green, orange and red sectors, respectively)

PREDICTA B results indicated that CR (Figure 1, left) is the most important soil/stubble-borne disease nationally, followed by root lesion nematodes. However, rhizoctonia root rot (Figure 1, right) and take-all also pose significant risks and other less common diseases may be important locally. A comprehensive range of maps is available at

http://pir.sa.gov.au/research/services/molecular_diagnostics/predicta_b.

Over time these results reveal the effects of changing cropping practices on pathogen levels. For example, the dramatic impact of the adoption of cereal cyst nematode (CCN) resistant cereal varieties and rotation with non-host crops on CCN soil levels is evident between 2002 and 2018 (Figure 2).

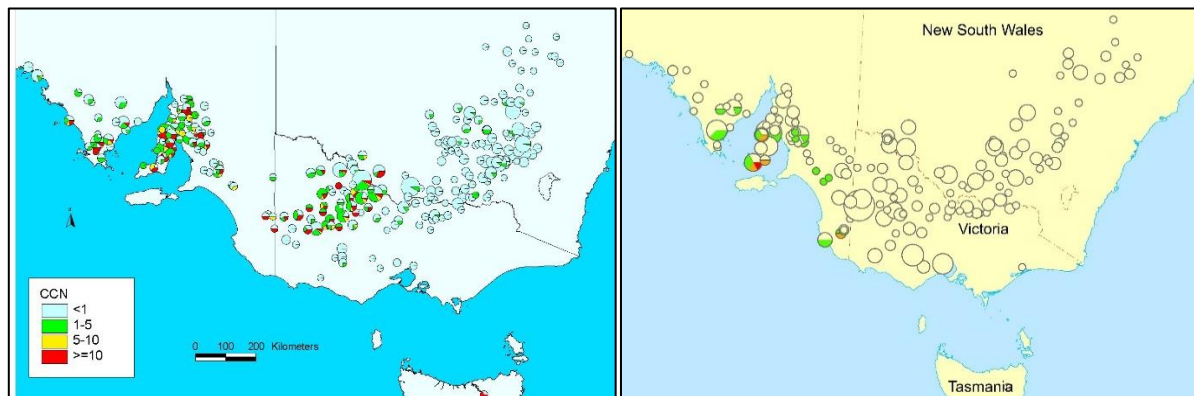


Figure 2. Distribution and levels of cereal cyst nematode detected by PREDICTA B in grower paddocks prior to seeding in 2002 (left) and 2018 (right)

The continued inclusion of new tests within the PREDICTA B system is valuable to determine the changing distribution, epidemiology and importance of a wide range of pathogens associated with the new CA practices across Australia. Use of PREDICTA B by growers and researchers has raised awareness of the risks posed by soil- and stubble-borne pathogens across regions. This technology is also allowing researchers to examine the impact of cropping practices on multiple soil- and stubble-borne pathogens, research which was previously considered too complex. PREDICTA B is also supporting development of improved management strategies to limit losses from diseases under CA.

Inter-row sowing and disease

The adoption of inter-row sowing using GPS guidance is a relatively recent innovation in CA in Australia to improve stubble handling. *Fp* is a stubble-borne pathogen, so inoculum becomes concentrated in the previous cereal rows with CA. Paddock surveys across 44 sites in the northern region in 2005 reported an average 45% reduction in the incidence of *Fp* infection and 51% decrease in the severity of CR with inter-row sowing (Simpfendorfer 2012). In replicated small plot experiments inter-row sowing reduced *Fp* incidence and CR severity resulting in 27% fewer whiteheads and a 6% yield benefit in bread wheat-durum wheat cycles over three seasons (Verrell *et al.* 2017).

The main value of inter-row sowing is that it reduces the rate of *Fp* inoculum build-up in a cereal/pulse or oilseed crop sequence. This benefit is not evident in continuous cereal production because inoculum survives too long in the inter-row spaces. Inter-row sowing is a useful component of an integrated disease management system for CR when combined with rotation of non-host crops. In the northern region, rotation of cereals with non-host oilseed and pulse crops reduced crown rot infection (by 3.4-41.3%) and increased wheat yield (by 0.24-0.89 t/ha) compared with a cereal-wheat rotation (Kirkegaard *et al.* 2004). Further research combining crop sequencing with inter-row sowing, found that using mustard-wheat and chickpea-wheat rotations increased wheat yield by 40-44% compared with continuous wheat with a further 11-16% yield benefit from inter-row sowing, depending on the row placement sequences (Verrell 2014).

A combined crop sequence and row placement strategy is now recommended for CA in the northern region. The strategy has two simple principles:

- sow break crops (oilseed or pulse) between standing wheat rows which need to be kept intact; and
- sow the following wheat crop *directly over* the row of the previous seasons break crop.

This ensures a four-year gap between wheat crops sown on the same row, resulting in decreased incidence of CR in wheat and improved germination of the break crops.

Take-all, caused by *Ggt*, was less severe as the distance of seed placement to the inoculum source increased (Kabbage and Bockus 2002). Mathematical modelling suggested that sowing parallel to and between previous cereal rows would reduce yield loss to *Ggt* (Garrett *et al.* 2004). Field experiments in South Australia confirmed that inter-row sowing improved yield in the presence of take-all (McCallum 2007). In summary, inter-row sowing, using precision row placement can limit the impact of pathogens such as *Fp* and *Ggt* with CA where inoculum is predominantly confined to the previous cereal rows.

Impact of seeding equipment on soil-borne diseases

It is well established that different soil openers (tynes or discs) used when sowing crops have a significant influence on the severity of rhizoctonia root rot (Rovira 1990). Disturbance below seeding depth using knife-points disrupts the hyphal network of rhizoctonia in the soil surface, assisting crop roots to escape early infection and reduce disease impact. Rhizoctonia risk is generally considered greater when sowing using single disc seeders than knife-points. Preliminary studies in South Australia in 2015 examined the potential of a specifically engineered ‘sweep’ (Figure 3b) mounted in-front of a single disc to excavate the top 2-3 cm of soil, where rhizoctonia inoculum was concentrated, away from the seeding row. The crop established well with no signs of bare-patches, although rhizoctonia recovered by mid-winter to cause severe disease on the crown roots (P. Bogacki pers. comm.).

