



Breaking the brown bridge for residue-borne fungal disease control in broadacre agricultural systems. A review

Katia Taylor¹ · Frédéric Suffert² · Valérie Laval² · Simon R. Law¹ · Mohamed Cassim Mohamed Zakeel¹ · Luke G. Barrett¹ · Susan J. Sprague¹

Received: 21 April 2026 / Accepted: 23 September 2026
© The Author(s) 2026

Abstract

Crop residues, plant material remaining post-harvest, provide critical ecosystem services, including reducing erosion, conserving soil moisture, and building soil organic matter. Globally, a “residue revolution” is underway, with substantial increases in the quantity and persistence of residues driven by the expansion and intensification of annual crop production systems, widespread adoption of conservation agriculture principles, and growing recognition of the system benefits gained through residue retention. However, crop residues also act as reservoirs for damaging fungal crop pathogens, allowing them to persist between seasons and initiate residue-borne disease epidemics via inoculum carryover. Current management relies heavily on in-season management via genetic resistance and chemical controls, rather than preventative strategies that address off-season inoculum carryover. Consequently, broadacre production systems are increasingly vulnerable, as pathogens adapt to overcome genetic and chemical controls, partly due to the large populations persisting on residues. Despite this growing risk, previous review articles have overwhelmingly focused on individual pathogens or in-season management, with limited examination of the universalities of residue-borne diseases with respect to off-season survival and reproduction on residues. Here, we review an interdisciplinary body of research to address this gap. We (i) summarize key aspects of residue-borne pathogen biology, including reproduction, survival, and dispersal; (ii) outline global trends in agriculture collectively driving residue-borne disease risk; (iii) evaluate current and emerging management strategies that target residue-borne pathogen inoculum using an integrated disease management pyramid, with emphasis on breaking the “brown bridge” of off-season inoculum carryover; (iv) highlight key social and economic barriers to the adoption and integration of these management strategies; and (v) outline future research and investment priorities for the development of sustainable, systems-integrated solutions. This review provides growers, agronomists, and researchers with a framework for managing crop residues to reduce residue-borne disease risk while preserving the agronomic and ecological benefits of crop residue retention.

Keywords Stubble-borne disease · Sustainable disease management · Stubble retention · Conservation agriculture · Biocontrol · Inoculum reservoir · Plant pathogen survival · Disease prevention · Crop rotation · Management trade-offs

Contents

1 Introduction

- 1.1 Crop residues as an agroecological resource
- 1.2 Crop residues as an epidemiological risk
- 1.3 off-season ecology of residue-borne diseases

2 Global trends shaping the residue retention dilemma

- 2.1 Recent shifts in global agricultural land use and crop diversity impacting the production and persistence of crop residues
- 2.2 Conservation agriculture and residue retention
- 2.3 Reduced fungicide options

3 Management strategies

3.1 Physical

- 3.1.1 Temporal and spatial separation of host from inoculum (crop rotation and intercropping)
- 3.1.2 Sowing and harvest practices
- 3.1.3 Residue removal and enhanced decomposition (burning, burial, flooding)

✉ Katia Taylor
katia.taylor@csiro.au

¹ CSIRO Agriculture and Food, Acton, ACT 2601, Australia

² Université Paris-Saclay, INRAE, UR BIOGER,
91123 Palaiseau, France

3.2 Biological

3.2.1 Enhancing residue decomposition by amelioration of microbial nutrient deficits

3.2.2 Role of host genetics in inoculum dynamics and off-season pathogen survival

3.2.3 Biocontrol strategies

3.3 Chemical

3.3.1 Mineral fertilizers for pathogen inhibition

3.3.2 Fungicides

4 Toward integrated disease management

4.1 Decision support

4.2 System complexity

4.3 Social and economic factors

4.4 Future directions and research opportunities

5 Conclusions

Acknowledgments

Funding

Competing interests

Ethics approval and consent to participate

Consent for publication

Availability of data and material

Authors' contributions

References

1 Introduction

Crop diseases are a significant constraint to agricultural productivity and global food security, reducing crop yields and quality by ~16% globally (Oerke 2006). Many economically important crop diseases are caused by fungal residue-borne pathogens (RBPs) that complete part of their lifecycle while persisting between host crops on infected residues (Figure 1). Crop residues are plant material that remains in agricultural fields after harvest of the economic product, including basal stems, roots, leaves, chaff, husks, haulms, and other plant debris (Suttie 2000). The term is often used interchangeably with stubble, although stubble can also refer specifically to intact basal stems of harvested plants. Through a combination of weathering and degradation by microbes, molluscs, and other invertebrates, crop residues gradually decompose to become plant detritus and eventually soil organic matter (SOM). Estimates suggest that over half of the world's agricultural phytomass, the total organic mass of crop plants (living or dead), is in the form of crop residues (Smil 1999). Every year, approximately 3.7 billion tons of residues, mainly from corn, wheat, and rice, are generated from food crops worldwide (Lal 2005). Growing appreciation of the agroecological benefits that crop residues provide throughout the degradation process, including prevention of erosion and soil moisture loss, can

be described as a “residue revolution” and has been largely catalyzed by the widespread adoption of conservation agriculture (CA) practices, a key pillar of which is residue retention.

For residue-borne diseases (RBDs), crop residues constitute the principal substrate for both off-season survival and the primary inoculum production that initiates subsequent epidemics. Furthermore, the large pathogen populations persisting on residues serve as reservoirs of pathogen genetic diversity, supporting pathogen evolution and adaptation. Despite the evolutionary and epidemiological significance of off-season RBP survival, the evolution of pathogen populations on crop residues has received relatively limited attention. Research on RBPs and their management has historically prioritized reactive in-crop control measures, underpinned by substantial investment in fungicide development and breeding of resistant cultivars. These strategies are increasingly compromised by changes in the agrochemical regulatory environment and pathogen adaptation to overcome chemical controls and genetic resistance. As such, RBDs now represent a significant and escalating threat to the long-term sustainability of intensive crop production.

The “residue revolution” is thus defined by the convergence of agroecological opportunity and disease risk due to increased crop residue retention. The central challenge is how residues can be managed to mitigate the impact of plant disease without compromising agricultural productivity and environmental goals. Failure to adequately resolve this tension threatens the long-term viability and sustainability of intensive cropping systems and necessitates a fundamental shift from reliance on a narrow set of control strategies to genuinely multi-disciplinary solutions that account for whole-system complexity. In this review, we focus on the management of fungal RBDs in broadacre agricultural systems during the residue phase, the primary “brown bridge” sustaining off-season pathogen survival. We outline the benefits and risks associated with crop residue retention, explore key aspects of RBP biology, examine major changes in global agricultural systems with implications for RBP management, and critically examine current management approaches. We highlight emerging technologies and innovative strategies that target off-season pathogen survival, inoculum production, and management. Finally, we propose an integrated disease management framework that considers pathogen epidemiology, farming system complexity, and social and economic factors. By framing residues as both a valuable resource and a critical intervention point for disease control, this review provides a foundation to encourage further research and investment in strategies that balance residue benefits with pathogen risk.



Fig. 1 **a** Widespread adoption of conservation agriculture practices is driving increases in the quantity and persistence of crop residues (plot on left) compared to conventional tillage which hastens residue decomposition (plot on right). **b** Crop residue functions as a “brown bridge” between growing seasons for residue-borne pathogens, including blackleg disease of canola caused by *Leptosphaeria macu-*

lans with ascospores released from pseudothecia (seen as black fruiting bodies on stubble) resulting from sexual recombination. **c** Inter-row sowing of a chickpea crop between rows of standing residue from the previous season’s wheat crop, highlighting how the practice of inter-row sowing increases the quantity of residues persisting in the paddock. Photo credit: Katia Taylor, Susie Sprague, and Tony Swan.

1.1 Crop residues as an agroecological resource

Prior to the widespread adoption of synthetic fertilizers and mechanization, crop residues played an integral role in agricultural production systems, providing feed and bedding for farm animals, thereby contributing to nutrient cycling through manure (Suttie 2000). Residues declined in perceived value with the advent of mechanized agriculture and were frequently removed or burnt. Once regarded largely as a waste product, crop residues are increasingly recognized as a valuable resource providing agroecological, economic, and system-level benefits (Li et al. 2020). In particular, surface-retained residues play a key role in conserving soil moisture (Bussière and Cellier 1994; Gill and Jalota 1996). Residues slow the movement of water on the soil surface, reducing run-off and allowing water to infiltrate the soil (Freebairn and Boughton 1981), as well as acting as a mulch to reduce soil moisture evaporation (Felton et al. 1987; Whitbread et al. 2000; Foley and Silburn 2002). Under prolonged dry conditions, crop residues are less effective at preventing soil moisture loss from evaporation (Felton et al. 1987; Verburg et al. 2012) with wheat residue loads > 5 t/ha required to achieve significant soil-water savings over extended dry periods in Australia (Bond and Willis 1970). The benefits of residue retention for conserving soil moisture depend on a combination of factors including evaporative demand, soil-water

storage capacity, and rainfall amount and frequency (Gregory et al. 2000; Wolgast Broberg 2002; Monzon et al. 2006).

Crop residues also contribute nitrogen and other nutrients to the soil for plant growth. The impact of residue retention on nitrogen cycling is complex, influenced by multiple mechanisms whose relative effects are in turn influenced by crop residue quality and environmental conditions. For an in-depth and mechanistic overview of the literature on soil nitrogen cycling in response to crop residue retention, see Chen et al. (2014) and Cao et al. (2024). In general, the supply of organic carbon and nitrogen in crop residues stimulates microbial activity, leading to increased microbial nitrogen immobilization (Moritsuka et al. 2004; Gruber and Galloway 2008). The nitrogen immobilized in microbial biomass can later be released and become available for crop uptake during periods of high nitrogen demand (Kuzyakov and Xu 2013). In winter-dominant farming systems, the mineralization of organic nitrogen is often linked to summer rainfall events during the fallow, a major source of nitrogen for subsequent winter crops (Angus et al. 1998; Hunt et al. 2013). Overall, the impact of crop residue retention has been shown to be beneficial both for increasing crop nitrogen uptake (Li et al. 2023; Dan et al. 2023; Wu et al. 2023) and reducing overall nitrogen losses from the soil-plant system (Wang et al. 2015; Murphy et al. 2016; Xu et al. 2021).

Residues also constitute the primary source material for soil organic matter (SOM), a key determinant of soil health and plant productivity in agroecosystems (Wood and Edwards 1992; Weil and Magdoff 2004; Wood et al. 2018). Inextricably linked to SOM is soil organic carbon (SOC), which also increases with crop residue retention (Ranaivoson et al. 2017). It is estimated that retaining crop residues in the order of 4 to 5 t ha⁻¹ can contribute 0.38 t ha⁻¹ year⁻¹ of SOC to the 0–20-cm topsoil layer (Ranaivoson et al. 2017). Crop residue cover also plays an important role in protecting soil physical properties against natural and anthropogenic perturbations (Blanco-Canqui et al. 2006; Blanco-Canqui and Lal 2009; Klopp and Blanco-Canqui 2022). Residues help prevent excessive compaction, sealing, and crusting of the soil surface (Kladvko and Unger 1994), all of which reduce water infiltration, and restrict seedling emergence (Baumhardt et al. 2004). Residue retention significantly improves soil aggregate formation, primarily through the provision of organic matter, as SOM concentration is positively correlated with soil aggregate stability (Rhoton et al. 2002; Bossuyt et al. 2005; Blanco-Canqui et al. 2006). Additionally, residues protect soil aggregates from raindrops and other erosive forces (Kladvko and Unger 1994; Blanco-Canqui and Lal 2009), release chemical substances and compounds that help glue aggregates together, and promote soil biological activity by macro- and micro-organisms that help form and stabilize aggregates (Blanco-Canqui and Lal 2009). Like many of the ecological services provided by crop residues, their impact on soil aggregate stability is influenced significantly by the amount of crop residues being retained, as well as soil type and climatic conditions. For an in-depth analysis, refer to Klopp and Blanco-Canqui (2022) or Blanco-Canqui and Lal (2009).

Other more intangible and underappreciated agro-ecological functions supported by residue conservation include weed suppression, microclimate buffering, and physical scaffolding of subsequent crops (Palm et al. 2014). Residue cover suppresses weed emergence and growth by restricting light and exerting allelopathic effects (Chauhan et al. 2012). Crop residue volumes of 1 t ha⁻¹ or more can reduce weed emergence and biomass by 50% compared to a no-till bare soil (Ranaivoson et al. 2017). Furthermore, crop residue cover also buffers abrupt fluctuations in soil temperature, moderating freeze-thawing and wetting-drying cycles of surface soil (Kladvko and Unger 1994).

Together, these benefits illustrate why residue retention has become an integral practice in broadacre farming systems, but they also set the stage for a significant trade-off with disease risk.

1.2 Crop residues as an epidemiological risk

Between cropping seasons, crop residues can serve as inoculum reservoirs of major crop pathogens and increase the risk of epidemics (Bailey 1996; Bockus and Shroyer 1998; Bailey and Lazarovits 2003). For instance, the incidence of wheat pathogens such as *Pyrenophora tritici-repentis* (Adee and Pfender 1989), *Oculimacula yallundae* (Vera and Murray 2016), and *Zymoseptoria tritici* (Suffert and Sache 2011) is greater in subsequent wheat crops when residues remain in the field after harvest. Likewise, reduced tillage and prolonged residue retention are responsible for the increased global incidence of Fusarium head blight (*Fusarium graminearum*) (Miller et al. 1998; Dill-Macky and Jones 2000), with stubble retention practices resulting in up to 81% higher incidence of Fusarium crown rot (*Fusarium pseudograminearum*) in the first year after adoption (Summerell et al. 1989). Similarly, proximity to infected canola residue significantly influences blackleg disease severity (*Leptosphaeria maculans* syn. *Plenodomus lingam*) (Marcroft et al. 2004a; Bousset et al. 2015). As these RBPs cause significant economic losses and are a threat to global food production, effective management is a priority in broadacre agriculture (Table 1). For example, take-all disease (*Gaeumannomyces graminis*) of wheat and barley causes yield losses of up to 50% (Gutteridge et al. 1993; Kwak and Weller 2013) and rice blast (*Pyricularia oryzae* syn. *Magnaporthe oryzae*) causes yield losses of up to 30% annually (Nalley et al. 2016). A summary of estimated yield and economic losses from major RBDs can be found in Table 1.

A major challenge associated with RBPs is the persistence of infection structures (mycelium, spores, etc.) on crop residues. Depending on environmental conditions, these structures can remain viable for months or years, serving as sources of inoculum for infection of subsequent host crops. For example, *L. maculans* can survive on infected canola residues for 1–5 years (Hall 1992), and *Bipolaris sorokiniana*, the cause of common root rot in cereals, survives on wheat residues at the soil surface for at least 2 years (Duczek et al. 1999). The mycelia of *F. pseudograminearum* survive for up to 3 years in infected cereal residues (Summerell and Burgess 1988) but can survive on residues buried 20 to 25 cm deep for more than 4 years (Champeil et al. 2004).

In addition to the disease risks posed by off-season inoculum build-up on crop residues, there are also substantial risks related to the evolutionary dynamics of pathogen populations. The persistence of large effective pathogen population sizes on crop residues increases the evolutionary potential and likelihood of adaptation (McDonald and Linde 2002; Bousset and Chèvre 2013; Zhan 2016). Crop residues provide a matrix for sexual reproduction of some RBPs, thereby

Table 1 Overview of estimated economic impacts from fungal residue-borne diseases

Host	Disease	Causal agent	Economic importance	Reference
Wheat, barley, rye, oat	Fusarium head blight	Primarily <i>Fusarium graminearum</i>	Yield losses worth in excess of a billion dollars per year globally.	Alkinsammi et al (2006); Wegulo et al (2015)
Wheat	Fusarium crown rot	<i>Fusarium pseudograminearum</i>	Annual yield loss estimates up to 35%	Smiley et al (2005); Murray and Brennan (2009)
Wheat	Septoria leaf blotch	<i>Zymoseptoria tritici</i> (teleomorph <i>Mycosphaerella graminicola</i>)	Between €800–2400 million per annum in the EU alone	Torriani et al (2015); Fones & Gurr (2015)
Wheat	Tan spot	<i>Pyrenophora tritici-repentis</i>	Grain yield losses up to 36% per annum	Ciuffetti et al (2014); Cook et al (2024)
Wheat, barley, rye	Take-all disease	<i>Gaeumannomyces graminis</i>	Severe yield loss (20–50%) in several countries	Gutteridge et al (1993); Kwak et al (2013)
Wheat, barley	Spot blotch	<i>Bipolaris sorokiniana</i>	Yield losses of 10–60% reported	Agostinetto et al (2015); Vaish (2011)
Barley	Net form of net blotch (NFNB)	<i>Pyrenophora teres f. teres</i>	Yield losses of 10–40%, with potential for total loss under conducive conditions	Mathre (1997); Murray and Brennan (2010)
Sorghum	Stalk rot and head blight	<i>Fusarium</i> spp. (<i>F. andiyazi</i> , <i>F. thapsinum</i> , <i>F. incarnatum</i> , <i>F. equiseti</i>)	Approximately 11% grain yield loss has been reported in NSW, Australia.	Kelly et al (2017); Leslie et al (1990)
Canola	Black Leg	<i>Leptosphaeria maculans</i>	Annual yield losses of 10–20% in Canada and the UK and up to 90% yield loss in Australia	Fitt et al. 2006; Sprague et al. 2006; Zhang & Fernando 2018
Rice	Rice blast	<i>Pyricularia oryzae</i> (aka <i>Magnaporthe oryzae</i>)	30% production loss worldwide	Nalley et al (2016)
Rice	Rice bacterial blight	<i>Xanthomonas oryzae</i> pv. <i>oryzae</i>	20–50% yield loss.	Ou (1985); Niones et al (2022); Fiyaz et al (2022)
Rice	Rice brown spot	<i>Cochliobolus miyabeanus</i> (Anamorph: <i>Bipolaris oryzae</i>)	Yield loss is generally over 10%.	Savary et al (2000); Barnwal et al (2013); Sato et al (2008)
Oat	Septoria leaf blotch	<i>Parastagonospora avenae</i> (teleomorph <i>Phaeosphaeria avenaria</i>)	Serious disease of oats in several countries. Yield losses of up to 50%	Clark et al (1975)
Corn	Northern corn leaf blight	<i>Setosphaeria turcica</i>	Causes over 10% yield reductions	Levy & Pataky (1992); Pan et al (2022)
Chickpea	Ascochyta blight	<i>Ascochyta rabiei</i>	Yield losses from 10 to 100% depending on conditions	Singh et al (2022)

increasing opportunities for genetic recombination that can enhance virulence and adaptation of pathogen populations to genetic resistance, fungicides, and changing climatic conditions (Kerdran et al. 2019c). Unlike the measurable benefits of managing off-season pathogen growth for disease suppression, putting a value on evolutionary outcomes is more difficult, even though resistance provides numerous direct and indirect benefits to farmers and society more broadly (Gefferes et al. 2023).

1.3 Off-season ecology of residue-borne diseases

Residue-borne diseases (RBDs) caused by fungi are distinct from, yet overlap with, soil-borne diseases, whose etiological agents can persist in soil without the specific substrate provided by plant residues, e.g., *Rhizoctonia solani* and *Sclerotinia* spp. (Figure 2). RBDs are frequently grouped together with soil-borne diseases, in part because it is difficult to draw a clear distinction since some pathogens can survive in the soil in the absence of plant debris but will enter a saprotrophic phase of their lifecycle on plant debris if it is available, e.g., *F. pseudograminearum* and *B. sorokiniana*. These pathogens can be defined as either soil-borne or residue-borne. In this review, we define RBDs as those in which host infection is initiated by primary inoculum produced on crop residues.

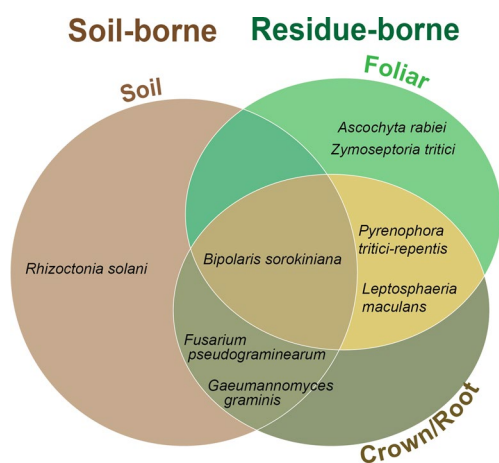


Fig. 2 Here, we define a residue- or stubble-borne disease (for consistency in this review we will use the term residue-borne disease (RBD) as any crop disease where the etiological agent infects its host via primary inoculum derived from crop residues. Soil-borne diseases (in brown) can persist in the soil in the absence of any crop residues, whereas residue-borne diseases (in green/yellow) require the presence of residues. The distinction between residue-borne and soil-borne diseases is blurry, as some pathogens, e.g., *Bipolaris sorokiniana*, can persist in the absence of plant debris, but when plant debris is present, they will enter a saprophytic phase of their lifecycle. Residue-borne diseases can be further categorized as either foliar, e.g., *Zymoseptoria tritici*, or crown/root, e.g., *Fusarium pseudograminearum*.

Fungal RBPs have diverse lifecycles and infection strategies, with life stage transitions shaped by biotic and abiotic factors. Many RBPs have a necrotrophic stage where they cause host cell death during colonization of living tissue, followed by a saprotrophic phase where nutrition is obtained from dead or decaying tissue, e.g., *B. sorokiniana*. Some RBPs also have a hemi-biotrophic phase, colonizing living host tissues without killing them, before later switching to necrotrophy followed by saprotrophy, e.g., *L. maculans*, *Z. tritici*, *Parastagonospora nodorum*, and *P. tritici-repentis*. Other RBPs are obligate biotrophs that do not saprotrophically colonize residue, but over-winter in residues via long-lived, specialized resting structures such as teliospores, as is the case for many rusts like *Melampsora lini* and *Puccinia graminis*, although these are not the main focus of this review. The individual lifecycle characteristics, pathogen morphology, biotrophic and necrotrophic phases of fungal RBPs, and related in-season disease symptoms, are covered widely in numerous reviews. Here, we specifically focus on elements of RBP ecology that pertain to off-season growth and reproduction on crop residues.

RBP inoculum derived from plant residues can be in the form of differentiated structures resulting from (i) sexual reproduction (perithecia and apothecia that release ascospores when mature), (ii) asexual reproduction (conidia, sporangia, chlamydospores, teliospores, etc.), or (iii) undifferentiated structures such as mycelium. Each of these different primary inoculum sources has their own specific characteristics with respect to dispersal modes and scales, and persistence. Ascospores are typically airborne and can be dispersed across large distances between fields (Mahaffee et al. 2023). For example, *L. maculans* ascospores can travel up to 8 km from their source (Bokor et al. 1975; McGee 1977; Howlett 2004), whereas asexual pycnidiospores typically spread within fields to adjacent plants via rain splash or physical contact (Bokor et al. 1975; Howlett 2004; Suffert et al. 2011; Khaliq et al. 2020). Likewise, mycelia require physical contact with susceptible host tissues as they spread locally through direct hyphal growth (Doehlemann et al. 2017).

A significant challenge with RBPs lies not only in quantifying primary inoculum load over time, but also in interpreting the significance of inoculum loads for disease risk. Primary inoculum decay rate, i.e., how long it takes for a specific proportion (e.g., 50%) to break down, is influenced by factors such as agroclimatic conditions, management practices, and microbial community composition. How these factors influence inoculum persistence is largely unknown for the majority of RBPs. Furthermore, inoculum load is often not a robust predictor of disease outcomes, partly because infection and epidemic development are mediated by interactions between host susceptibility, environmental conditions, critical infection windows, and pathogen

virulence, and partly because the proximity of the susceptible crop to the inoculum source may have a greater impact on disease risk than the quantity of inoculum. Consequently, single point estimates of inoculum abundance may provide limited insight into epidemic risk in the absence of a broader context.

Another differentiating feature between RBPs with significant management implications is the number of infection cycles a pathogen completes per season (Figure 3). Monocyclic plant diseases, those with only one infection cycle per season, are better suited for management of primary inoculum from residues since the relationship between inoculum load and disease outcomes is more closely correlated. In contrast, polycyclic diseases with multiple infection cycles per season such as *Septoria tritici* blotch continually re-infect the plant throughout the growth period; hence, a reduction in primary inoculum does not always influence disease severity (Morais et al. 2016b). For polycyclic diseases in particular, even low levels of inoculum are sufficient to trigger epidemics in susceptible hosts under ideal conditions. For example,

the presence of infected residues can locally affect the early dynamics of an epidemic of *Z. tritici* blotch, but the quantity of inoculum is not truly limiting for initiation (Morais et al. 2016b). Similarly, *Ascochyta rabiei* inoculum levels can persist at low levels for several years, eventually initiating epidemics in chickpea when conditions are favorable (Kaiser 1973; Singh et al. 2022; Foresto et al. 2023). Whether polycyclic pathogens actually complete multiple infection cycles will depend on a range of factors, including climatic conditions during the growing season and host resistance, and thus, whether a pathogen is monocyclic or polycyclic can ultimately differ from one situation to another. For example, *L. maculans* and *Z. tritici* have both sexual and asexual spores; residue-borne ascospores (sexual) act as primary inoculum responsible for epidemic initiation, followed by pycnidiospore (asexual) production from leaf lesions if conditions are conducive, which is not universally the case (Li et al. 2007). While reductions in primary inoculum of polycyclic diseases may not consistently reduce disease severity, management of off-season inoculum loads and carryover

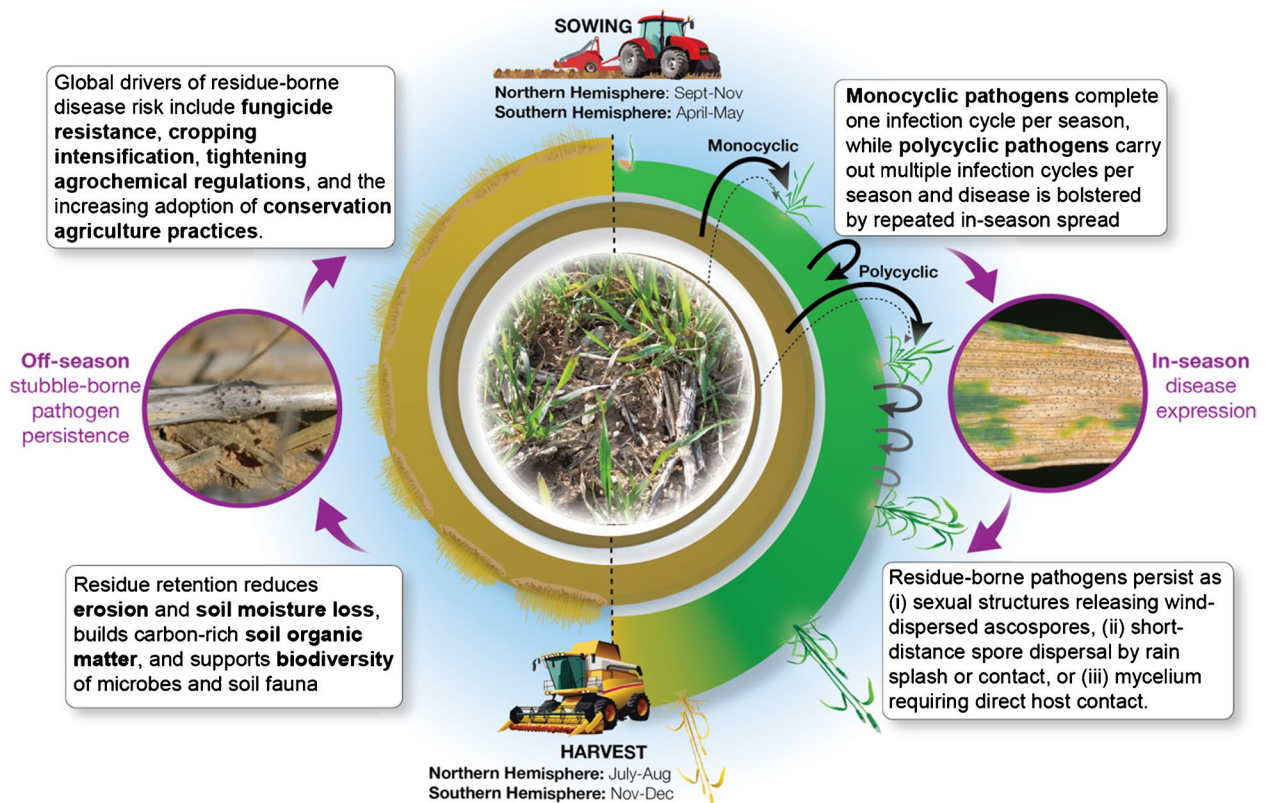


Fig. 3 Crop residues are both a resource and risk. Residues are present for an extended period, often for several years, whereas the living crop is only present for a few months. Crop residues serve as reservoirs for residue-borne pathogens (RBPs), which can persist for years on crop residues before infecting subsequent host crops. The quantity of residues persisting in fields is increasing globally, as the agroeco-

logical benefits of residue retention are becoming widely appreciated, driving increased RBD risk. Fungal RBPs survive on crop residues and disperse to susceptible hosts via diverse and specialized structures. RBPs have diverse lifecycle traits with implications for RBD management, including the distinction between monocyclic and polycyclic infection cycles

may still provide beneficial epidemiological outcomes. For example, the trajectory of epidemic development may shift such that the host crop is outside a susceptible window or disease progression is delayed, thereby enabling more timely management interventions.

An additional distinction between RBPs is the timing at which off-season survival structures are formed. For example, sexual reproduction of *Z. tritici* can start on senescing basal leaves of wheat that form a developing litter layer while the crop is still standing. As a result, ascospores may be produced and theoretically cause reinfection within the same growing season, particularly under wet conditions, or be carried over to subsequent seasons (Brown et al. 1978; Hunter et al. 1999; Bathgate and Loughman 2001; Eriksen et al. 2001; Suffert et al. 2011). In contrast, primary inoculum of other pathogens, such as *L. maculans*, is initiated on senescent material post-harvest (Khangura et al. 2007; Bondad et al. 2025a, b). These differences have important consequences for epidemic dynamics, particularly in relation to how and when pathogens transition between seasons and fields, and whether these transitions overlap or are discrete.

Given the diverse modes of survival, infection cycles, and reproductive strategies of RBPs, no single management approach will be universally effective as a control strategy. Understanding the biological, ecological, and evolutionary dynamics of fungal RBPs and how these processes fit into a farming systems context is essential for devising effective and sustainable disease management strategies.

2 Global trends shaping the residue retention dilemma

In recent decades, there have been considerable changes in the area, location, and management of agricultural land for production of annual crops with implications for the emergence, prevalence, management, and economic impact of RBD's. Drivers include a combination of technological innovation, economic incentive, input intensification, policy change, production shifts, and changing climate.

2.1 Recent shifts in global agricultural land use and crop diversity impacting the production and persistence of crop residues

Worldwide, the area of land used for annual crop production increased by 12% between 2000 and 2021 to a total of 1.1 Bha, primarily due to expansion in Africa and South America with the replacement of fallow and natural vegetation, such as pastures and tree cover (Potapov et al. 2021; FAO 2025). This global trend is consistent with changes in land use for crop production in Australia and regions of South America. In Australia, the area dedicated to cropping

increased from 22 to 35.9 Mha between 1995 and 2020, with declining wool prices largely responsible for driving a shift from perennial pastures for sheep grazing to annual cropping systems (ABARES, 2024). There has been a similar transformation of perennial pasture-based systems to annual cropping in regions of South America (de Faccio Carvalho et al. 2021), with total cropping area more than doubling in Argentina from 17.8 to 37.9 Mha across a similar time-frame (Secretaria de Agricultura, Ganaderia y Pesca, 2025). In contrast, the area of cropped land in the USA and Europe has remained relatively stable over recent decades, with approximately 140 Mha in the USA (Ye et al. 2024) and 59 Mha in Europe (FAO 2025). While total cropping area has not expanded in these regions, other factors have impacted the availability and suitability of land for agricultural production, including increasing urbanization of landscapes and changes in climate suitability for crop production (Ye et al. 2024). Since 2000, crop production has increased 56% due to increased demand from human population growth and increased utilization of crops for energy production and livestock feed (FAO 2023). As land use has not expanded at the same rate as production, the aforementioned increases have been achieved via advances in genetic, technological, and agronomic factors as well as intensification of cropping systems with a concomitant increase in the volume of crop residues, a trend which will continue as agricultural systems innovate to achieve the productivity gains required to meet increasing demand.