In a CR infested site, planting using a tyne resulted in better plant establishment, higher tiller density and improved grain yield compared with a disc opener (Verrell *et al.* 2017). This yield advantage was considered to be due to the ‘excavating’ effect of the tyne, removing *Fp* inoculum from the seed furrow. Moving cereal stubble away from the sown row using a row cleaner in front of a single disc (Figure 3a) also reduced the incidence of *Fp* (by 3.7%) and whiteheads (by 13.6%) but did not increase yield (Verrell *et al.* 2017).

Improving the efficacy of fungicide strategies

Targeted fungicide application for crown rot CR infection is concentrated below ground and at the base of infected tillers which is likely to limit the activity of foliar fungicide applications. Simpfendorfer *et al.* (2014) showed that across 22 field sites in northern NSW in 2013/14, targeted fungicide application at the base of tillers using inter-row droppers with angled nozzles (Figure 4a) provided an average 5 % yield benefit (0.19 t/ha) in the absence of CR inoculation and a 15 % (0.37 t/ha) yield benefit in the CR inoculated treatment. However, the average level of benefit remained 0.98 t/ha less than uninoculated control plots. Normal foliar fungicide application 50 cm above the crop canopy did not provide any yield benefit. Targeting the in-crop application of fungicides at the base of infected wheat plants provided a minor (5-15 %) yield improvement but may be a useful addition to an integrated control strategy to manage CR.

Liquid banding of fungicide for Rhizoctonia Rhizoctonia is still a major constraint to cereal production in low to medium rainfall districts in the southern and western regions of Australia (Figure 1). Improved integrated management including early sowing, grass free canola, pulse and pastures (Gupta *et al.* 2012), knife point seeding systems and fungicides has reduced the impact of rhizoctonia root rot. These

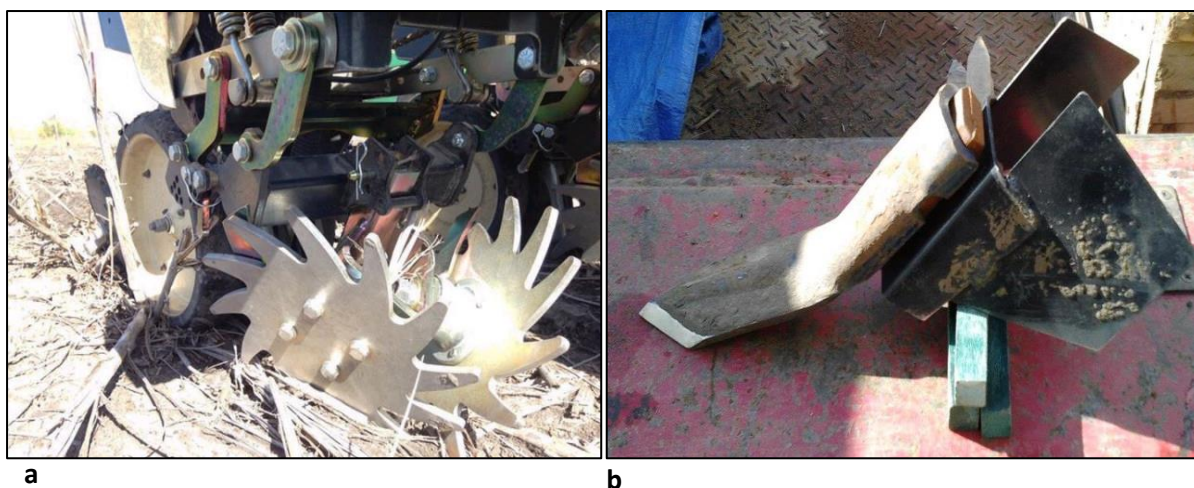


Figure 3. Row cleaner used to move cereal stubble away from sowing row (a); sweep used to shift surface soil and stubble out of planting row (b);



Figure 4. Inter-row droppers used to target fungicide application at the base of wheat tillers to improve in-crop control of crown rot (a); liquid application system used to apply fungicide above (b) and below the seed (c) at sowing to manage *Rhizoctonia* root rot (photos: Jack Desbiolles, Uni SA)

changes in agronomy have resulted in a significant shift in the symptomology of rhizoctonia root rot from ‘bare patches’ due to seedling infection to development of uneven growth in mid-winter due to infection of crown roots when soil temperatures drop to $<10^{\circ}\text{C}$. Infection can then continue to develop on the root system until the crop matures, and can spread to the seminal root system, limiting water uptake in periods of high evapotranspiration.

Several fungicide seed treatments are registered in Australia for the control of rhizoctonia in cereal crops. However, extensive field evaluation in the southern and western region found that on average seed treatments only provided an average 5% (0 to 18%) yield benefit in wheat and barley (McKay *et al.* 2014). Rainfall post sowing is needed to move fungicide applied to seeds into the root zone with roots growing outside the fungicide zone being unprotected.

The fungicides azoxystrobin + metalxyl-m (Uniform®, Syngenta) and penflufen (EverGol Prime®, Bayer CropScience) have recently been registered for liquid streaming to control rhizoctonia. Twenty-one fungicide efficacy trials comparing seed treatments with liquid streaming in either barley or wheat were conducted in SA and WA from 2011-2013. These experiments found that application via dual

banding, in-furrow 3-4 cm below the seed (Figure 4b) and on the surface behind the press wheel (Figure 4c), provided the most consistent yield (0.20 to 0.53 t/ha in wheat and 0.37 to 0.87 t/ha in barley) and root health benefits across seasons (McKay *et al.* 2014).