The expansion and intensification of annual crop production have been accompanied by shifts in spatiotemporal crop diversity, which is foundational for the successful management of RBDs via separation of susceptible host crops from infected residues. Crop diversity, reflected in both the number of species cultivated (richness) and their relative abundance across production systems (evenness) has declined in recent decades. At subcontinental scales, crop species richness increased markedly during the 1980s and 1990s but stabilized from the early 2000s onward, with regional variation that was largely independent of agricultural expansion (Mariani et al. 2021). In parallel with the increase in species richness, national-level data indicate that production in the 1970s and 1980s became increasingly homogenous, dominated by a limited number of species (Martin et al. 2019). Indeed in 2021, 80% of global cropped area was sown to the cereals corn, rice, and wheat (FAO 2023). In addition, landscape heterogeneity has declined with a general increase in the size of fields (White and Roy 2015; Clough et al. 2020).

There is growing interest in reversing the spatiotemporal decline in crop diversity to address critical sustainability challenges in agrifood systems (Gaudin et al. 2015; Storkey et al. 2019; Mortensen and Smith 2020; Messéan et al. 2021; Smith et al. 2023). However, adoption remains constrained by increased management complexity and costs,

risks of unintended pest or disease outcomes, and limited market opportunities for alternative non-commodity crops (Mortensen and Smith 2020).

2.2 Conservation agriculture and residue retention

Over the past several decades, there has been widespread global adoption of conservation agriculture (CA) practices, driven in large part by the importance of conserving soil moisture and soil carbon and preventing soil erosion (Soane et al. 2012). CA promotes a set of three management principles: minimum mechanical soil disturbance (i.e., no- or minimal-tillage), permanent soil organic cover with living or dead crops or pastures, and species diversification through varied crop sequences (FAO 2025; <http://www.fao.org/ag/ca/>). While no-till agriculture emerged from the dustbowl of the 1930s in mid-west USA to combat soil erosion (Derpsch 1998), global expansion of CA practices has predominantly occurred since the mid to late 1990s, facilitated by the availability of herbicides and technological advances in farm machinery (Derpsch et al. 2010). The adoption of farm machinery such as stripper headers and disc seeders has also resulted in greater volumes of crop residues remaining after harvest (Klinner et al. 1987; Derpsch et al. 2014; Swan et al. 2023; USDA 2023). Current estimates of the amount of global agricultural land managed under CA systems are between 180 Mha (Kassam et al. 2019) and 215 Mha, up to 15% of global arable land (Prestele et al. 2018). This contrasts sharply with the early 1970s, when only ~2.7 Mha was managed under CA (Derpsch 1998), and with 1999 estimates placing no-till area at ~45 Mha (Kassam et al. 2009; Derpsch et al. 2010).

The regional adoption rates of CA vary widely but are highest in South America (63.2%), Australia and New Zealand (45.5%), and North America (28.1%) (Prestele et al. 2018; Kassam et al. 2019). In contrast, CA adoption rates are <10% of arable land in Africa, Europe, Asia, Russia, and Ukraine (Prestele et al. 2018; Kassam et al. 2019). The factors determining CA adoption in a specific region are diverse and include competing uses for crop residues (such as for livestock feed and fuel), access to appropriate machinery (such as inter-row seeders), and varying degrees of institutional and cultural attachment to tillage. Temperature and rainfall conditions are also a key determinant of adoption since residue decomposition is slow in cold, wet climates and can inhibit early-season soil warming, whereas in warm, dry climates the ecosystem services provided by CA, such as prevention of soil erosion and moisture loss, provide greater systems benefits. Most agricultural land managed under CA is rain-fed annual cropping systems in the mid-latitudes between 30 and 50° (Friedrich et al. 2012; Kassam et al. 2019). In these farming systems, the proportion of cropping area managed under CA is much higher. For example, in

Australia most broadacre cropping farms retain stubble (85% of farms) and minimize tillage (68% of farms) (Coelli and ABARES 2021).

In addition to the many soil and ecosystem benefits accrued through CA adoption, there are economic benefits associated with adoption of no-till combined with other conservation agriculture principles, largely due to reduced production costs from decreased energy and labor consumption compared with conventional systems (Erenstein et al. 2012). Fuel savings from CA are reported in the order of about 60% (Kassam et al. 2019) and represents a significant reduction in on-farm emissions. Such reductions enable growers to meet the sustainability targets of some markets, such as canola exported into the European Union (CSIRO 2019; Australian Oilseeds Federation 2022). In countries such as the USA, Canada, Australia, Brazil, Argentina, India, and China, CA is promoted by national agricultural development programs or backed by institutional support (Kassam et al. 2019). Furthermore, CA is actively promoted as a management practice to help mitigate anthropogenic climate change. An example is the “4 per mille Soils for Food Security and Climate” initiative, which aims to increase global SOC stocks by 0.4% per year (Minasny et al. 2017), promoted through the UN Framework Convention on Climate Change (Ogle et al. 2019). Farmers can earn carbon credits for switching to CA practices in voluntary carbon farming schemes such as Verra, or in some countries government-regulated programs such as the Australian Carbon Credit Unit (ACCU) scheme issued by the Clean Energy Regulator (Holzleitner and Gawlik 2022; Cariappa et al. 2024). These schemes are further incentivizing uptake of CA practices, in addition to the soil health and economic benefits outlined above.

2.3 Reduced fungicide options

The increased risk of RBDs associated with the adoption of CA practices has largely been mitigated by widespread reliance on chemical control and genetic resistance. However, the tightening of fungicide regulations, particularly in the European Union (EU), is significantly narrowing the options available for managing RBDs in broadacre cropping systems. The EU has already banned several key fungicides, including chlorothalonil (2019), ipconazole (2024), and dimethomorph and mepanipyrim (2025), due to concerns over toxicity, environmental persistence, and endocrine disruption. These regulatory changes are part of a broader international movement toward phasing out highly hazardous pesticides (HHPs) by 2035, championed by the UN Environment Assembly (UNEA) and the Global Framework on Chemicals (GFC). The implications of fungicide bans extend beyond domestic use to trade barriers, with many countries enforcing strict maximum residue limits (MRLs) on imported agricultural products.

For example, the MRL for a banned pesticide in the EU is often set to the limit of quantification (0.01 mg/kg), effectively banning any detectable residue. This regulatory landscape is forcing producers to reconsider their reliance on fungicides, not only for domestic compliance but also to maintain access to international markets. The potential for future bans or restrictions underscores the salience of proactive adaptation.

In addition to regulatory constraints, growers face reduced access to fungicides due to the evolution of resistance in pathogen populations, accelerated by repeated fungicide exposure. Resistance is particularly problematic in pathogens such as *L. maculans*, *F. pseudograminearum*, and *Z. tritici*. For example, triazole fungicides like tebuconazole and prothioconazole, once the backbone of *Z. tritici* blotch control, are now facing widespread resistance in northern hemisphere *Z. tritici* populations (Sykes et al. 2018; Jørgensen et al. 2020). Similarly, quinone outside inhibitor (QoI) fungicides such as azoxystrobin and pyraclostrobin are increasingly ineffective against *Z. tritici* in Europe and North America due to resistance (Estep et al. 2015; Lavrukaitė et al. 2024). Furthermore, several new-generation carboxamide fungicides with broad-spectrum activity have been introduced for the control of RBDs in broadacre crops. These fungicides act by inhibiting succinate dehydrogenase (SDH) in complex II of the mitochondrial respiratory chain, thereby disrupting fungal respiration. However, due to their single-site mode of action, these fungicides are prone to resistance development (Fraaije et al. 2012). For instance, resistance to SDHI fungicides was recently detected for the first time in *L. maculans* of canola in Australia (GRDC 2024).

The evolving regulatory environment surrounding fungicide use is reshaping disease management in broadacre cropping systems. With key fungicides under threat from

bans, resistance, and trade restrictions, the current reliance on chemical control is becoming increasingly untenable (Corkley et al. 2022). With diminishing fungicide options for managing in-season disease loads, managing disease during the off-season becomes critical. This necessitates a shift toward sustainable, integrated approaches that prioritize off-season pathogen management and reduce fungicide dependency.

3 Management strategies

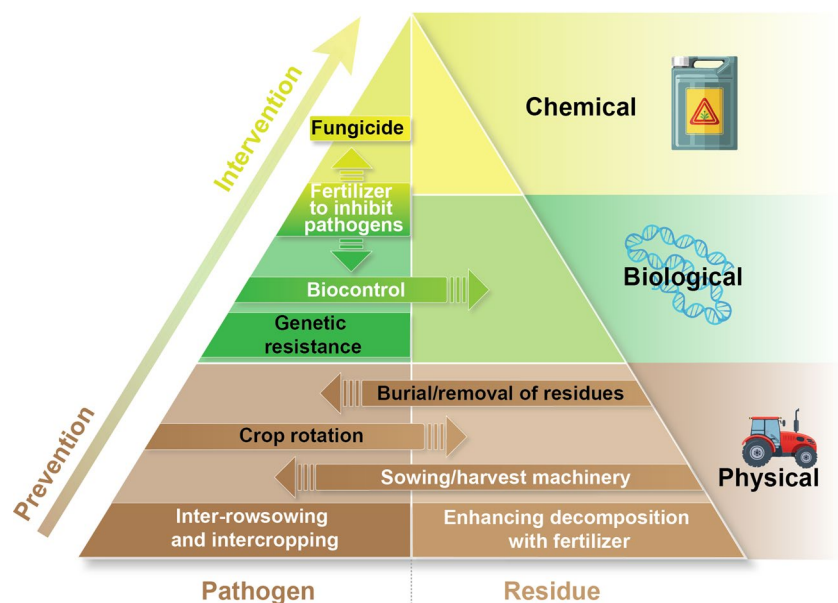
Considering the challenges and global changes described above and informed by the biology and epidemiology of RBPs, we now provide an overview of current management strategies that target off-season inoculum production and carryover to susceptible crops. These control strategies are presented within the framework of a modified integrated disease management pyramid, with interventions categorized as *Physical*, *Biological*, or *Chemical*, and ranging from preventative to increasingly interventionist (Figure 4).

3.1 Physical

3.1.1 Temporal and spatial separation of host from inoculum (crop rotation and intercropping)

Crop rotation, or crop sequencing, is a practical way to limit epidemics caused by RBPs as it disrupts pathogen lifecycles by temporally separating susceptible host crops. This allows both crop residues and the inoculum on crop residues, to decay before the next susceptible host crop is planted, thereby eliminating the “brown bridge” effect (Thompson et al. 2015). To ensure effective temporal separation

Fig. 4 An overview of the residue-borne disease management strategies covered in this review, presented within an integrated disease management pyramid. Strategies at the base of the pyramid are more focused on prevention but become more focused on intervention moving up the pyramid. Current strategies are in black text, while still emerging strategies are in white, highlighting opportunities for future research investment



of inoculum and susceptible host, the design of crop rotations must account for pathogen-specific inoculum survival dynamics, which are well characterized for many RBPs (see Section 2.3). For example, even when 90% of canola residues had disappeared 2 years post-harvest, significant quantities of *L. maculans* ascospores were still discharged from recalcitrant crown and taproot residues for a further 3–5 years (Petrie 1995). Thus, *L. maculans* ascospore production can far exceed the mean 3-year rotation period typically followed by canola producers in the semi-arid regions of Saskatchewan (Canada) or the common 2-year canola-cereal-canola rotation in Australia (Norton et al. 1999; Smith et al. 2013). *Z. tritici* pycnidiospores are better preserved on surface residues than on buried debris (Brokenshire 1975), yet the persistence of *Z. tritici* ascospores is poorly understood despite their capacity for long-distance dispersal (Suffert et al. 2011). *F. graminearum* can survive for more than 4 years on residues buried at 20–25 cm and for 2 years on damaged wheat grain left both on the soil surface or at 5–10 cm depth; however, ascospores are produced only on residues at the soil surface (Inch and Gilbert 2003; Champeil et al. 2004; Leplat et al. 2013). Together, these examples highlight the need for disease-specific rotation recommendations. A minimum 2-year break between wheat crops is recommended to prevent glume blotch (*P. nodorum*), whereas 1 year may suffice for controlling tan spot (*P. tritici-repentis*) (Duczek et al. 1999), and barley should not be grown within 2 years of a previous barley crop to control net blotch (*Pyrrenophora teres*). In addition, due to the climate-dependent nature of residue decomposition and inoculum production, the ideal rotation length will likely vary depending on local environmental conditions, as shorter rotations may suffice in wetter climates more conducive to residue break down.

The effectiveness of crop rotation as a management strategy is influenced by spatial and epidemiological factors, including the dispersal capacity of different inoculum types and the distribution of host species across the landscape. For RBPs whose inoculum forms require direct host contact or disperse over short distances, crop rotations can be effective at preventing carryover to subsequent host crops and can be managed by individual farmers at the farm or paddock scale. In contrast, for RBPs with long-distance inoculum dispersal, consideration of both local residue management and landscape-scale host distribution and connectivity is required (Alabouvette et al. 2006; Suffert and Sache 2011). As even small amounts of inoculum dispersed across long distances can initiate epidemics, paddock-scale crop rotations reduce but rarely eliminate early-season risk (Marcroft et al. 2003; Khangura et al. 2007; Keller et al. 2010, 2011; Morais et al. 2016a, b). At the landscape scale, optimization of crop rotations can help disrupt spatial connectivity between inoculum reservoirs and fields of susceptible crops, by considering the agroecosystem as a field mosaic to which

coevolutionary theory between host and pathogen metapopulations can be applied (Bousset and Chèvre 2013). In such a representation, landscape-level inoculum pressure is determined by the abundance, distribution, and connectivity of infected residues across the surrounding fields relative to the focal field. Conducting empirical experiments to optimize landscape-scale management approaches is complicated by a range of factors, including in the sampling and identification of diverse fungal spores (Van der Heyden et al. 2021). Modelling approaches, integrating crop rotations, landscape mosaics, and crop mixtures, offer a more feasible alternative for landscape-scale management of inoculum sources. Previously, such landscape-level models have mainly focused on the evolutionary dynamics of pathogen virulence to optimize resistance gene deployment (Rimbaud et al. 2018, 2021) but could be applied to the regional management of residues acting as inoculum sources. Although it is theoretically possible to regionally co-ordinate crop rotations to reduce inter-field inoculum dispersal, local crop rotation remains the most practical compromise due to agronomic and social constraints (Krupinsky et al. 2002; Fu et al. 2021). Implementing effective landscape-scale management would require a coordinated effort by multiple growers with potentially competing interests and represents a significant challenge for integrated disease management of RBDs (Sherman et al. 2019; Geffersa et al. 2023).

In addition to the temporal and spatial dynamics of inoculum carryover and dispersal, crop rotations need to consider host-pathogen compatibility. In practice, growers cultivate multiple host crops of the same pathogen (e.g., maize and wheat which both host *F. graminearum*; Guo et al. 2010) or even the same crop (e.g., continuous wheat) over several consecutive years in the same field, which generally exacerbates disease problems. Where pathogens have broad host ranges (e.g., *F. pseudograminearum* can infect wheat, barley, and oats), choice of the rotation crop should be informed by the host specificity of the pathogen. Rotation efficacy can also be influenced by the choice of non-host crop and impacts on residue decomposition. Crops with dense canopies, such as canola, can promote moist microclimates that enhance residue decomposition while those with more open canopies such as pulses (e.g., lentil or chickpea) are drier with slower residue decomposition (Kirkegaard et al. 2004).

Intercropping, the practice of growing more than one species in close association simultaneously, plays an underappreciated role in preventing carryover of RBDs via barrier effects of non-host plants to dispersal of primary inoculum from crop residues. Total splash dispersal of *Mycosphaerella pinodes* conidia, the causative agent of aschochyta blight of field pea, was reduced by 39–78% in pea intercropped with cereal (as measured indirectly by lesion number), compared with monocropped pea at full density (Schoeny et al. 2010). Non-host plants provided the greatest contribution to disease

suppression early in the cropping season, by providing a physical barrier to conidial movement within the intercrop canopy. While in this study conidia were not residue-borne, but rather a central conidial suspension surrounded by potted plants to simulate pea and pea-wheat canopies (Schoeny et al. 2010), the barrier effects can reasonably be extended to splash dispersal from crop residues. Intercropping in separate rows is less effective than in mixed rows in controlling common bacterial blight in bean (Fininsa and Yuen 2002) and aschochyta in chickpea (Zhou et al. 2023), possibly because spore dispersal interference is greatest in mixed rows. Furthermore, orienting the inter-cropped rows perpendicular to the main wind direction could further enhance the barrier effect provided by non-host plants, as was shown for *Phytophthora infestans* of potato intercropped with either spring wheat or grass clover (Bouws and Finckh 2008). Provision of barrier against primary inoculum from residues may vary significantly depending on the canopy characteristics of the crops used in the intercropping mixture, and further research is needed to identify optimal species mixtures with the most effective obstruction of primary inoculum dispersal from infected residues for each RBD crop-pathogen complex.

3.1.2 Sowing and harvest practices

In addition to landscape-scale management of RBDs (Section 4.1.1), interrupting the “brown bridge” by segregating hosts from inoculum with inter-row sowing can reduce carryover of several RBPs that infect via direct contact. Inter-row sowing supported by satellite-guidance allows precise seeding of new crops between standing rows of residue from the previous year, where the seed bed is generally more supportive of crop establishment. Increased adoption of conservation agriculture and no-till practices have prompted increased uptake of inter-row sowing as significant amounts of residue remain standing or intact post-harvest. For example, 25–48% of canola stubble remained standing (vertical) in fields after 1 year in Australia (McCredden et al. 2018). These practices also result in slower degradation of crop residues as they remain standing rather than knocked down in contact with the soil, further increasing the persistence of residues (Simpfendorfer et al. 2020). Although inter-row sowing is associated with greater residue persistence, it has also been proposed as a strategy to spatially separate inoculum from a susceptible host when grown consecutively (i.e., wheat-wheat), and for RBPs where the primary inoculum requires direct contact for infection, i.e., mycelium/hyphae. In this context, the majority of inoculum remains concentrated in the rows of the previous crop, assuming the rows are not disrupted or redistributed during tillage or harvest events. Inter-row sowing between previous cereal rows reduced both the incidence of *F. pseudograminearum* detected at the crown by 6% and the incidence of whiteheads—a symptom of crown rot associated with small or no

grain development—by 14.4/m², with an overall increase in grain yield of 6% (0.14 t/ha) (Verrell et al. 2017). Similar to *F. pseudograminearum*, one of the primary inoculum sources for *G. graminis* var. *tritici* (take-all disease) is mycelia from infected intact cereal crowns in the stubble row from the previous year (Moore and Cook 1984). Take-all disease severity declined with increasing distance between seed and mycelia from infected cereal crowns in the stubble row from the previous year (Moore and Cook 1984; Kabbage and Bockus 2002).

Management of RBPs with inter-row sowing depends on the pathogen and type of inoculum. For pathogens like *L. maculans* where airborne ascospores are the primary inoculum, inter-row sowing in combination with no-till practices in CA systems is actually associated with greater total inoculum loads over a 2-year period (Sprague et al. 2025). In these systems, spore loads can be higher in the second-year post-harvest once standing stubble is knocked down and comes into contact with the soil surface, as soil moisture promotes spore production (Sprague et al. 2025). This change in stubble position, from horizontal to vertical, results in a significant delay in *L. maculans* spore release and an overall decrease in total spore release from vertical stubble of 66% relative to horizontal stubble (McCredden et al. 2018; Bondad et al. 2025 a, b). This delay in *L. maculans* spore release shifts the window of blackleg carryover closer to the next canola crop in W-C-W-C rotation (Sprague et al. 2025), suggesting in CA systems, a double break crop may be necessary to prevent *L. maculans* carryover. Taking into account differences in pathogen reproductive structures, the farming system context, and the temporal dynamics of residue decomposition, physical separation of inoculum from host via inter-row sowing can be an effective strategy to reduce inoculum carryover.

Choice of seeding and harvest machinery also influences both crop residue persistence and intra-field dispersal of infected residues. Compared to the lower disturbance disc opener, there was a 34% reduction in *F. pseudograminearum* DNA detected in seed slots post-sowing with tine seeders, attributed to the excavating effect of the tine removing inoculum from the seed slot as opposed to the minimal disturbance produced when sowing with a disc seeder (Verrell et al. 2017). The use of row cleaners to “sweep” away residue in front of the ground engaging gear reduced the incidence of FCR and whiteheads (Verrell et al. 2017). At crop maturity, harvest machinery determines the physical structure of crop residues by influencing the proportion of stubble that is threshed, chopped, and redistributed across the soil surface as trash versus the proportion that remains intact and standing. Stripper front harvesting systems improve harvest efficiency by removing only the grain heads, leaving the remainder of the senesced plant intact as standing residue (Tado et al. 1998). In wheat crops, stripper fronts leave tall standing

residue (50–60 cm) with minimal surface trash, whereas draper fronts or conventional combine harvesters typically leave shorter standing residues (<30 cm) and distribute a large proportion of the biomass as surface trash across the field. Taller wheat residue from stripper headers allowed *F. pseudograminearum* to colonize ~90% more of the residue within 6 months post-harvest and persist at higher levels compared to the shorter residue from a draper front harvester (Petronaitis et al. 2025). Thus, shorter harvest heights can limit vertical saprotrophic colonization and reduce overall inoculum loads of *F. pseudograminearum*. However, multi-year crop sequence experiments are required to fully understand how harvest height influences primary inoculum build-up and persistence on crop residues, and how these effects interact with residue-borne pathogens and management strategies across the entire cropping sequence. For example, lower harvest height of cereals may be beneficial when preceding a short-stature crop such as chickpea, since inoculum on tall cereal residue will likely spread across a paddock during harvest of the short-stature rotation crop, undermining the efficacy of inoculum avoidance strategies such as inter-row sowing (Petronaitis et al. 2025).

Altering harvest height may also be a potential strategy for manipulation of residue layers with greater ecological significance for RBP reproduction and inoculum development. The different layers of host crops, from the soil to the head, can contribute differently to pathogen reproduction. For example, vertical stratification of inoculum has been observed in wheat pathogens such as *Z. tritici*, for which ascospore production is highest in tissues 25–35 cm above the ground, corresponding to the part of the stubble typically retained at harvest (Suffert et al. 2018a), and *F. pseudograminearum*, which is most frequently recovered from mid-stem rather than crown tissues (Summerell and Burgess 1988). Likewise in canola, *L. maculans* pseudothecia predominantly form and discharge ascospores from basal stem and crown tissue while the closely related *Leptosphaeria biglobosa* colonizes and produces ascospores from higher parts of the stem (West et al. 2002). Field-based vertical transects quantifying pathogen and inoculum distribution along standing stubble would be required to assess the relevance to other RBPs. Should upper stem or leaf tissues be primary sites of pathogen reproduction, mechanical solutions could be identified or engineered to remove these tissues and deposit them in contact with the soil to accelerate decomposition.

3.1.3 Residue removal and enhanced decomposition (burning, burial, flooding)

Residue removal is among the most direct approaches to manage RBDs in broadacre farming systems, with several

methods employed to reduce sources of pathogen inoculum. In conventional tillage systems, burial of residues can eliminate the inoculum itself, or in the case of partial burial, inoculum can be reduced by enhancing decomposition of residues that serve as the primary substrate for inoculum production. Numerous studies have demonstrated that decomposition of crop residues is enhanced by full incorporation into soil (Douglas et al. 1980; Holland and Coleman 1987; Hubbard and Jordan 1996; Nicolardot et al. 2007). Burial of residues not only enhances their decomposition but can directly reduce the survival of RBPs (Bockus and Shroyer 1998; Lupwayi et al. 2004). For example, pseudothecia of *P. tritici-repentis* showed strong survival in standing stubble and upper mulch layers, but not in straw or mulch in direct contact with the soil (Pfender and Wootke 1988). For burial to effectively reduce a significant amount of inoculum, full incorporation of residues is often required. Summerell and Burgess (1988) demonstrated that *F. pseudograminearum* was recovered at significantly lower levels only when residues were fully buried, while partial incorporation or shallow tillage had negligible effects. Likewise, Fusarium head blight incidence and severity were found to be lower in conventionally tilled plots (moldboard plow) than in minimum-tillage plots (chisel plow) (Miller et al. 1998; Dill-Macky and Jones 2000). These findings underscore that residue decomposition with an associated reduction in inoculum is generally greatest with close contact between infested residues and soil microbes, maintained under conditions of adequate soil moisture and warm temperatures (Burgess and Griffin 1968). Seasonal factors such as rainfall and soil moisture thus play a critical role in determining decomposition rates and inoculum development and decay (Klein et al. 1988). Management practices that promote residue burial therefore help suppress diseases in successive crops (Swan et al. 2000), with deeper tillage potentially necessary in high-risk years or environments, although at a significant trade-off with soil disturbance and fuel and labor costs (Keck and Hung 2018; Srivastava 2025).

Theoretically, burial of crop residues promotes decomposition by bringing residues into proximity with soil microbes, thereby reducing pathogen survival structures during the fallow period (Klein et al. 1988). The mechanism by which inoculum loads are reduced during residue decomposition is uncertain and is likely context-specific. RBPs may be out-competed or antagonized by other soil- and residue-associated microbes or eliminated due to the rapid decomposition of the physical substrate required for their survival, or affected by both processes. (Summerell et al. 1989; Hershman and Perkins 1995; Gosende et al. 2003; Marcroft et al. 2003; Pereyra et al. 2004; Pereyra and Dill-Macky 2008; Leplat et al. 2013; Kerdraon et al. 2019b). In contrast, *F. pseudograminearum* colonies and macroconidia on wheat residues decreased with increasing incorporation

depth but residue decomposition was fastest at shallower soil depths (Yi et al. 2002). These varied responses highlight the significant gaps in our understanding of RBP epidemiology during the off-season, in particular how pathogen ecology is influenced by interactions with the soil microbiome more broadly.

Crop residue burning, including narrow windrow burning to control weed seeds, is still practiced by some farmers to manage crop residues (McCool et al. 2008; Kutcher and Malhi 2010). In Australia, rates of burning have declined primarily due to environmental concerns but burning is still employed prior to sowing to reduce high stubble loads to ensure good crop establishment (Smith et al. 2007; Scott et al. 2010). In Europe, the burning of agricultural residues is prohibited under the Common Agricultural Policy. In many parts of Asia, however, residue burning remains widespread, particularly in China, India, Thailand, and Indonesia (Lin and Begho 2022; Yin et al. 2024; Khanna et al. 2025), where it is often the fastest and most economical method for clearing fields with high residue loads. Similarly in the USA, residue burning remains an important residue-disposal option for many growers (McCarty 2011). A combination of anecdotal information, farmers' perceptions, and limited studies suggest that burning can substantially reduce residue biomass and suppress disease incidence (Hardison 1974; Marcroft et al. 2003; Chen et al. 2005). For instance, residue burning has proven effective in reducing *Fusarium* crown rot in wheat, where the primary inoculum consists of hyphae embedded in the stubble matrix (Burgess et al. 1996). By removing this substrate, burning restricts saprotrophic fungal growth and inoculum persistence. Burning-induced reductions in crop residues have been shown to lower *L. maculans* ascospore discharge per hectare in canola; however, the level of residue reduction required to achieve economic benefits through reduced disease and increased yield is uncertain (Marcroft et al. 2003). For RBPs with aerially dispersed spores, burning residue in a single field is unlikely to reduce inoculum loads in the landscape where unburned infected residues are located nearby. Furthermore, burning does not guarantee complete pathogen eradication with efficacy dependent on factors such as fire intensity and pathogen location. For instance, burning did not significantly reduce net blotch disease severity in barley (*P. teres*) (Kutcher and Malhi 2010), likely because the portion of infected residues closest to the ground remained unburned, preventing the complete elimination of pathogen survival structures protected within the residues.

Flooding represents another method to enhance stubble degradation and suppress pathogen survival. For example, flooding for 14 days substantially reduced recovery of *Leptosphaeria* spp. from canola stubble, with complete elimination after 6 weeks, regardless of temperature (Pelula et al. 2013). In flooded rice systems, continuous flooding

accelerates residue breakdown and creates anaerobic conditions that are hostile to many aerobic pathogens (Devêve and Horváth 2000; Ueki et al. 2018). Removal of residues via grazing, baling, and biomass utilization for biofuel production offer additional avenues for managing RBPs on aboveground plant tissue while providing economic benefits. Grazing and baling physically remove pathogen-harboring residues from fields, reducing inoculum load and carryover. Likewise, the conversion of crop residues to biofuels through various processing methods eliminates potential inoculum sources and contributes to renewable energy generation, although harvest height can influence the volume of biomass available for collection. Of course, residue removal for grazing, baling, and biofuel production is only effective at controlling RBPs with inoculum concentrated in the parts of the residue that are harvested or grazed, whereas RBPs that persist in crowns or roots remain unaffected.

3.2 Biological

3.2.1 Enhancing residue decomposition by amelioration of microbial nutrient deficits

Crop residues are converted into soil organic matter (SOM) by soil- and residue- associated microbial communities. During decomposition, carbon (C) from residues is either respired as CO₂ or stabilized into microbial biomass, eventually contributing to microbial necromass formation (Meng et al. 2024). SOM and the microbial communities from which it is derived, are more nutrient (nitrogen, phosphorus, sulfur) rich than crop residues (Kirkby et al. 2011). This nutrient deficit limits the humification efficiency (net conversion of residue carbon to SOM carbon) of residues, and it is well established that residues with a lower C:N ratio decompose faster and have a higher humification efficiency. For example, compared to maize residues with a higher C:N ratio, wheat residues were slower to decompose in a greenhouse experiment (Yi et al. 2002). However, after 8 months of weathering in the paddock, when C:N ratio of wheat residues was comparable with maize, the difference in decomposability between the two residue types disappeared (Yi et al. 2002). Leguminous cover crops, grown over the fallow period for a purpose other than their harvested products, could play an underappreciated role here, by creating conditions favorable for microbial activity and decomposition of residues infected with RBPs. Rye residues decomposed more rapidly when sown with a red clover cover crop (27%) compared with just rye residues (17%), possibly due to additional nitrogen fixed by the red clover stimulating microbial decomposition of the rye residues (Bottenberg et al. 1997).

In support of the concept that a microbial nutrient deficiency hampers both breakdown of residues and conversion to SOM, amendment of residues with sufficient nutrients

increased the net humification efficiency in a range of soils in both controlled and field experiments (Kirkby et al. 2013, 2014, 2016). More importantly in the context of RBDs, adding inorganic nutrients with residues results not only in an increase in the microbial biomass but also an increase in the mass of residues decomposed during the incubation period (Kirkby et al. 2014). Whether the observed enhancement in residue decomposition is sufficient to influence persistence of RBPs requires further investigation but given the physical persistence of residues underpins the carryover of RBPs, it is possible that enhancing residue breakdown via nutrient addition may be an effective, and as yet under-utilized, strategy to hasten reductions in RBD inoculum loads. Additionally, the observed increase in microbial biomass in response to nutrient amendments highlights that nutrient addition significantly alters the residue microbiome, highlighting the potential to manipulate microbial antagonists or competitors of RBPs.

The challenge with fertilizer application to residues is ensuring the accurate co-location of fertilizer with residues, rather than fertilizer potentially settling in bulk soil, where there is minimal residue present. For optimal microbial degradation of residues, access to the substrate through co-location with the NPS fertilizer and the crop residues may be critical. This has potential implications for the method of fertilizer application to residues, i.e., fertilizer in liquid form may distribute more homogeneously compared with fertilizer in pellet form and contribute toward more efficient degradation of residues, although this requires further investigation.

3.2.2 Role of host genetics in inoculum dynamics and off-season pathogen survival

Host genetics not only shapes the in-season pathobiome and disease expression, but also off-season inoculum production and interactions between pathogenic and beneficial microorganisms. Despite this, most efforts to breed for genetic control of RBPs focus exclusively on selection for control of in-season interactions between living host plants and their pathogen. Host genetics may offer unexplored avenues for acting on RBPs during the “residue” phase of the plant life cycle, with key targets discussed below, including, (i) indirect control of inoculum production, (ii) direct control of inoculum production, and (iii) microbial interactions.