Liquid streaming fungicides is a significant development in the control of rhizoctonia root rot in CA and provides several benefits compared with applying fungicides as seed or fertiliser treatments. These benefits include a greater capacity to target placement to improve protection of both the crown and seminal root systems from rhizoctonia root rot, greater flexibility to vary fungicide application rate and to target areas of the paddock that will provide the greatest return on investment, and the ability to not apply fungicides to areas where run-off may contaminate water courses. The decision to apply fungicides to a specific paddock can be delayed until seeding which eliminates the risk of contaminating trucks and augers that will be used later in the season to transport grain. An additional expense is required with liquid systems which can be a barrier to adoption. However, due to flexibility in liquids which can be applied this has seen more rapid adoption in the western than the southern region where these systems were already being used for nutrient application.

Newer modes of action Fungicide management of foliar diseases in Australia has traditionally been based on the use of demethylation inhibitor (DMI, Group 3) triazole fungicides. However, evolving issues with the development of fungicide resistance to DMIs in Australia and availability of new modes of action including quinone outside inhibitors (QoI or strobilurins, Group 11) and succinate dehydrogenase inhibitors (SDHI, Group 7) has driven a re-evaluation of fungicide management strategies.

Spot-form of net blotch (SFNB), caused by the fungus *Pyrenophora teres f. maculata*, is a common foliar disease of barley across Australia due to the widespread cultivation of susceptible varieties, stubble retention and favourable climatic conditions (McLean *et al.* 2009). The SDHI seed treatment, fluxapyroxad (Systiva®, BASF) was registered in Australia for the control of a range of fungal diseases in barley, including SFNB, in 2015. In two field experiments conducted in the northern region in 2016, Systiva® was found to have similar efficacy as a first node (GS31) application of foliar fungicides when both strategies were backed up by a second foliar fungicide application at awn peep (GS49) (Simpfendorfer and Street 2017). Systiva® provided useful levels of SFNB suppression post GS49 under moderate disease pressure at Tamworth but activity waned by this growth stage under higher disease pressure at Dubbo in 2016. Foliar application of bixafen + prothioconazole (SDHI + DMI; Aviator® Xpro®, Bayer CropScience) was also included in this study and provided improved control of SFNB and reduced yield loss compared with azoxystrobin + cyproconazole (QoI + DMI, Amistar Xtra® Syngenta) which was then better than propiconazole (DMI, Tilt®250 Syngenta) in these experiments (Simpfendorfer and Street 2017). Similar findings on the value of Systiva® for early control of SFNB in barley have been produced in the southern region (McLean and Hollaway 2015).

Recent Australian studies have also found that the inclusion of these newer QoI or SDHI actives in fungicide management strategies has improved the control of yellow spot and septoria tritici blotch in wheat along with net-blotch (both net-form and SFNB), scald and powdery mildew in barley (Poole and Wylie 2017), blackleg in canola (Horbury 2016) and ascochyta blight in chickpeas (K Moore, pers. comm.) compared with existing DMI only standards.

Disease forecasting models Disease forecasting models can assist in determining the risk of disease occurrence as well as the probability that the intensity of the infection will increase (Campbell and Madden 1990). Reliable and timely crop disease forecasts can assist growers to manage disease especially by guiding appropriate and/or timely application of fungicides. Disease forecasts can prevent or reduce the unnecessary application of fungicides in seasons when climatic conditions are not conducive to pathogen development or infection.

In Australia, this has been well demonstrated through the development and application of the 'Blackspot Manager' model in the management of ascochyta blight in field peas in the Western Australia, South Australia, Victoria and southern NSW (Galloway 2018). Blackspot Manager calculates when the majority of spores (~60%) have been released from field pea stubble and the risk of infection is reduced

to low levels. Growers can then decide to delay sowing field peas until their region is designated as having low disease risk or, if sowing when risk is high, they can plan a foliar fungicide program to reduce the severity of *Ascochyta* blight.

A similar model to predict the maturity of *Leptosphaeria maculans* ascospores on canola residues from previous crops based on weather conditions has been developed in Western Australia (Pratt and Salam 2018). The model aims to improve blackleg management in canola, including fungicide timing, and was released for use by growers in both western and eastern Australia in 2018. Further disease forecasting models are currently under development in Australia for yellow spot (*Pyrenophora tritici-repentis*) in wheat crops and sclerotinia stem rot (*Sclerotinia sclerotiorum*) in canola.

Breeding for tolerance to soil- and stubble-borne diseases

A tolerant cultivar is defined as one that loses significantly less yield or quality compared with other cultivars, when exposed to an equivalent level of pathogen burden (van den Berg *et al.* 2017). Tolerance in wheat to the root lesion nematode *Pratylenchus thornei* (*Pt*) was first identified in 1984 with an ongoing breeding and selection program in Australia (Thompson *et al.* 2008). Nationally, the adoption of wheat varieties with moderate or higher levels of tolerance to *Pt* has risen from 24% in 2010 to 62% in 2016 (Murray and Brennan, unpublished data). This has significantly reduced yield losses, especially in the northern region where this plant pathogenic nematode is endemic, and highlights the potential value of this approach to limit the impact of soil-borne pathogens which increase in CA systems.

No major genes for CR resistance exist (Liu and Ogbannaya 2015). However, wheat varieties differ in both their levels of tolerance and resistance to CR; these are separate mechanisms both of which can reduce the extent of yield loss (Forknall *et al.* 2019). Recent research has established the relative 'tolerance' of different bread wheat, barley and durum varieties to CR in Victoria and SA (Evans and Hollaway 2017), WA (Hüberli *et al.* 2017), southern NSW (Milgate and Baxter 2018), central/northern NSW and southern Qld (Simpfendorfer *et al.* 2016b). Growers can adopt cereal varieties with improved yield performance in the presence of CR infection as proven in their region to minimise losses. In a relatively short period of time the yield benefit of switching between wheat varieties in the presence of CR infection has risen from 5-10% in 2007 (Daniel and Simpfendorfer 2008) to 20-40% in 2015 (Simpfendorfer 2016b).

A key limitation to resistance and tolerance breeding for CR remains a lack of research and knowledge of the genetic basis of the mechanisms which confer tolerance. An understanding is required of the underlying mechanism(s) which confer improved tolerance (*e.g.* resistance to the pathogen, root architecture, heat stress tolerance, tolerance of abiotic factors such as salinity or sodicity) to refine further and target breeding efforts. Heat tolerance traits such as waxy leaves and leaf rolling have been reported to enhance the water use efficiency of wheat crops (Richards *et al.* 2010) which may also reduce the expression of CR.

Breeding for desirable root architectural traits, such as narrow root angle and high root number (Manschadi *et al.* 2006), which improve access to stored moisture deep in the soil, may also reduce the impact of CR under terminal drought conditions which are frequently experienced in the northern region of Australia. However, in environments with shallow soils where the crop relies on sporadic rainfall in-season (*e.g.* western and southern regions), a wider root growth habit and shallow root system may be preferable to maximise soil water uptake (Alahmad *et al.* 2018).

Selection for tolerance may be a better strategy to improve yield and raise the pathogen threshold before losses occur where major genes for disease resistance are not available. Priority diseases for improving crop tolerance under CA include rhizoctonia root rot and take-all in cereals as well as root lesion nematodes (*Pratylenchus* spp.) in pulses and oilseeds, which can be exposed to high populations when grown following susceptible wheat cultivars. Preliminary research has been conducted on the value of more rapid root replacement in chickpea cultivars to improve tolerance to phytophthora root rot (S Bithell pers. comm.).

Microwave radiation – a novel approach to manage stubble-borne pathogens

New microwave field applicator prototypes are being developed in Australia for the control of weeds in paddocks (Brodie *et al.* 2015). Microwave radiation may also offer a rapid and chemical-free approach to reduce the survival of stubble-borne pathogens in crop residues and allow them to remain intact. Preliminary laboratory research has demonstrated that microwave radiation is an effective method for significantly reducing the survival of *Fp* in durum wheat stubble (Petronaitis *et al.* 2018). To date, the practical adoption of microwave radiation to control soil- and stubble-borne pathogens within paddocks has largely been limited by the availability of suitable large-scale equipment. More research is required, including consideration of alternate radiation sources such as infrared, before such technology can be used to manage stubble-borne pathogens under field conditions.

Challenges to reduce disease risk in CA systems

There are several inherent challenges associated with managing crop diseases under CA systems. These include likely impacts of future climate change predictions, issues around weeds and crop intensification and the continuing evolution of pathogen populations.

Climate change

It is widely acknowledged that the increased adoption of CA systems will be critical in growers adapting to future climate change scenarios including increased temperatures, elevated CO₂, greater variability in rainfall and increased frequency of droughts. Crop production will become more reliant on the stored soil water benefits associated with adoption of CA to buffer against these climatic changes. The potential impact of climate change on a wide range of crop diseases has been modelled in various studies as reviewed by Luck *et al.* (2011). This review concluded that the importance of necrotrophic wheat diseases such as yellow spot, septoria tritici blotch and septoria nodorum blotch in wheat are likely to decrease with climate change.

Crown rot infection in cereal crops is predicted to increase in significance with climate change. Increasing atmospheric CO₂ concentration has been shown to directly increase the production of *Fp* biomass in wheat tissue (Melloy *et al.* 2010). The production and survival of CR inoculum in retained stubble is predicted to increase as a consequence. Furthermore, reduced reliability of rainfall and elevated temperatures, especially during grain filling, are further likely to increase the severity and yield loss from CR. It has even been suggested that CR would be a good indicator of global climate change (Moya-Elizondo 2013).

Changes in rainfall patterns and increased frequency of droughts are further likely to increase the longevity of stubble-borne pathogens in CA systems by reducing the rate of residue decomposition. These conditions are also likely to alter the rate of spore maturity and release from residues over time with necrotrophic stubble-borne pathogens such as *Pyrenophora* spp., *Septoria* spp. and *Ascochyta* spp. which may alter the timing of currently recommended management strategies.

Weeds as alternate hosts for plant pathogens

CA systems rely on herbicides to replace cultivation for the control of weeds. This has led to the evolution of herbicide resistant weeds across Australian cropping areas (see Chapter 10). Resistance to glyphosate alone, the main herbicide which has underpinned the adoption of NT globally, has been recorded in ten grass weed species and seven broadleaf species in Australia (Preston 2019). Many of these weeds are alternate hosts of different crop pathogens which can undermine recommended disease management strategies. The impact of weeds on disease can be two-fold in some instances, such as with grass weeds and CR. The reported hosts of *Fp* include 15 grass species including ryegrass, black oats and barley grass (Alahmad *et al.* 2018) which can be important sources of inoculum especially during break crop periods. These weeds can further reduce stored soil water levels during fallow periods and/or provide in-crop competition with cereal plants for moisture which can increase stress during grain-filling and exacerbate the expression of whiteheads in CR infected tillers (Alahmad *et al.* 2018).

Furthermore, some herbicides have been shown to increase the severity of disease such as the pre-sowing application of sulphonylurea with rhizoctonia root rot (Rovira 1990).

Increased cropping intensification

The adoption of CA facilitates the intensification of cropping often with the removal of longer pasture ley phases. This can increase disease incidence by reducing the time for inoculum levels to decline between susceptible crop species. However, even when rotations are implemented the shared host range of some pathogens can still result in increased disease incidence. For instance, bread wheat, durum wheat, barley, sorghum and maize are all hosts of *Fusarium graminearum* and when grown in close rotation increase the risk of fusarium head blight (FHB), especially in durum wheat which is very susceptible (Obanor *et al.* 2013). *Sclerotinia sclerotiorum* has an even wider host range including winter pulse crops (chickpea, lentils, lupins and faba beans), winter oilseeds (canola) and summer broad leaf crops (sunflowers, mungbeans, soybean and cotton). These limit rotation options, especially with the increasing intensification of high value pulse crops such as chickpeas and lentils in Australia. The widespread adoption of wheat-chickpea-wheat rotations in the northern region supports *Pt* populations while wheat-canola-wheat rotations in the southern and western regions will promote *Pn* populations due to the growth of successive susceptible hosts to these different RLN species.