(i) Indirect influence on off-season inoculum production For many RBPs, it is generally recognized that there is a relationship between in-season disease severity and subsequent off-season inoculum loads. For example, in blackleg of canola, an influence of disease severity on subsequent inoculum production on residues is well established (McGee 1977). Stems with severe basal stem canker produce more

L. maculans pseudothecia and ascospores, than stems with less severe stem canker (Petrie 1995; Marcroft et al. 2004b; Lô-Pelzer et al. 2009). Furthermore, the intensity of sexual reproduction was shown to depend on disease severity at harvest, with higher disease severities leading to the production of more pseudothecia (Bousset et al. 2021; Fortune et al. 2021). A similar relationship has been described in *Z. tritici*, with more severe epidemics associated with higher levels of ascospore production during the early epidemic stage of the following year (Cowger et al. 2002; Suffert et al. 2018b). As with *L. maculans*, this positive relationship between disease severity and ascospore production is underpinned by increased intensity of sexual reproduction following more severe disease outbreaks, due to higher probability of opposite mating types meeting (Suffert et al. 2018a). Given this well-established relationship between disease severity and inoculum production, it follows that any host genetic resistance that decreases in-season disease severity indirectly influences off-season inoculum production as well. (Marcroft et al. 2004b; Lô-Pelzer et al. 2009; Bousset et al. 2021).

(ii) Direct influence on off-season inoculum production In addition to reducing primary inoculum by limiting in-season pathogen growth, for some pathosystems host genotype has been shown to directly impact inoculum production on residues. A study in canola looking at the effect of host resistance on the carryover of inoculum between consecutive years found that host genotype has a direct effect on inoculum production, independent of disease severity, and accounts for up to 17% of variance in the formation of *L. maculans* fruiting bodies (Bousset et al. 2021). On the other hand, many RBPs can colonize, reproduce, and sporulate on residues with varying levels of genetic resistance (Summerell and Burgess 1988), on residues of non-host crops (Duczek et al. 1999, 2011), and in the absence of visible in-season infection (Orellana-Torrejon et al. 2022a; Suffert et al. 2025). Sexual reproduction involving avirulent strains of *Z. tritici* can occur on residues from resistant plant genotypes and produce substantial numbers of ascospores (Orellana-Torrejon et al. 2022a), highlighting that host resistance does not prevent transmission of avirulent strains. Furthermore, saprotrophic colonization of cereal residues by *F. pseudograminearum* (crown rot), *P. tritici-repentis* (yellow leaf spot), and *B. sorokiniana* (common root rot) did not directly correlate with in-season disease resistance ratings (Petronaitis et al. 2022b). All three pathogens colonized oat and barley stubble more extensively than bread wheat residues, even though in general oat exhibits lower disease incidence and severity for all three diseases (Rees and Platz 1979; Hosford Jr et al. 1987; Wildermuth and McNamara 1987; Knight and Sutherland 2017). Moreover, barley is not a recognized host for *P. tritici-repentis* (Petronaitis et al.

2022b). The authors suggested that the larger, hollow tillers of barley and oat provide a more favorable micro-environment for saprophytic pathogen growth compared with the denser stems of bread wheat. Indeed, the biochemical composition and physical architecture of residues strongly influences saprotrophic colonization. Residue traits such as lignin content, carbon-to-nitrogen ratio, and overall chemical composition have a demonstrated impact on decomposition rates and pathogen colonization potential (Lukas et al. 2014; Reddy et al. 2026). These traits are closely linked to the genetic characteristics of the host cultivar (Cardinal et al. 2003; Krakowsky et al. 2005; Frei 2013), even though the host plant has senesced. Thus, while current in-season disease resistance ratings may not be indicative of saprotrophic growth, host genetics have the potential to directly affect off-season saprotrophic survival of pathogens via residue-mediated effects. Future research could more explicitly explore this relationship between crop residue characteristics and the growth and reproductive dynamics of RBPs on crop residues, e.g., whether altering the morphology or chemical composition of the host generates differential pathogen colonization and survival responses.

(iii) Indirect influence on microbial interactions Crop residues act as an ecological interface between plant and soil, supporting diverse microbial communities that include both beneficial microbes and plant pathogens (Kerdraon et al. 2019c). Host genetics can influence interactions between these microorganisms, thus affecting pathogen survival, population structure and disease progression in subsequent cropping cycles (Kerdraon et al. 2019a). Canola cultivars with effective resistance against *L. maculans* can impact the relative composition of the residue-associated microbiome. For example, several microbial genera, including *Hydropisphaera* and *Pantoea*, were more abundant on residues of canola lines carrying the *Rlm11* resistance gene compared with near isogenic lines without the resistance gene (Kerdraon et al. 2020). Furthermore, host genetics can influence dynamics between local *Leptosphaeria* spp. populations, namely the closely related species *L. maculans* and *L. biglobosa*, which both cause blackleg of canola, although *L. maculans* is more aggressive than *L. biglobosa*. Pseudothecia formed on stubble from the Quartz cultivar, carrying the *Rlm7* resistance gene against blackleg disease, are often dominated by *L. biglobosa*, because *Rlm7* effectively controls blackleg caused by *L. maculans* but not *L. biglobosa* (Huang et al. 2018; Mitrousia et al. 2018). Supporting this, previous work showed that *L. biglobosa* discharged more ascospores than *L. maculans* from mature pseudothecia on stems of cvs Roxet and Excel carrying *Rlm7* across multiple cropping seasons (Sidique 2016). These findings indicate that host genetics should be viewed as a lever that can influence the persistence of both beneficial and pathogenic

microorganisms, informing breeding initiatives or cultivar selection.

Competition between different pathogen genotypes is also shaped by the genetic structure of host populations. Introducing host varietal diversity in wheat fields through deployment of cultivar mixtures (different cultivars of the same crop grown in the same field) slowed the rate of virulence evolution in *Phaeosphaeria nodorum* pathogen populations (Sommerhalder et al. 2011). These heterogeneous host environments create bottlenecks that limit the dominance of aggressive pathotypes, thereby reducing the accumulation of homogeneous inoculum and promoting the maintenance of intra-species pathogen diversity. In practice, this means farming practices that increase within-field genetic diversity of hosts, such as cultivar mixtures, not only reduce in-season disease severity but also influence the saprotrophic phase by slowing pathogen specialization and adaptation (Burdon et al. 2016). Such dynamics are further influenced by the reproductive biology of the pathogen. In field experiments, the frequency of avirulent *Z. tritici* strains was higher after sexual reproduction on the residues of resistant wheat cultivars grown in a mixture than after sexual reproduction on the residues of a pure stand (Orellana-Torrejon et al. 2022b, a). Thus, cultivar mixtures can increase transmission of avirulence and reduce the transmission of virulence to the next epidemic season, limiting the breakdown of resistance genes (McDonald et al. 2022). In certain situations, the epidemiological processes occurring on residues, if well characterized and managed at appropriate spatiotemporal scales, could present an opportunity to improve durability of resistance gene efficacy (Orellana-Torrejon et al. 2022b, a). Further work is required to understand this interplay between host diversity, pathogen competition, and reproductive constraints and how it shapes both off-season survival and the composition of inoculum available at the start of the next growing season.

3.2.3 Biocontrol strategies

Environmental concerns surrounding synthetic pesticides, including fungicides, are leading to increased regulatory pressure around their ongoing use and novel registration. This has intensified interest in sustainable alternatives for disease management, such as biocontrol strategies, which offer an ecologically compatible solution by harnessing antagonistic or competitive microorganisms (or their bioactive constituents) to suppress pathogens. While commercial biocontrol products exist for soil-borne and root pathogens, crop residues have been relatively underexplored as targets for bioregulation in RBD management, reflecting the limited attention that has been paid to epidemiological processes occurring during the inter-epidemic period. Yet, depending

on the biology of the pathogens involved, the application of biocontrol agents targeting crop residues could complement the activity of agents applied to the phyllosphere during the epidemic phase to help reduce primary inoculum pressure.

A number of approaches have been explored, including inoculation with beneficial taxa that can inhibit pathogens through mycoparasitism, antibiosis, and/or competition for nutrients and space. Several studies have demonstrated the feasibility of targeting pathogen propagules on crop residues using these organisms. For instance, *Trichoderma harzianum* combined with urea and nitrate amendments displaced *F. pseudograminearum* from infected barley straw (Lakhe-sar et al. 2010), while *T. koningii* completely eliminated *F. pseudograminearum* from wheat straw after 6 months incubated in moist soil at 25 °C (Wong et al. 2002). Similarly, *Aureobasidium pullulans* limited *A. rabiei* (syn. *Didymella rabiei*) growth on chickpea through competition, and *Clonostachys rosea* suppressed both sexual and asexual reproduction of *A. rabiei* via mycoparasitism (Dugan et al. 2005). A biofungicide formulation derived from a *Streptomyces* strain also showed promise against *A. rabiei*, by reducing *in planta* disease development and conidial spore production (Bullock et al. 2026). Moreover, springtails (class Collembola), among the most widespread soil arthropods, have been investigated as potential biocontrol agents against RBPs (Friberg et al. 2005; Innocenti and Sabatini 2018; Bourgeois et al. 2023), including *Fusarium* spp. (Goncharov et al. 2020) and *Z. tritici* (Salmon et al. 2021; Bourgeois et al. 2024). Under controlled conditions, the springtail *Heteromurus nitidus* showed promising results regarding grazing of *Z. tritici* fruiting bodies on wheat residues, reducing pycnidiospore numbers by ten-fold (Bourgeois et al. 2024).

Recent advances in biocontrol development have also sought to bolster the predatory capacity and host specificity of biocontrol candidates using experimental evolution. For example, after demonstrating that the myxobacteria *Myxococcus xanthus*, a broad-spectrum predator of fungi, can suppress *Zymoseptoria tritici* populations on wheat straw, an experimental framework was developed to iteratively enhance this antagonistic activity (Eisner et al. 2023). Over 40 growth cycles, a subset of myxobacterial populations developed enhanced killing efficiency relative to their ancestors (Eisner 2025). However, across the taxa tested, these improvements in killing efficiency were in the minority, suggesting that experimental evolution may be more useful as a complementary tool for identifying adaptive traits and mechanisms relevant to biological control, rather than as a standalone platform for generating superior antagonists.

By regulating the mineralization and humification of crop residues, microbes directly influence fungal saprotrophic processes in addition to acting as pathogen antagonists. Crop residues are predominantly composed of cellulose (40–50 wt%), hemicellulose (15–25 wt%), and lignin (20–30 wt%),

protein, and soluble sugars (glucose, fructose, etc.) (Fu et al. 2021). Since few organisms degrade lignin, the decay rate and community composition of plant detritus are largely governed by lignin content (Osono 2007; McGuire et al. 2010; Talbot et al. 2011; Cline and Zak 2015). Therefore, the introduction of microbes with enhanced ligninolytic and cellulolytic capacity can positively influence the decomposition of residues (see Rowińska et al. 2024 for a review of biopreparations for the decomposition of crop residues). For example, *Trichoderma atroviride* provided the dual benefit of faster residue decomposition via xylanase activity (targeting hemicellulose) and direct antagonism of *F. graminearum* through antibiotic secondary metabolite production (Cabrera et al. 2020). Advances in culture-omics and experimental evolution could accelerate the discovery of microbes with superior residue-degrading capabilities and tolerance to the often-hostile high temperatures and drought conditions associated with summer fallow periods, which could serve as the next generation of crop residue bioproducts. Numerous non-microbial products marketed to accelerate stubble decomposition are also available, such as Tillzyme™, which contains purified laccase enzymes targeting lignin and plant derived humic and fulvic acids, and PhycoTerra™, which comprises algal-based solids.

Building on these classical methods, next-generation biocontrol research is shifting toward community-level and systems-based approaches. Synthetic microbial communities (SynComs) and prebiotic amendments designed to stimulate native beneficial microbial populations have shown promise in accelerating residue decomposition and reducing off-season inoculum loads (Alahmad et al. 2023). For example, a consortium of four fungal strains, a consortium of four bacterial strains, and a consortium combining all eight fungal and bacterial strains were tested for their rice residue-degrading capacity (Fatima et al. 2025). The consortium containing both bacterial and fungal isolates, in combination with a urea supplement, had the highest net stubble degradation and enzymatic activities, likely due to synergistic cross-feeding between bacterial and fungal decomposers e.g., complementary cellulose and lignin depolymerization. These approaches aim to mimic or amplify naturally disease-suppressive microbiomes and may represent a pathway toward more resilient, context-specific biological control (Tsolakidou et al. 2019). Despite crop residues being critical reservoirs of both pathogens and potential antagonists, few studies have taxonomically and functionally characterized their complex microbial communities (Cobo-Díaz et al. 2019; Kerdraon et al. 2019a, b). Co-occurrence network analyses from residue microbiome analyses could help to identify keystone taxa with putative antagonistic roles to pathogens, informing the rational design of SynComs or prebiotic treatments to maintain or enhance the activity of resident beneficial organisms.

Regardless of whether biological control is achieved through single-strain inoculants, experimentally evolved antagonists, or SynComs-based approaches, their efficacy will ultimately be influenced by the farm management system into which these interventions are deployed. For example, crop rotations will alter the quality (e.g., C:N ratio and lignin content) of residues, in addition to the baseline composition and functional capacity of the resident microbial community with which a biocontrol product must integrate. Similarly, nutrient amendment of crop residues can differentially stimulate specific components of the microbiome, which could impede the activity of a biocontrol product or create novel niches that enhance its establishment and activity. Consequently, the success of residue-optimized biocontrol strategies will depend not only on the efficacy of the biological agent itself, but also on how effectively it is integrated with existing residue management practices. In the short term, biocontrol agents targeting RBPs on residues are unlikely to replace fungicides outright but could be a valuable addition to the “chemical-free” toolkit and support reduced fungicide dependence.

3.3 Chemical

3.3.1 Mineral fertilizers for pathogen inhibition

In addition to the indirect role of nutrient amendments to address limits in microbial decomposition of crop residues, fertilizer and other soil amendments can directly inhibit fungal pathogens. For instance, lime (calcium carbonate) application can reduce or control soilborne pathogens, including clubroot caused by *Plasmodiophora brassicae* in canola (Bochow 1960; Niwa et al. 2008; Fox et al. 2022), *Fusarium* wilt caused by *Fusarium vasinfectum* in cotton (Albert 1946), and root rots caused by *Fusarium spp.* in field pea (Chittem et al. 2016). The disease-suppressive effect of lime applications is generally attributed to increased soil pH, although it appears that calcium also independently plays a role (Jones and Woltz 1969; Dixon 2009). It remains to be seen whether RBPs are susceptible at all to the neutralizing effects of lime application, given the physical protection provided by residues may buffer against changes in soil chemistry.

Similar to lime application, much of the existing research on fertilizer amendments to inhibit fungal pathogens largely focuses on soilborne diseases. For instance, amendment with bloodmeal and fishmeal eliminated soilborne verticillium wilt of tomato (*Verticillium albo-atrum*) in pot trials (Wilhelm 1951) and incorporation of various N-rich organic amendments (soymeal, meat and bone meal, and poultry manure) in the field significantly reduced the incidence of the soilborne pathogens causing verticillium wilt and common scab of potato (Conn and Lazarovits 1999; Lazarovits

et al. 1999). There is compelling evidence that ammonia liberation from N-rich amendments is the mechanism by which plant pathogens are suppressed or even eliminated (Wilhelm 1951; Gilpatrick 1969; Huber and Watson 1970; Mian and Rodriguez-Kabana 1982; Shiau et al. 1999). Incorporation of N-rich hairy vetch (*Vicia villosa*) as green manure for a summer cotton crop suppressed *Thielaviopsis basicola* (Rothrock et al. 1995), with high levels of ammonia liberated during decomposition responsible for the suppressive effect (Candole and Rothrock 1997). Ammonia is toxic to many fungi (Ko et al. 1974; Tsao and Oster 1981; Schippers et al. 1982; Chun and Lockwood 1985), attributed to its ability to penetrate and disrupt cell membranes (Macmillan 1956; Rush and Lyda 1982).

Evidence of off-season suppression of RBPs by amelioration with N-rich amendments is more limited. Excess nitrogen produced divergent responses among species of cereal foot-rot fungi, positively influencing growth of *Ophiobolus graminis* and *Fusarium roseum* f. sp. *cerealis*, having no effect on *Cercospora herpotrichoides* or *Curvularia ramosa*, and curtailing saprotrophic growth of *Cochliobolus sativus* and *Phialophora radicola* (Garrett 1972). This result highlights that the suppressive effect of N will likely be pathogen-specific and may also be influenced by the presence or activity of other microbes. The form of fertilizer also influences the persistence of individual microorganisms on residues. For example, the treatment of wheat and maize residues infected with *F. graminearum* treated with nitrolime (calcium cyanamide) significantly reduced the number of colonies and macroconidia that formed on buried residues, unlike a treatment with calcium ammonium nitrate (Yi et al. 2002). It is unlikely that *Fusarium* is the only RBP that exhibits differential responses to fertilizer type, and future research should explore the individual preferences or sensitivities of RBPs to specific nutrient sources to inform fertilizer choice, particularly in the context of fertilizer applied to enhance residue decomposition and suppress pathogen growth on residues.

3.3.2 Fungicides

Fungicides are commonly applied for RBD control during the growing season in broad-acre systems. They are not designed, tested, or registered for control of pathogens residing on crop residues, which are often less accessible and present in more resistant survival forms. However, experiments conducted on canola stubble contaminated with *L. maculans* showed that treatment with flutriafol or glufosinate-ammonium reduced the number of ejected ascospores (5×10^5 vs 25×10^5 ascospores per stem) and resulted in significantly lower early infection levels at the seedling stage in field conditions (Wherrett et al. 2003). These results are consistent with earlier studies from the 1980s using several

fungicides (ethyl mercury phosphate, triarimol, fenarimol, carbendazim, tridemorph, and benomyl), which achieved up to 90% efficacy and suggested, somewhat simplistically, that it may be possible to break the lifecycle of *L. maculans* and thereby obviate the need for subsequent control measures (Humpherson-Jones and Burchill 1982). Similar findings were reported in field conditions by Fortune et al. (2021). Particularly for pathogens with long-distance dispersal mechanisms, the viability of such a strategy becomes more questionable when the broader cropping system is considered, as is now common in agroecological approaches and within the current European context of pesticide-use reduction. The treatment would need to be extremely effective, even 90% reduction may be insufficient, not only on the treated field but also across all nearby fields that could act as inoculum sources due to the potential for aerial dispersal of inoculum (see Section 4.2). Even a small proportion of untreated residues would substantially diminish the overall efficacy of a fungicide-based strategy at the landscape scale, making the impact over a growing season negligible. Indeed, for some RBDs such as *Septoria tritici* blotch, primary inoculum is rarely a limiting factor (see Section 5), and partial reductions usually only delay the early development of the epidemic (Suffert and Sache 2011; Morais et al. 2016b). Moreover, it is important to recognize that post-harvest treatments would benefit the subsequent susceptible crop only if a similar crop is grown nearby, but not necessarily on the treated field itself when crop rotation is practiced. This makes the treatment economically difficult to justify at the field scale. Finally, because residues are distributed across the landscape, the larger the area covered by the target crop, the less relevant a localized residue treatment becomes.

Several studies have examined the impact of fungicides on the phyllosphere (Karlsson et al. 2014; Knorr et al. 2019) and soil communities (Bending et al. 2007; Wang et al. 2020; Lupwayi et al. 2024), but few studies have directly investigated the impact of in-season fungicides application on pathogen survival on residues (Beare et al. 1993). Fungicide application may have varying effects on the overall pathobiome, depending not only on the active ingredient but also on the broader fungal community, which is largely inherited from the plant (Kerdraon et al. 2019c). Application of the fungicide hymexazol to soil microcosms changed the microbial community, but these were due to indirect effects (i.e., through interactions among microorganisms) rather than direct toxicity (Meyer et al. 2024). When fungicide-sensitive species are suppressed, microbial interaction networks within residues or in the soil/rhizosphere may be altered. Negative effects, such as reductions in fungal abundance, are often observed over a period of weeks to months but diminish over time as the community stabilizes or other

species occupy the vacant niches (Meyer et al. 2021; Riedo et al. 2023). Agricultural practices such as residue retention, mulching, or tillage strongly influence how microbial communities respond to fungicides (Meyer et al. 2021). These findings suggest that fungicide use may have detrimental effects on microbial biodiversity and could interfere with the effectiveness of potential biocontrol strategies currently being explored. From a plant health perspective, this can be counterproductive, as it may destabilize existing ecological balances. Even when pathogenic fungi are present, they can often be maintained below damaging thresholds by beneficial organisms (Schlatter et al. 2017).

Residue decomposition can be temporarily slowed and the persistence of RBD inoculum indirectly promoted following foliar fungicide application (Yi et al. 2002; Meyer et al. 2021; Lupwayi et al. 2024). This effect depends on the residual fungicide concentration on crop residues, which in turn is influenced by the rate and frequency of application, as well as environmental conditions. Moreover, joint analyses of fungicide residues and mycotoxin production reveal variable and complex effects on mycotoxins in cereal residues and grain (e.g., deoxynivalenol [DON] produced by *Fusarium* spp.). Depending on the fungicide, the timing of application, and weather conditions, some treatments reduced DON in grain but contamination in residues remained stable or even increased (da Luz et al. 2017; Bissonnette et al. 2018; Ju et al. 2023). However, a few studies indicate that both traditional chemical control and biocontrol strategies can be combined. For example, applied to corn residues in the field, the widely used fungicide difenoconazole combined with a *Trichoderma* sp. bioagent successfully controlled northern corn leaf blight (NCLB) and *Fusarium* stalk rot, both of which are exacerbated when maize residue is retained under conservation tillage (Wang et al. 2025b). The combined treatment outperformed both single fungicide and single biocontrol applications. These results highlight the synergistic potential of integrating chemical and biological control agents to manage RBPs, offering a practical and sustainable strategy for disease management in residue-intensive conservation agriculture systems.

Overall, post-harvest fungicide application to suppress inoculum on residues does not currently appear to be a viable or sustainable strategy to control primary inoculum of RBPs. Such applications are highly constrained by ecological, epidemiological, and economic factors, and what's more can disrupt naturally occurring beneficial microbial balances. This is particularly relevant in Europe where agricultural policies and practices increasingly favor agroecological approaches and discourage solutions that rely solely on chemical control, instead promoting biocontrol strategies that harness existing microbial community equilibria.

4 Toward integrated disease management

4.1 Decision support

Effective management of RBPs during the off-season requires balancing the agronomic benefits of residue retention with the need to suppress pathogen inoculum in the “brown bridge” between crops. This balance is complicated by diverse RBPs affecting multiple crops within rotations, the substantial spatial variability in residue loads and disease pressure across regions, farms, and within paddocks, and significant knowledge gaps in pathogen biology. Given this complexity, the central role of infected residues as sources of primary inoculum and reservoirs of genetic diversity for RBPs provides management leverage points that operate outside the growing crop. In contrast, most current frameworks focus on in-season control to minimize or avoid crop losses within a given pathosystem (e.g., sowing time, fungicide applications, or cultivar selection) and consideration of primary inoculum sources is typically limited to spatial and/or temporal proximity to susceptible hosts or diagnosis via molecular assays that quantify pathogen DNA (e.g., PredictaB in Australia). These approaches inadequately capture the biological and spatial complexity at play during the residue phase, limiting their capacity to guide residue management strategies.

Accurate diagnosis of RBPs and determining when and where they impose an economic constraint to productivity underpins management decisions by growers. While field surveys commonly document the presence and frequency of pathogens in residues and soils, data on realized crop losses or profitability are surprisingly limited (Savary et al. 2019). In this context, digital tools such as yield monitors on harvesters, satellite platforms, and UAV-based sensors can provide more complete and informative datasets that complement traditional approaches constrained by spatiotemporal sampling density (Soussi et al. 2024; Xing et al. 2026). Moreover, these technologies enable integration of multiple data layers to generate a more holistic understanding of disease impacts. For example, soil moisture, plant stress indicators, crop biomass measurements, and yield maps can be combined with conventional disease diagnostics to identify under-performing fields or zones with higher precision and guide targeted scouting and diagnosis to address the fundamental question: which RBPs are limiting productivity on my farm and at what cost?

Even when RBPs are confirmed as productivity constraints, quantifying inoculum load and translating it into meaningful disease risk estimates remains a major challenge. Molecular diagnostic assays applied to stubble and soil typically quantify pathogen DNA, but these measurements do not directly reflect the abundance of infective propagules nor provide a reliable, quantitative link to disease risk (Poole

et al. 2015). Similarly, in-crop measures of disease severity seldom correspond directly to inoculum load. Relatively basic and time-consuming microbiological methods are still sometimes used, such as quantifying the number of *Z. tritici* ascospores ejected from wheat residues on Petri dishes (Suffert et al. 2018a). Classic spore traps, also used to quantify *Z. tritici* ascospores *in situ* (Morais et al. 2016b), might be complemented or replaced by modern spore samplers (e.g., BioScout Pty Ltd) providing the most accurate direct measurements of airborne disease inoculum, utilizing machine-learning to generate near real-time data. These data can inform in-season management decisions and be integrated with spatial, environmental, and management datasets to elucidate underlying mechanisms driving inoculum production, release, and dispersal. Accordingly, systematic data sharing of diagnostic results, field observations, and measured disease and yield outcomes would facilitate data integration, support broader learning across regions, and strengthen the evidence base. More broadly, substantial knowledge gaps remain regarding pathogen biology and the influence of different crop, residue, and soil management practices on inoculum load and decay rates—critical factors for determining the feasibility and value of interventions.

The relationship between inoculum load and subsequent disease risk is highly context-dependent and is strongly influenced by environmental conditions, residue quantity, spatial proximity, and crop susceptibility. To represent these interactions at scale, modelling and remote sensing technologies offer a pathway to enabling a system-level management framework. Rainfall patterns, temperature, residue nutrition, and management practices are key determinants of inoculum carryover. The Agricultural Production Systems Simulator (APSIM) is a process-based farming systems modelling framework that integrates crop growth, soil-water and nutrient dynamics, and management practices to simulate agricultural systems over time (Keating et al. 2003; Holzworth et al. 2014; Verburg et al. 2025). APSIM includes modules describing surface organic matter decomposition and residue dynamics according to weather conditions, soil factors, and residue composition (C:N ratio) (Probert et al. 1998; Thorburn et al. 2001). These modules simulate the decline of surface cover and consequent effects on soil moisture, evaporation, and run-off, which provides useful mechanistic representation of residue management impacts on key ecosystem services. While pest modules are available in APSIM, they are not part of the core framework; however, recent advances have leveraged APSIM modules to model management and environmental factors driving RBP inoculum production and disease risk (Bondad et al. 2025a, b). Together, such frameworks provide a strong foundation for assessing trade-offs in disease suppression and agronomic benefits of residue management interventions.

Further research could explore the relationships between residue quantity and inoculum load and between inoculum load and disease risk for specific RBPs and incorporate this with existing APSIM modules simulating residue decomposition, to produce disease risk predictions accurately informed by off-season risk factors.

Remote sensing technologies can further support this system-level management approach. Remotely sensed data can be used to reconstruct cropping history (Xue et al. 2024; Donmez et al. 2025), map residue cover and persistence (Pepe et al. 2023), identify fields or zones most likely to harbor infected residues (Sørensen et al. 2025), and identify areas where crop losses may be exacerbated by abiotic factors, such as soil constraints (Yang et al. 2015), thereby targeting residue management, or crop avoidance where it is most warranted (Pasut et al. 2026). Integrated with existing inoculum assays and local agronomic knowledge, sensing-based landscape characterization can improve prioritization of interventions and support rotation and field selection strategies that reduce exposure to residue-borne inoculum before epidemic initiation (Amarathunga et al., *in review*). Furthermore, integration of these data streams into landscape-scale risk models can inform proactive field selection and rotation strategies that reduce exposure to residue-borne inoculum before planting (Newlands 2018). In this way, sensing tools contribute most strongly to RBD management not by reacting to disease expression within crops, but by enabling proactive strategies to disrupt epidemic initiation at its source and to identify where to target interventions.

4.2 System complexity

Farm management decisions related to RBD control are embedded within complex and dynamic agricultural systems characterized by multiple, interacting components. Agricultural landscapes typically comprise annual and perennial crops, livestock, cover crops, pasture, weeds, and semi-natural vegetation as well as machinery, infrastructure, and human environments, all of which interact across spatial and temporal scales. Consequently, farmers are often balancing competing objectives across these different elements of a farm enterprise. Research studies on biotic constraints to agricultural productivity, particularly pests and disease, typically simplify management tactics in relation to farming systems variables and rarely include social, economic or broader system variables. In a review of pest management, 83% of studies ($n = 3407$) considered no more than two out of 15 farming system variables (Wyckhuys et al. 2023). On-farm adoption of new technologies or approaches is hindered by the lack of integration

into complex systems, as well as poor understanding of the social and behavioral factors that underlie management decisions (Lewis et al. 1997; Giller et al. 2011; Geffersa et al. 2023).

Here, we present an example of the complex nature of such trade-offs in relation to the management of RBDs and technology adoption. Draper front harvesters cut crops lower to the ground, while stripper front harvesters remove and thresh grain from only the heads of wheat crops, with the remainder of the crop left intact in the field post-harvest. Significant cost savings can be achieved with stripper fronts with fuel reductions of up to 50%, lower maintenance costs due to less mechanical wear, and improved harvest efficiency with consequent reductions in labor costs of up to 15% (Chegini and Mirnezami 2016; Birchip Cropping Group 2017; Condon et al. 2023). In dryland production systems, the taller residue can alter microclimatic conditions such as windspeed, soil temperature, and solar radiation, which enhance moisture retention and provide more favorable conditions for crop establishment, growth, and water and nitrogen use efficiency, thus producing higher yields (Cutforth et al. 2006, 2011; Broster et al. 2020; Schlegel et al. 2023). Shading from the taller residues also suppresses weed growth, thereby increasing fallow water storage by 25–30% (Chauhan et al. 2012; Hunt et al. 2013; Condon et al. 2023). Furthermore, the taller stubble provides a scaffold supporting semi-erect pulse crops improving their harvestability and grain yield (Cutforth et al. 2002; Yang et al. 2021). Despite the significant efficiencies and systems benefits provided by harvesting with a stripper front, the implications for RBDs are less clear-cut. *F. pseudogrammarum* saprotrophically colonizes stubble post-harvest, with almost complete colonization of standing stubble by 6 months post-harvest independent of harvest height (Petronaitis et al. 2025). Yet yield loss due to *Fusarium* crown rot is exacerbated by moisture stress during anthesis, which is more likely to occur if soil is unprotected by stubble (Beddis and Burgess 1992; Wildermuth et al. 1997; Smiley and Machado 2019; Xu et al. 2023). In addition to hosting inoculum of RBDs, standing stubble can act as a physical barrier to limit the spread of disease propagules. Chickpea sown in inter-rows between standing cereal stubble had increased grain yield (24–132%) and lower *Ascochyta* blight severity compared to chickpea sown into mulched stubble (Mawalagedera et al. 2022). Moreover, retained stubble can increase the severity and duration of frost events, a major constraint to production in many regions globally, either through physical effects on soil-heat transfer or by harboring ice-nucleating bacteria (Biddulph et al. 2019, 2022). This example highlights the multi-faceted interactions and need for holistic approaches to RBD management that consider the differing objectives in an agricultural system.

4.3 Social and economic factors

4.3.1 Delayed benefits but immediate costs

Many residue-borne pathogens accumulate inoculum over multiple seasons, leading to epidemics referred to as poly-etic, with disease risk at any point in the landscape shaped by historical cropping sequences, residue loads, and host susceptibility. Consequently, the benefits of residue management interventions (e.g., key ideas in this paper) will be delayed, uncertain, and potentially difficult to attribute to specific actions, while the costs are borne immediately. In actuality, the full benefits of residue management interventions may never become clearly apparent. This temporal disconnect (short-term pain, long-term gain) has potential to bias decision-making toward short-term optimization even where the epidemiological rationale for longer-term inoculum management is well established (Carroll et al. 2018). As a result, RBDs may remain problematic even if substantial advances are made in managing pathogen survival, dispersal, and infection.