The increased intensification of canola and pulses in different regions further means that previous recommendations around only growing these crops once every three years in the same paddock to limit the incidence of disease are no longer practical. Buffer zones of around 500 m between current canola or pulse crops with residues of these same species from the previous season are also recommended to limit the development of fungal pathogens such as *Ascochyta* spp. and *Leptosphaeria maculans* which have limited wind-borne dispersal. These recommendations were useful over a decade ago when these industries were starting to develop in the different regions but have become impractical with the increased intensification of canola and/or pulse production.

Fungicide resistance

Recent findings on the improved efficacy of Qol and SDHI based fungicides are promising for improved disease management in Australian cereal and pulse crops, especially given that most of these diseases are known to increase with the adoption of CA (Table 2). However, Qol fungicides are considered at high risk of resistance evolution within fungal pathogens and the risk of resistance to SDHI fungicides is considered medium to high (FRAC 2018). This is concerning given that DMI fungicides are only considered to be at medium risk yet multiple instances of DMI fungicide resistance have been recorded in Australia for a range of pathogens (Anon. 2016). To prolong the activity of Qol and SDHI fungicides along with existing triazole products, they need to be used judiciously and in combination with other management strategies. Australian growers are urged to use integrated disease management (IDM) strategies to limit losses from crop diseases such as crop rotation, cultivar resistance, inoculum monitoring and disease forecasting; with fungicides being only one component. IDM will reduce disease pressure and the reliance on fungicides as the sole management tool but importantly also delays the development of resistance to these valuable chemical options.

'Breakdown' of host resistance genes by fungal pathogens

Canola production is challenged by the fungal pathogen *Leptosphaeria maculans* having a high evolutionary potential which means that extensive sowing of a cultivar in a region can lead to blackleg resistance bred into a cultivar becoming ineffective within three years (Sprague *et al.* 2006). The ability of *L. maculans* to evolve rapidly to 'break down' disease resistance bred into canola cultivars makes it a high-risk pathogen within Australian cropping systems (Van de Wouw *et al.* 2014). Marcroft *et al.* (2012) showed that rotating canola cultivars with different resistance genes minimised blackleg pressure by manipulating *L. maculans* populations. Annual monitoring of avirulence allele frequencies in *L. maculans* populations across Australia provides power to anticipate which cultivars will be most successful in future growing seasons (Van de Wouw *et al.* 2017). Growers can rotate canola cultivars from different blackleg resistance groups when required to reduce the severity of blackleg and

prolonging effectiveness of resistance genes. Ultimately, this process has allowed the continued expansion of canola production in Australia (Van de Wouw *et al.* 2017).

Pyrenophora teres f. teres (Ptt), the cause of net-form of net blotch (NFNB) in barley, is a highly variable pathogen with thirteen different pathotypes identified in Australia (Platz *et al.* 2000). This is challenging for the management of this stubble-borne pathogen. Sexual reproduction in *Ptt* means that progeny of crosses that carry increased virulence to different resistance genes present in cultivars are selected for overtime by the successive production of an individual barley variety. This has seen increased severity of NFNB on the barley varieties, Commander and Shepherd, in the northern region in recent years through their selection for previously rare *Ptt* pathotypes (Fowler and Platz 2017).

Conversely, the Australian *Ascochyta rabiei* (syn. *Phoma rabiei*) population, cause of ascochyta blight in chickpeas, has low genotypic diversity with only one mating type detected to date. This potentially precludes substantial genetic diversity through recombination which may result in the evolution of new pathotypes of the pathogen (Mehmood *et al.* 2017). However, isolates of *A. rabiei* which cause increased disease severity on widely adopted 'resistant' host genotypes such as Genesis090 and PBA HatTrick have been identified. A greater frequency of highly aggressive isolates within the ARH01 haplotype group appear to have created 'super isolates' with the highest pathogenicity ranking. This represents a significant risk to the Australian chickpea industry – not only are the isolates widely adapted across diverse geographical environments, but there are a disproportionately large number of aggressive isolates, indicating fitness to survive and infect the best Australian resistance sources (Mehmood *et al.* 2017).

Conclusion

Australian growers have persisted with CA and increased adoption, especially in the western region, despite the associated increased challenges with disease management. A range of new innovations in disease management under CA systems continue to support this trend. Pragmatism with occasional tillage and stubble burning can form part of a more resilient and integrated approach, and as climate shifts continue pathologists will need to be alert to the potential for emerging problems and work closely with agronomists and breeders to develop solutions.

References

- Alahmad S, Simpfendorfer S, Bentley AR, Hickey LT (2018) Crown rot of wheat in Australia: *Fusarium pseudograminearum* taxonomy, population biology and disease management. *Australasian Plant Pathology* **47**, 285-299
- Anonymous (2016) Sampling report annual review 2016: Fungicide resistance group. Centre for Crop and Disease Management. www.ccdm.com.au/wp-content/uploads/2017/06/FRG-Annual-Report-2016.pdf
- Barbetti MJ, Khangura RK (1999) Managing blackleg in the disease-prone environment of Western Australia. *Proceedings of 10th International Rapeseed Congress*, Canberra, Australia
www.regional.org.au/au/gcirc/3/8.htm
- Beddis AL, Burgess LW (1992) The influence of plant water stress on infection and colonization of wheat seedlings by *Fusarium graminearum* Group 1. *Phytopathology* **82**, 78-83
- Bhathal JS, Loughman R, Speijers J (2003) Yield reduction in wheat in relation to leaf disease from yellow (tan) spot and septoria nodorum blotch. *European Journal of Plant Pathology* **109**, 435-443
- Bockus WW, Shroyer JP (1998) The impact of reduced tillage on soilborne plant pathogens. *Annual Review of Phytopathology* **36**, 485-500
- Brennan JP, Murray GM (1989) Australian wheat diseases: Assessing their economic importance. *Agricultural Science* **2**, 26-35
- Brennan JP, Murray GM (1998) *Economic Importance of Wheat Diseases in Australia*. (NSW Agriculture: Wagga Wagga)
- Brodie G, Gixti M, Hollins E *et al.* (2015) Assessing the impact of microwave treatment on soil microbial populations. *Global Journal of Agricultural Innovation, Research and Development* **2**, 25-32
- Bwyne AM, Jones RA, Proudlove W (1999) Effects of different cultural practices on spread of cucumber mosaic virus in narrow-leaved lupins (*Lupinus angustifolius*). *Australian Journal of Agricultural Research* **50**, 985-996
- Campbell CL, Madden LV (1990) *Introduction to Plant Disease Epidemiology*. (John Wiley and Sons: New York)