4.3.2 Farming system constraints

In practice, disease and residue management decisions are made within the context of the broader farming system. Disease risk is only one factor that needs to be considered. Crop residues play important roles in soil conservation, moisture retention, nutrient cycling, and, in mixed farming systems, livestock feed supply (Blanco-Canqui and Lal 2009). These competing objectives may constrain the feasibility of disease-focused residue interventions, particularly when they increase operational complexity or when future disease control benefits trade-off with more immediate alternative benefits (Scott et al. 2010). Disease-focused management recommendations that assume residue manipulation is a discrete, independent lever may therefore overestimate adoption and impact. Even highly effective strategies may have minimal uptake if they conflict with other priorities or impose additional labor, machinery, or logistical demands during critical periods of the production cycle. These constraints help explain why current residue-borne disease management strategies often rely heavily on downstream interventions, such as cultivar resistance or in-crop chemical control, rather than integrated approaches to achieve sustained reductions in inoculum.

4.3.3 Individual pain for shared gain

A further challenge arises from retained inoculum and the collective nature of epidemiological risk. Cooperation and coordination in plant disease management have previously been addressed (Sherman et al. 2019), but rarely in the context of managing inoculum sources in broadacre agricultural systems, a topic of critical importance, as highlighted in this

review. Inoculum produced within individual fields often contributes to disease pressure at spatial scales larger than the individual farm, particularly for pathogens capable of medium–long-distance dispersal. Under these conditions, the benefits of residue management are likely partially shared, while the costs are borne by individual growers (Filho et al. 2016). This can lead to systematic under-investment in practices that reduce collective inoculum loads. Local/individual adoption of residue management strategies may therefore fail to deliver effective disease suppression unless adopted at community/larger scales. This misalignment between the scales of epidemic processes and the scales of farm decision-making represents a major challenge for the management of residue-borne diseases and underscores the need for disease management frameworks that explicitly account for socio-economic and operational realities alongside pathogen biology.

4.4 Future directions and research opportunities

Several outstanding questions and potential research avenues have already been highlighted in this review, including:

Pathogen biology

- Investigating how the persistence of fruiting bodies (e.g., pseudothecia) and their ability to release airborne spores is influenced by different biotic and abiotic factors
- Refining the relationships between crop residue quantity, inoculum load, and disease risk under various environmental and management conditions, to inform simulations of disease risk

Physical

- Assess the impact of different tillage and residue management practices on inter-field airborne inoculum dispersal to optimize landscape-scale management of inoculum sources
- Investigate which intercropping combinations provide optimal barrier effects against inoculum carryover
- Using vertical transects along residue stems, measure inoculum and pathogen levels, to potentially inform selection of harvest height
- Incorporate local weather and remotely sensed vegetation data (e.g., Lidar) to improve estimates of inoculum dispersal patterns and the shape of the dispersal gradient tail, which determines the distance beyond which the impact of a given inoculum source on a focal field can reasonably be considered negligible compared to closer sources

Biological

- Examine the relationship between residue nutrient profiles and the growth and reproductive dynamics of RBPs to inform breeding initiatives and management strategies
- Investigate whether genetic traits offer potential for controlling RBDs through in-season mechanisms (e.g., reduced sporulation rates, increased pathogen latent periods to reduce infection cycles) and off-season mechanisms (e.g., restricting saprophytic colonization of residues)
- Perform co-occurrence network analyses from residue microbiomes to identify keystone taxa with putative antagonistic roles to pathogens, informing the rational design of SynComs or prebiotic treatments to promote the activity of resident beneficial organisms

Chemical

- Assess the impact of late in-crop fungicide application on off-season pathogen growth and microbiome dynamics
- Explore the individual preferences or sensitivities of RBPs to specific nutrient sources to inform fertilizer choice

In addition, there are several other promising and necessary areas of future research.

4.4.1 Emerging chemical-free technologies: microwave radiation and cold plasma

While still in its infancy, microwave radiation is emerging as a potential chemical-free approach for reducing fungal inoculum within crop residues. Experiments on major residue-borne cereal pathogens demonstrated that microwave radiation eliminates conidia of *B. sorokiniana*, macroconidia of *F. pseudograminearum*, and *F. cerealis* from spore solutions (Petronaitis et al. 2022a) and reduces *F. pseudograminearum* mycelia from infected cereal stubble (Petronaitis et al. 2018). The effectiveness of microwave treatment is positively correlated with stubble moisture content, suggesting application of microwave technology might be maximally effective following rainfall events (Petronaitis et al. 2022a). The energy required to heat the crown portions of both wheat and barley stubble was greater than the energy required to heat the stem portions, highlighting that the treatment specifics will depend on where the target pathogen resides (e.g., *F. pseudograminearum* and *B. sorokiniana* both reside in the crown, whereas *P. teres* resides in the stem) (Petronaitis et al. 2022a). Unlike conventional control strategies that provide incomplete efficacy and target-limited pathogen spectra,

microwave radiation technology delivers broad-spectrum pathogen control (Petronaitis et al. 2026). This lack of specificity could come with unintended impacts on microbial communities essential for crop residue decomposition and eventual conversion to SOM, a potential limitation of this technology that requires further investigation. Although the technology is not yet scalable or market-ready for broadacre systems, these preliminary studies indicate that targeted microwave treatment may have future utility managing off-season inoculum build up across a range of economically important RBPs (Petronaitis et al. 2026). Alternative physical treatments such as cold plasma that act primarily on surface-bound pathogens and infrared radiation which penetrates deeper than microwaves are also being investigated as complementary control options (Kaur et al. 2020). However, microwave, cold plasma, and infrared treatments alike still require significant research, development, and validation, particularly when it comes to translating laboratory findings to field conditions (Kaur et al. 2022, 2024) and demonstrating their economic and environmental costs do not offset pathogen-control benefits.

4.4.2 Landscape-scale modelling for optimized crop residue management

Landscape-scale models have been discussed in the context of managing regional inoculum sources (Section 4.1.1) but could also be employed to assess the effects of residue management practices on landscape-scale inoculum pressure to inform optimized approaches. Such models could integrate the effect of tillage practices and crop varieties, which shape pathogen sub-population dynamics, thus influencing inoculum pressure. This would enable assessment of strategies such as mandatory tillage of new resistant varieties to limit the emergence and persistence of virulent strains and thus delay resistance breakdown, analogous to the rationale behind fungicide protection of resistant varieties (Taylor and Cunniffe 2023). Symmetrically, varieties carrying resistance genes that have already been largely overcome could be preferentially deployed in CA systems that do not lead to a significant increase in RBD risk and may even reduce it. This could be achieved, for example, through carefully designed variety mixtures with complementary resistance genes, which can slightly dilute avirulent strains, as suggested by the results of Orellana-Torrejon et al. (2022b). This kind of optimization would be particularly relevant in regions with small fields and high crop diversity, like Europe, but less applicable in areas with large, more homogeneous fields and rotations, such as Australia or the USA. Effective parameterization of this type of model requires a detailed characterization of pathogen biology, especially reproductive mode and survival on crop residues, as well as

the field-level epidemiological impact of the hypothesized selection and counter-selection processes.

4.4.3 Shifts in climate drivers of RBPs

Climate change has the potential to significantly alter the pathogen and residue dynamics on which current and emerging control strategies are predicated. In many parts of the world, seasonal rainfall patterns are shifting (Pook et al. 2009; Cai et al. 2012; Lawes et al. 2025) and rainfall events are becoming heavier but less frequent (O’Gorman 2015; Seneviratne et al. 2021). This is particularly significant for residue decomposition, as rainfall is a key determinant of residue breakdown. Depending on soil type and porosity, water penetration may be higher with heavier rainfall events (He et al. 2012; Yinglan et al. 2018) leading to enhanced residue decomposition via increased soil moisture. Conversely, if in-season rainfall declines significantly, there may be reduced crop biomass with consequent reductions in the volume of crop residues, influencing inoculum loads. Indeed, general declines in growing season rainfall and increases in temperature extremes have led to production projections decreasing (Wang et al. 2017). This highlights the complexity of predicting how climate change-driven changes to rainfall and temperature patterns will influence farming systems, and more specifically RBD management.

Similarly, understanding how climate change impacts pathogen lifecycles is also critical for informing future risk assessments and decision-making on RBD management. A growing body of evidence indicates that climate change is shifting the environmental drivers (temperature, humidity, wind, rainfall) that determine fungal growth, survival, sporulation, dispersal, and host infection windows, thereby altering the lifecycles of RBPs and the risk they pose to crop production (Nnadi and Carter 2021; Zhou et al. 2024). Controlled experiments with cereal residues have demonstrated that higher relative humidity increases colonization of cereal residues by RBPs, including *P. tritici-repentis* and *B. sorokiniana* (Petronaitis et al. 2022b). As relative humidity is generally expected to decrease due to a warmer climate (Lutsko 2021; Rogers et al. 2021), post-harvest saprotrophic colonization of crop residues and inoculum build-up may be reduced under warmer conditions. Likewise, changing precipitation patterns could support RBD management, increased fallow rainfall could shift peaks in spore production earlier to fall prior to sowing, or high temperatures during the fallow months may restrict saprotrophic colonization of residues. On the other hand, projected increases in wind speed for some regions (Kara and Sahin 2023; Wang et al. 2025a) could increase the dispersal of fungal spores across fields and regions, and heavier rainfall events may intensify

dispersal of inoculum via rain splash. Climate change is likely already driving shifts in RBP lifecycles, and research is needed to understand these changes and how management approaches need to be adapted accordingly.

4.4.4 Economics of conservation agriculture

The economic analysis of CA benefits relative to losses incurred by residue-borne diseases is critical to inform decision-making around trade-offs with residue management. Accurately quantifying the economic benefits of CA adoption is complex, in part due to the numerous indirect contributions of CA to agricultural profitability. For example, the economic benefits of early sowing are well established (Hunt et al. 2019) and are supported by the retention of summer soil moisture due to stubble retention (one of the CA principles) (see Section 2.1). Furthermore, although there has been some work to quantify the economic impact of individual RBDs (see Table 1), this is complicated by poor and inaccurate diagnosis and reporting, including potential confusion between RBD symptoms and abiotic factors such as frost damage, poor nutrition, or incorrect sowing depths (Paul et al. 2005). A more comprehensive economic analysis of CA benefits and economic losses caused by RBDs is required to support on-farm decision-making in this space.

5 Conclusions

Crop residues perform important functions that underpin conservation agriculture systems by enhancing soil health, water retention, and nutrient cycling. However, their increasing volume and persistence in modern broadacre systems have amplified the prevalence and severity of residue-borne diseases. This review highlights that current management practices alone are insufficient to adequately suppress the off-season proliferation and evolution of residue-borne pathogens. Given residues serve as both an ecological resource and a persistent disease risk, management strategies that explicitly target the residue phase of pathogen life cycles are crucial for the long-term viability and sustainability of conservation agriculture systems.

This inter-disciplinary review of the existing literature identifies several avenues with the potential to target inoculum buildup and carryover. Physical interventions such as crop rotation, residue burial, harvest height manipulation, and enhanced residue decomposition can effectively disrupt the persistence of infected residues. Emerging biological strategies, including antagonistic microbes, residue-degrading consortia, and interventions that accelerate residue decomposition, merit further evaluation under field

conditions. Chemical options, although sometimes effective, are increasingly constrained by pesticide regulation, resistance development, and their potential to disrupt beneficial microbial communities. Collectively, these findings highlight that no single intervention is sufficient; instead, integrated management of physical, biological, and chemical management strategies is required.

Effective residue-borne disease management must also account for social and economic factors. Decisions about residue management intersect with agronomic objectives such as erosion control, soil moisture conservation, machinery and labor efficiencies, and livestock feed supply. These system-level constraints shape growers' capacity to adopt residue-focused disease interventions, underscoring the need for strategies that align disease control with broader production goals. Where disease management strategies are at odds with other agronomic goals, trade-offs must be informed by accurate estimates of losses to support decision-making. Additionally, because many residue-borne pathogens disperse across paddocks and farms, landscape-scale coordination may be necessary to achieve meaningful reductions in inoculum load.

Overall, the evidence presented here underscores the need for a shift from in-season, crop-focused disease management toward a system-spanning, whole-season perspective that recognizes crop residues as a critical intervention point. Progress will depend on improved understanding of pathogen survival dynamics, advances in crop breeding and microbiome science, technological advances, and the development of decision-support tools that link residue loads to inoculum loads and disease risk. By integrating biological, agronomic, and socio-economic considerations, future management frameworks can more effectively break the "brown bridge" and support productive and resilient farming in systems shaped by the residue revolution.

Acknowledgements We acknowledge the CSIRO-INRAE linkage program, which supported K.T. and S.R.L. to visit F.S. and V.L. at INRAE and begin discussions about this review topic.

Authors' contributions All authors contributed to writing the original draft and to reviewing and editing it.

Funding Open access funding provided by CSIRO Library Services.

Data Availability Data sharing not applicable to this article as no datasets were generated or analyzed during the current study.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- ABARES Land Use. <https://www.agriculture.gov.au/abares/aclump/land-use>. Accessed on 2 Apr 2026
- Adee EA, Pfender WF (1989) The effect of primary inoculum level of *Pyrenophora tritici-repentis* on tan spot epidemic development in wheat. *Phytopathology* 79:873–877. <https://doi.org/10.1094/Phyto-79-873>
- Agostinetto L, Casa RT, Bogo A et al (2015) Barley spot blotch intensity, damage, and control response to foliar fungicide application in southern Brazil. *Crop Prot* 67:7–12. <https://doi.org/10.1016/J.CROPRO.2014.09.012>
- Akinsanmi OA, Backhouse D, Simpfendorfer S et al (2006) Genetic diversity of Australian *Fusarium graminearum* and *F. pseudograminearum*. *Plant Pathol* 55:494–504. <https://doi.org/10.1111/J.1365-3059.2006.01398.X>
- Alabouvette C, Olivain C, Steinberg C (2006) Biological control of plant diseases: the European situation. *Eur J Plant Pathol* 114:329–341. <https://doi.org/10.1007/S10658-005-0233-0>
- Alahmad A, Edelman L, Castel L et al (2023) Prebiotics: a solution for improving plant growth, soil health, and carbon sequestration? *J Soil Sci Plant Nutr* 23:6647–6669. <https://doi.org/10.1007/s42729-023-01517-8>
- Albert WB (1946) The effects of certain nutrient treatments upon the resistance of cotton to *Fusarium vasinfectum*. *Phytopathology* 36:703–716
- Angus JF, Van Herwaarden AF, Fischer RA, Heenan DP, Howe GN (1998) The source of mineral nitrogen for cereals in south-eastern Australia. *Aust J Agric Res* 49:511–522. <https://doi.org/10.1071/A97125>
- Australian Oilseeds Federation (2022) Australian canola and the EU biodiesel market. https://australianoilseeds.com/wp-content/uploads/2024/04/AOF_education_factsheets-biodieselWEB2021025.pdf. Accessed on 15 Sep 2026
- Bailey KL (1996) Diseases under conservation tillage systems. *Can J Plant Sci* 76:635–639. <https://doi.org/10.4141/CJPS96-113>
- Bailey KL, Lazarovits G (2003) Suppressing soil-borne diseases with residue management and organic amendments. *Soil Tillage Res* 72:169–180. [https://doi.org/10.1016/S0167-1987\(03\)00086-2](https://doi.org/10.1016/S0167-1987(03)00086-2)
- Barnwal MK, Kotasthane A, Magculia N et al (2013) A review on crop losses, epidemiology and disease management of rice brown spot to identify research priorities and knowledge gaps. *Eur J Plant Pathol* 136:443–457. <https://doi.org/10.1007/S10658-013-0195-6>
- Bathgate JA, Loughman R (2001) Ascospores are a source of inoculum of *Phaeosphaeria nodorum*, *P. avenaria* f. sp. *avenaria* and *Mycosphaerella graminicola* in Western Australia. *Australas Plant Pathol* 30:317–322. <https://doi.org/10.1071/AP01043>