- Coutts BA, Strickland GR, Kehoe MA *et al.* (2008) The epidemiology of wheat streak mosaic virus in Australia: case histories, gradients, mite vectors, and alternative hosts. *Australian Journal of Agricultural Research* **59**, 844-853
- Daniel R, Simpfendorfer S (2008) The impact of crown rot on winter cereal yields. GRDC Update www.grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2008/06/the-impact-of-crown-rot-on-winter-cereal-yields
- Davidson JA, Kimber RBE (2007) Integrated disease management of ascochyta blight in pulse crops. In (Eds. B Tivoli, A Baranger, FJ Muehlbauer, BM Cooke) “Ascochyta Blights of Grain Legumes” (Springer: Dordrecht)
- de Boer RF and Kollmorgen, JF (1988) Effects of cultivation and stubble retention on soil- and stubble-borne pathogens of wheat in Victoria – an overview. *Plant Protection Quarterly* **3**, 3-4
- de Boer RF, Kollmorgen JF, Macauley BJ, Franz PR (1991) Root rot and yield of wheat in the Victorian Mallee. *Australian Journal of Experimental Agriculture* **31**, 367-372
- de Boer RF, Steed GR, Kollmorgen JF, Macauley BJ (1993) Effects of rotation, stubble retention and cultivation on take-all and eyespot of wheat in northeastern Victoria, Australia. *Soil & Tillage Research* **25**, 263-280
- Dodman RL, Wildermuth GB (1989) The effect of stubble retention and tillage practices in wheat and barley on crown rot caused by *Fusarium graminearum* Group 1. *Plant Protection Quarterly* **4**, 98-99
- Duczek LJ, Piening LJ (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
- Duczek L, Sutherland K, Reed S *et al.* (1999) Survival of leaf spot pathogens on crop residues of wheat and barley in Saskatchewan. *Canadian Journal of Plant Pathology* **21**, 165-173
- Evans M, Hollaway G (2017) Varieties an escape route in heavy disease years. GroundCover issue 128 May-June www.grdc.com.au/resources-and-publications/groundcover/groundcover-issue-128-may-june-2017/varieties-an-escape-route-in-heavy-disease-years
- Forknall CR, Simpfendorfer S, Kelly AM (2019) Using yield response curves to measure variation in the tolerance and resistance of wheat cultivars to *Fusarium* crown rot. *Phytopathology* (accepted) doi.org/10.1094/PHYTO-09-18-0354-R
- Fowler R, Platz G (2017) Increased levels of net form of net blotch in Commander and Shepherd. GRDC Update www.grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2017/02/increased-levels-of-net-form-of-net-blotch-in-commander-and-shepherd
- FRAC (2018) FRAC Code List ©*2018: Fungicides sorted by mode of action (including FRAC Code numbering) www.frac.info/docs/default-source/publications/frac-code-list/frac_code_list_2018-final.pdf?sfvrsn=6144b9a_2
- Galloway (2018) Finding the safe planting window for blackspot. Department of Primary Industries and Rural Development www.agric.wa.gov.au/n/5582
- Garrett KA, Kabbage M, Bockus WW (2004) Managing for fine-scale differences in inoculum load: seeding patterns to minimize wheat yield loss to take-all. *Precision Agriculture* **5**, 291-301
- Goodwin SB (2007) Back to basics and beyond: increasing the level of resistance to *Septoria tritici* blotch in wheat. *Australasian Plant Pathology* **36**, 532-538
- Gupta VVSR, McKay A, Diallo S *et al.* (2012) *Rhizoctonia solani* AG8 inoculum levels in Australian soils are influenced by crop rotation and summer rainfall. *Proceedings of 7th Australasian Soilborne Diseases Symposium*, Fremantle p33
- Horbury R (2016). Control of blackleg with soil and foliar fungicides. www.farmtrials.com.au/trial/18665
- Hüberli D, Gajda K, Connor A, Van Burgel A (2017) Choosing the best yielding wheat and barley variety under high crown rot. GRDC Update www.grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2017/02/choosing-the-best-yielding-wheat-and-barley-variety-under-high-crown-rot
- Kabbage M, Bockus, WW (2002) Effect of placement of inoculum of *Gaeumannomyces graminis* var. *tritici* on severity of take-all in winter wheat. *Plant Disease* **86**, 298-303
- Kennedy TF, McDonald JG, Connery J, Purvis G (2010) A comparison of the occurrence of aphids and barley yellow dwarf virus in minimum-till and conventional-till autumn sown cereals. *The Journal of Agricultural Science* **148**, 407-419
- Kirkegaard JA, Hunt JR (2010). Increasing productivity by matching farming system management and genotype in water-limited environments. *Journal of Experimental Botany* **61**, 4129-4143
- Kirkegaard JA, Simpfendorfer S, Holland J *et al.* (2004). Effect of previous crops on crown rot and yield of durum and bread wheat in northern NSW. *Australian Journal of Agricultural Research* **55**, 321-334
- Lehmensiek A, Platz GJ, Mace E *et al.* (2007) Mapping of adult plant resistance to net form of net blotch in three Australian barley populations. *Australian Journal of Agricultural Research* **58**, 1191-1197

- Liu C, Ogonnaya FC (2015) Resistance to Fusarium crown rot in wheat and barley: a review. *Plant Breeding* **134**, 365-372
- Luck J, Spackman M, Freeman A *et al.* (2011) Climate change and diseases of food crops. *Plant Pathology* **60**, 113-121
- MacLeod WJ, MacNish GC, Thorn CW (1993) Manipulation of ley pastures with herbicides to control take-all. *Australian Journal of Agricultural Research* **44**, 1235-1244
- Manschadi AM, Christopher J, deVoil P, Hammer GL (2006). The role of root architectural traits in adaptation of wheat to water-limited environments. *Functional Plant Biology* **33**, 823-837
- Marcroft SJ, Van de Wouw AP, Salisbury PA *et al.* (2012) Effect of rotation of canola (*Brassica napus*) cultivars with different complements of blackleg resistance genes on disease severity. *Plant Pathology* **61**, 934-944
- McCallum M (2007). Multiple benefits from inter-row sowing with 2 cm RTK GPS. *Proceedings of 5th Australian Controlled Traffic and Precision Agriculture Conference*, University of Western Australia pp 118-121
- McDonald GK, Peck D (2009). Effects of crop rotation, residue retention and sowing time on the incidence and survival of ascochyta blight and its effect on grain yield of field peas (*Pisum sativum* L.). *Field Crops Research* **111**, 11-21
- McKay A, Bogacki P, Desbiolles J *et al.* (2014) Rhizoctonia control improved by liquid banding of fungicides. Grains Research Australia Adviser Update, Adelaide South Australia pp 245-249
www.grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2014/02/rhizoctonia-control-improved-by-liquid-banding-of-fungicides
- McKirdy SJ, Jones RAC (1997) Effect of sowing time on barley yellow dwarf virus infection in wheat: virus incidence and grain yield losses. *Australian Journal of Agricultural Research* **48**, 199-206
- McLean MS, Howlett BJ, Hollaway GJ (2009) The epidemiology and control of spot form of net blotch (*Pyrenophora teres f. maculata*) of barley: a review. *Crop and Pasture Science* **60**, 303-315
- McLean M, Hollaway G (2015) Spot form of net blotch yield loss and management in barley using fungicides and resistance in Victoria. GRDC Update www.grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2015/02/spot-form-of-net-blotch-yield-loss-and-management
- Mehmood Y, Sambasivam P, Kaur S *et al.* (2017) Evidence and consequences of a highly adapted clonal haplotype within the Australian *Ascochyta rabiei* population. *Frontiers in Plant Science* **8**, article 1029
doi.org/10.3389/fpls.2017.01029
- Melloy P, Hollaway G, Luck J *et al.* (2010) Production and fitness of *Fusarium pseudograminearum* inoculum at elevated carbon dioxide in FACE. *Global Change Biology* **16**, 3363-3373
- Milgate A, Baxter B (2018) Management of crown rot in southern NSW farming systems. GRDC Update www.grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2018/02/management-of-crown-rot-in-southern-nsw-farming-systems
- Moore K, Verrell A, Aftab M (2014) Reducing risk of virus disease in chickpea through management of plant density, row spacing and stubble – 2013 trials in northern NSW. GRDC Grains Research Update www.grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2014/03/reducing-risk-of-virus-disease-in-chickpeas
- Moya-Elizondo EA (2013) *Fusarium* crown rot disease: biology, interactions, management and function as a possible sensor of global climate change. *Ciencia Investigacion Agraria* **40**, 235-25
- Murray GM, Brennan JP (2009) Estimating disease losses to the Australian wheat industry. *Australasian Plant Pathology* **38**, 558-570
- Murray GM, Heenan DP, Taylor AC (1991) The effect of rainfall and crop management on take-all and eyespot of wheat in the field. *Australian Journal of Experimental Agriculture* **31**, 645-651
- Murray GM, Welling C, Simpfendorfer S, Cole C (2005) Stripe rust: understanding the disease in wheat. (NSW Department of Primary Industries: Orange)
- Obanor F, Neate S, Simpfendorfer S *et al.* (2013) *Fusarium graminearum* and *Fusarium pseudograminearum* caused the 2010 head blight epidemics in Australia. *Plant Pathology* **62**, 79-91
- Ophel-Keller K, McKay A, Hartley D *et al.* (2008) Development of a routine DNA-based testing service for soilborne diseases in Australia. *Australasian Plant Pathology* **37**, 243-253
- Pankhurst CE, Hawke BG, McDonald HJ *et al.* (1995a) Evaluation of soil biological properties as potential bioindicators of soil health. *Australian Journal of Experimental Agriculture* **35**, 1015-1028
- Pankhurst CE, McDonald HJ, Hawke BG (1995b) Influence of tillage and crop rotation on the epidemiology of *Pythium* infections of wheat in a red-brown earth of South Australia. *Soil Biology and Biochemistry* **27**, 1065-1073
- Petronaitis T, Forknall C, Simpfendorfer S (2018) Microwave radiation reduces survival of *Fusarium pseudograminearum* in durum wheat stubble. *Australasian Plant Pathology* **47**, 375-378

- Platz GJ, Bell KL, Rees RG, Galea VJ (2000) Pathotype variation of the Australian net blotch population. *Proceedings of 8th International Barley Genetics Symposium III*, 160-162
- Poole NF, Wylie T (2017) New fungicides and disease management strategies for wheat and barley. GRDC Update www.grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2017/03/new-fungicides-and-disease-management-strategies-for-wheat-and-barley
- Pratt J, Salam K (2018) Canola blackleg spore maturity forecast for Western Australia www.agric.wa.gov.au/n/6989
- Preston C (2019) The Australian Glyphosate Sustainability Working Group www.glyphosateresistance.org.au/
- Rahman L, Chan KY, Heenan DP (2007) Impact of tillage, stubble management and crop rotation on nematode populations in a long-term field experiment. *Soil & Tillage Research* **95**, 110-119
- Richards RA, Rebetzke GJ, Watt M *et al.* (2010) Breeding for improved water productivity in temperate cereals: phenotyping, quantitative trait loci, markers and the selection environment. *Functional Plant Biology* **372**, 85-97
- Roget DK, Neate SM, Rovira AD (1996) Effect of sowing point design and tillage practice on the incidence of rhizoctonia root rot, take-all and cereal cyst nematode in wheat and barley. *Australian Journal of Experimental Agriculture* **36**, 683-693
- Rovira AD (1990) The impact of soil and crop management practices on soil-borne root diseases and wheat yields. *Soil Use and Management* **6**, 195-200
- Simpfendorfer S (2012). Inter-row sowing reduces crown rot in winter cereals. *Proceedings of First International Crown Rot Workshop for Wheat Improvement* Narrabri, NSW
- Simpfendorfer S (2016a) Impact of common root rot and crown rot on wheat yield. NSW DPI Northern Grains Research Results, Tamworth NSW p125
- Simpfendorfer S (2016b) Crown rot – does cereal crop or variety choice matter? GRDC Update www.grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2016/02/crown-rot-does-cereal-crop-or-variety-choice-matter
- Simpfendorfer S, Street M (2017) Evaluation of fungicide management strategies to control spot form of net blotch in barley. GRDC Update www.grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2017/02/evaluation-of-fungicide-management-strategies-to-control-spot-form-of-net-blotch-in-barley
- Simpfendorfer S, Kirkegaard JA, Heenan DP, Wong PTW (2002) Reduced early growth of direct drilled wheat in southern New South Wales: Role of root inhibitory pseudomonads. *Australian Journal of Agricultural Research* **53**, 323-331
- Simpfendorfer S, Heenan DP, Kirkegaard JA *et al.* (2004) Impact of tillage on lupin growth and the incidence of pathogenic fungi in southern New South Wales. *Australian Journal of Experimental Agriculture* **44**, 53-56
- Simpfendorfer S, Fensbo F, Shapland R (2014) Targeted application improves efficacy of in-crop fungicides against crown rot in wheat. *Proceedings of 8th Australian Soilborne Diseases Symposium*, Hobart
- Sprague SJ, Marcroft SJ, Hayden HL, Howlett BJ (2006) Major gene resistance to blackleg in *Brassica napus* overcome within three years of commercial production in south-eastern Australia. *Plant Disease* **90**, 190-198
- Summerell BA, Burgess LW (1988) Stubble management practices and the survival of *Fusarium graminearum* Group 1 in wheat stubble residues. *Australasian Plant Pathology* **17**, 88-93
- Summerell BA, Burgess LW (1989) Factors influencing survival of *Pyrenophora tritici-repentis*: stubble management. *Mycological Research* **93**, 38-40
- Sweetingham MW (1986) Research into lupin root diseases. *Journal of the Department of Agriculture, Western Australia, Series 4* **27** (2), Article 4 www.researchlibrary.agric.wa.gov.au/journal_agriculture4/vol27/iss2/4
- Sweetingham MW, Loughman R, Porritt SE (1993) Cereal stubble mulching protects lupins from brown spot (*Pleiochaeta setosa* [Kirchn.] Hughes). *Australian Journal of Experimental Agriculture* **33**, 469-473
- Thompson JP, Owen KJ, Stirling GR, Bell KL (2008) Root-lesion nematodes (*Pratylenchus thornei* and *P. neglectus*): a review of recent progress in managing a significant pest of grain crops in northern Australia. *Australasian Plant Pathology* **37**, 235-242
- Ugalde D, Brungs A, Kaebnick M *et al.* (2007) Implications of climate change for tillage practices in Australia. *Soil & Tillage Research* **97**, 318-330
- van den Berg F, Paveley ND, Bingham IJ, van den Bosch F (2017) Physiological traits determining yield tolerance of wheat to foliar diseases. *Phytopathology* **107**, 1468-1478
- Van de Wouw AP, Marcroft SJ, Ware A *et al.* (2014) Breakdown of resistance to the fungal disease, blackleg, is averted in commercial canola (*Brassica napus*) crops in Australia. *Field Crops Research* **166**, 144-151
- Van de Wouw AP, Howlett BJ, Idnurm A (2017) Changes in allele frequencies of avirulence genes in the blackleg fungus, *Leptosphaeria maculans*, over two decades in Australia. *Crop and Pasture Science* **69**, 20-29

- Vanstone VA, Holloway GJ, Stirling GR (2008) Managing nematode pests in the southern and western regions of the Australian cereal industry: continuing progress in a challenging environment. *Australasian Plant Pathology* **37**, 220-234
- Verrell A (2014) Managing crown rot through crop sequencing and row placement. GRDC Update www.grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2014/07/managing-crown-rot-through-crop-sequencing-and-row-placement
- Verrell AG, Simpfendorfer S, Moore KJ (2017) Effect of row placement, stubble management and ground engaging tool on crown rot and grain yield in a no-till continuous wheat sequence. *Soil & Tillage Research* **165**, 16-22
- West JS, Kharbanda PD, Barbetti MJ, Fitt BDL (2001) Epidemiology and management of *Leptosphaeria maculans* (phoma stem canker) on oilseed rape in Australia, Canada and Europe. *Plant Pathology* **50**, 10-27
- Wildermuth GB, Tinline RD, McNamara RB (1992) Assessment of yield loss caused by common root rot in wheat cultivars in Queensland. *Australian Journal of Agricultural Research* **43**, 43-58
- Wildermuth GB, Thomas GA, Radford BJ *et al.* (1997) Crown rot and common root rot in wheat grown under different tillage and stubble treatments in southern Queensland, Australia. *Soil & Tillage Research* **44**, 211-224