- Baumhardt RL, Unger PW, Dao TH (2004) Seedbed surface geometry effects on soil crusting and seedling emergence. *Agron J* 96:1112–1117. <https://doi.org/10.2134/agronj2004.1112>
- Beare MH, Coleman DC, Pohlad BR et al (1993) Residue placement and fungicide effects on fungal communities in conventional and no-tillage soils. *Soil Sci Soc Am J* 57:392–399. <https://doi.org/10.2136/sssaj1993.03615995005700020018x>
- 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. <https://doi.org/10.1094/Phyto-82-78>
- Bending GD, Rodríguez-Cruz MS, Lincoln SD (2007) Fungicide impacts on microbial communities in soils with contrasting management histories. *Chemosphere* 69:82–88. <https://doi.org/10.1016/J.CHEMOSPHERE.2007.04.042>
- Biddulph B, Bekuma A, Jackson S et al (2022) Bacterial ice nucleation activity in rainfall and on crop residues may be increasing frost damage in WA cropping systems. In: Proceedings of the 20th Agronomy Australia Conference. Agronomy Australia, Toowoomba
- Biddulph B, Smith R, Turner C et al (2019) Stubble load increases frost severity, duration and damage in frost-prone landscapes in south-western Australia. In: Proceedings of the 19th Australian Agronomy Conference, 25–29 August 2019, Wagga Wagga
- Birchip Cropping Group (2017) Calculating the ROI for the use of a stripper front in the Mallee. <https://www.bcg.org.au/research-article/calculating-the-roi-for-the-use-of-a-stripper-front-in-the-mallee/>. Accessed on 15 Sep 2026
- Bissonnette KM, Kolb FL, Ames KA et al (2018) Effect of *Fusarium* head blight management practices on mycotoxin contamination of wheat straw. *Plant Dis* 102:1141–1147. <https://doi.org/10.1094/PDIS-09-17-1385-RE>
- Blanco-Canqui H, Lal R (2009) Crop residue removal impacts on soil productivity and environmental quality. *CRC Crit Rev Plant Sci* 28:139–163. <https://doi.org/10.1080/07352680902776507>
- Blanco-Canqui H, Lal R, Post WM et al (2006) Rapid changes in soil carbon and structural properties due to stover removal from no-till corn plots. *Soil Sci* 171:468–482. <https://doi.org/10.1097/01.SS.0000209364.85816.1B>
- Bochow H (1960) Über die Beeinflussung von Plasmodiophora brassicae Wor. durch Mineralsalze. *J Phytopathol* 40:420–421. <https://doi.org/10.1111/J.1439-0434.1960.TB01935.X>
- Bockus WW, Shroyer JP (1998) The impact of reduced tillage on soilborne plant pathogens. *Annu Rev Phytopathol* 36:485–500. <https://doi.org/10.1146/annurev.phyto.36.1.485>
- Bokor A, Barbetti MJ, Brown AGP et al (1975) Blackleg of rapeseed. *J Dep Agric West Aust Ser* 4 16:7–10. https://library.dpird.wa.gov.au/journal_agriculture4/vol16/iss1/3/
- Bond JJ, Willis WO (1970) Soil water evaporation: first stage drying as influenced by surface residue and evaporation potential. *Soil Sci Soc Am J* 34:924–928. <https://doi.org/10.2136/SSSAJ1970.03615995003400060030X>
- Bondad JJ, Whish JPM, Sprague SJ et al (2025a) Modelling crop management and environmental effects on the development of *Leptosphaeria maculans* pseudothecia. *Eur J Plant Pathol* 171:431–443. <https://doi.org/10.1007/S10658-024-02961-7>
- Bondad JJ, Whish JPM, Sprague SJ et al (2025b) Environmental and management determinants of blackleg crown canker disease (*Leptosphaeria maculans*) of canola (*Brassica napus*). *Australas Plant Pathol* 54:13–24. <https://doi.org/10.1007/S13313-024-01013-2>
- Bossuyt H, Six J, Hendrix PF (2005) Protection of soil carbon by microaggregates within earthworm casts. *Soil Biol Biochem* 37:251–258. <https://doi.org/10.1016/J.SOILBIO.2004.07.035>
- Bottenberg H, Masiunas J, Eastman C et al (1997) The Impact of Rye Cover Crops on Weeds, Insects, and Diseases in Snap Bean Cropping Systems. *J Sustain Agric* 9:131–155. https://doi.org/10.1300/J064v09n02_09
- Bourgeois TP, Prado S, Suffert F et al (2024) The collembolan *Heteromurus nitidus* grazes the wheat fungal pathogen *Zymoseptoria tritici* on infected tissues: opportunities and limitations for bioregulation. *Pest Manag Sci* 80:3238–3245. <https://doi.org/10.1002/PS.8026>
- Bourgeois TP, Suffert F, Dury G et al (2023) Dietary preferences of *Heteromurus nitidus* (Collembola) among wheat fungal communities: implications for bioregulation of two widespread pathogens. *Appl Soil Ecol* 188:104897. <https://doi.org/10.1016/J.APSOIL.2023.104897>
- Bousset L, Chèvre AM (2013) Stable epidemic control in crops based on evolutionary principles: adjusting the metapopulation concept to agro-ecosystems. *Agric Ecosyst Environ* 165:118–129. <https://doi.org/10.1016/j.agee.2012.12.005>
- Bousset L, Jumel S, Garreta V et al (2015) Transmission of *Leptosphaeria maculans* from a cropping season to the following one. *Ann Appl Biol* 166:530–543. <https://doi.org/10.1111/aab.12205>
- Bousset L, Vallée P, Delourme R et al (2021) Besides stem canker severity, oilseed rape host genotype matters for the production of *Leptosphaeria maculans* fruit bodies. *Fungal Ecol* 52:101076. <https://doi.org/10.1016/J.FUNECO.2021.101076>
- Bouws H, Finckh MR (2008) Effects of strip intercropping of potatoes with non-hosts on late blight severity and tuber yield in organic production. *Plant Pathol* 57:916–927. <https://doi.org/10.1111/J.1365-3059.2008.01860.X>
- Brokenshire T (1975) Wheat seed infection by *Septoria tritici*. *Trans Br Mycol Soc* 64:331–334
- Broster J, Hatty N, Eberbach P et al (2020) Influence of header front on stubble micro-climate and winter crop growth. GRDC Update Papers, Grains Research and Development Corporation. <https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2020/02/influence-of-header-front-on-stubble-micro-climate-and-winter-crop-growth>. Accessed on 15 Sep 2026
- Brown JS, Kellock AW, Paddock RG (1978) Distribution and dissemination of *Mycosphaerella graminicola* (Fuckel) Schroeter in relation to the epidemiology of speckled leaf blotch of wheat. *Aust J Agric Res* 29:1139–1145. <https://doi.org/10.1071/AR9781139>
- Bullock M, Thammavongsa B, Barrett LG et al (2026) Bioprotectants for the suppression of *Ascochyta rabiei* infection and inoculum production on chickpea (*Cicer arietinum*). *Biol Control* 212:105950. <https://doi.org/10.1016/J.BIOCONTROL.2025.105950>
- Burdon JJ, Zhan J, Barrett LG et al (2016) Addressing the challenges of pathogen evolution on the world's arable crops. *Phytopathology* 106:1117–1127. <https://doi.org/10.1094/PHYTO-01-16-0036-FI>
- Burgess LW, Backhouse D, Swan LJ et al (1996) Control of *Fusarium* crown rot of wheat by late stubble burning and rotation with sorghum. *Australas Plant Pathol* 25:229–233. <https://doi.org/10.1071/AP96042>
- Burgess LW, Griffin DM (1968) The recovery of *Gibberella zeae* from wheat straws. *Aust J Exp Agric Anim Husb* 8:364–370. <https://doi.org/10.1071/EA9680364>
- Bussière F, Cellier P (1994) Modification of the soil temperature and water content regimes by a crop residue mulch: experiment and modelling. *Agric for Meteorol* 68:1–28. [https://doi.org/10.1016/0168-1923\(94\)90066-3](https://doi.org/10.1016/0168-1923(94)90066-3)
- Cabrera M, Garmendia G, Rufo C et al (2020) Trichoderma atroviride as a biocontrol agent of Fusarium head blight by reducing the inoculum of the pathogen in wheat straw. *Terra Latinoam* 38:629–651. <https://doi.org/10.28940/terra.v38i3.664>
- Cai W, Cowan T, Thatcher M (2012) Rainfall reductions over Southern Hemisphere semi-arid regions: the role of subtropical dry zone expansion. *Sci Rep* 2:702. <https://doi.org/10.1038/srep00702>

- Candole BL, Rothrock CS (1997) Characterization of the suppressiveness of hairy vetch-amended soils to *Thielaviopsis basicola*. *Phytopathology* 87:197–202. <https://doi.org/10.1094/PHYTO.1997.87.2.197>
- Cao Y, Xie Y, Zhu T et al (2024) Response patterns of soil nitrogen cycling to crop residue addition: a review. *J Soil Sci Plant Nutr* 24:1761–1774. <https://doi.org/10.1007/S42729-024-01769-Y>
- Cardinal AJ, Lee M, Moore KJ (2003) Genetic mapping and analysis of quantitative trait loci affecting fiber and lignin content in maize. *Theor Appl Genet* 106:866–874. <https://doi.org/10.1007/S00122-002-1136-5>
- Cariappa AAG, Konath NC, Sapkota TB et al (2024) Evaluating the potential and eligibility of conservation agriculture practices for carbon credits. *Sci Rep* 14:1–13. <https://doi.org/10.1038/s41598-024-59262-6>
- Carroll CL, Carter CA, Goodhue RE et al (2018) A review of control options and externalities for verticillium wilts. *Phytopathology* 108:160–171. <https://doi.org/10.1094/PHYTO-03-17-0083-RVW>
- Champeil A, Fourbet JF, Doré T et al (2004) Influence of cropping system on fusarium head blight and mycotoxin levels in winter wheat. *Crop Prot* 23:531–537. <https://doi.org/10.1016/J.CROPRO.2003.10.011>
- Chauhan BS, Singh RG, Mahajan G (2012) Ecology and management of weeds under conservation agriculture: a review. *Crop Prot* 38:57–65. <https://doi.org/10.1016/J.CROPRO.2012.03.010>
- Chegin G, Mirnezami SV (2016) Experimental comparison of combine performance with two harvesting methods: stripper header and conventional header. *Agric Eng Int CIGR J* 18:192–200
- Chen B, Liu E, Tian Q et al (2014) Soil nitrogen dynamics and crop residues. A review. *Agron Sustain Dev* 34:429–442. <https://doi.org/10.1007/S13593-014-0207-8>
- Chen Y, Tessier S, Cavers C et al (2005) A survey of crop residue burning practices in Manitoba. *Appl Eng Agric* 21:317–323. <https://doi.org/10.13031/2013.18446>
- Chittem K, Khan MFR, Goswami RS (2016) Efficacy of precipitated calcium carbonate in managing fusarium root rot of field pea. *Phytoparasitica* 44:295–303. <https://doi.org/10.1007/S12600-016-0528-Z>
- Chun D, Lockwood JL (1985) Reductions of *Pythium ultimum*, *Thielaviopsis basicola*, and *Macrophomina phaseolina* in soil associated with ammonia generated from urea. *Plant Dis* 69:154–158
- Ciuffetti LM, Manning VA, Pandelova I et al (2014) *Pyrenophora tritici-repentis*: a plant pathogenic fungus with global impact. Genomics of plant-associated fungi: monocot pathogens. Springer, Berlin, pp 1–39. https://doi.org/10.1007/978-3-662-44053-7_1
- Clark RV, Gourley CO, Johnston HW et al (1975) Oat yield losses from Septoria leaf blotch at four locations in eastern Canada. *Can Plant Dis Surv* 55:36–43
- Cline LC, Zak DR (2015) Soil microbial communities are shaped by plant-driven changes in resource availability during secondary succession. *Ecology* 96:3374–3385. <https://doi.org/10.1890/15-0184.1>
- Clough Y, Kirchweber S, Kantelhardt J (2020) Field sizes and the future of farmland biodiversity in European landscapes. *Conserv Lett* 13:e12752. <https://doi.org/10.1111/conl.12752>
- Cobo-Díaz JF, Baroncelli R, Le Floch G et al (2019) Combined metabarcoding and co-occurrence network analysis to profile the bacterial, fungal and fusarium communities and their interactions in maize stalks. *Front Microbiol* 10:261. <https://doi.org/10.3389/fmicb.2019.00261>
- Coelli R, ABARES (2021) Natural Resource Management and Drought Resilience – survey of farm practices. <https://www.agriculture.gov.au/abares/research-topics/surveys/nrm-drought-resilience>. Accessed on 15 Sep 2026
- Condon G, Condon K, Swan T et al (2023) Fallow water impacts when harvesting with a draper front versus a stripper front in southern NSW. GRDC Update Papers, Grains Research and Development Corporation. <https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2023/07/fallow-water-impacts-when-harvesting-with-a-draper-front-versus-a-stripper-front-in-southern-nsw>. Accessed on 15 Sep 2026
- Conn KL, Lazarovits G (1999) Impact of animal manures on verticillium wilt, potato scab, and soil microbial populations. *Can J Plant Pathol* 21:81–92. <https://doi.org/10.1080/07060661.1999.10600089>
- Cook MJ, Edwards J, Rodoni B et al (2024) Grain yield and quality losses caused by tan spot in wheat cultivars in Australia. *PhytoFrontiers* 4:223–235. <https://doi.org/10.1094/PHYTO.FR-05-23-0063-R>
- Conservation Agriculture | Food and Agriculture Organization of the United Nations. <https://www.fao.org/conservation-agriculture/en/>. Accessed on 6 Apr 2026
- Corkley I, Fraaije B, Hawkins N (2022) Fungicide resistance management: Maximizing the effective life of plant protection products. *Plant Pathol* 71:150–169. <https://doi.org/10.1111/ppa.13467>
- Cowger C, McDonald BA, Mundt CC (2002) Frequency of sexual reproduction by *Mycosphaerella graminicola* on partially resistant wheat cultivars. *Phytopathology* 92:1175–1181. <https://doi.org/10.1094/PHYTO.2002.92.11.1175>
- Cutforth HW, Angadi SV, McConkey BG (2006) Stubble management and microclimate, yield and water use efficiency of canola grown in the semiarid Canadian prairie. *Can J Plant Sci* 86:99–107. <https://doi.org/10.4141/P05-073>
- Cutforth HW, McConkey B, Angadi S et al (2011) Extra-tall stubble can increase crop yield in the semiarid Canadian prairie. *Can J Plant Sci* 91:783–785. <https://doi.org/10.4141/cjps10168>
- Cutforth HW, McConkey BG, Ulrich D et al (2002) Yield and water use efficiency of pulses seeded directly into standing stubble in the semiarid Canadian prairie. *Can J Plant Sci* 82:681–686. <https://doi.org/10.4141/P01-111>
- da Luz SR, Pazdiora PC, Dallagnol LJ et al (2017) Mycotoxin and fungicide residues in wheat grains from fungicide-treated plants measured by a validated LC-MS method. *Food Chem* 220:510–516. <https://doi.org/10.1016/j.foodchem.2016.09.180>
- Dan X, He M, Meng L et al (2023) Strong rhizosphere priming effects on N dynamics in soils with higher soil N supply capacity: the ‘Matthew effect’ in plant-soil systems. *Soil Biol Biochem* 178:108949. <https://doi.org/10.1016/J.SOILBIO.2023.108949>
- de Faccio Carvalho PC, de Albuquerque Nunes PA, Pontes-Prates A et al (2021) Reconnecting Grazing Livestock to Crop Landscapes: Reversing Specialization Trends to Restore Landscape Multifunctionality. *Front Sustain Food Syst* 5:750765. <https://doi.org/10.3389/FSUFS.2021.750765>
- Derpsch R (1998) Historical review of no-tillage cultivation of crops. In: Proceedings, the 1st JIRCAS Seminar on Soybean Research. No-tillage Cultivation and Future Research Needs. JIRCAS Working Report, Iguassu Falls, Brazil
- Derpsch R, Franzluebbers AJ, Duiker SW et al (2014) Why do we need to standardize no-tillage research? *Soil Tillage Res* 137:16–22. <https://doi.org/10.1016/J.STILL.2013.10.002>
- Derpsch R, Friedrich T, Kassam A et al (2010) Current Status of Adoption of No-till Farming in the World and Some of its Main Benefits. *Int J Agric Biol Eng* 3:1–25. <https://doi.org/10.3965/J.ISSN.1934-6344.2010.01.0-0>
- Devêvre OC, Horwath WR (2000) Decomposition of rice straw and microbial carbon use efficiency under different soil temperatures and moistures. *Soil Biol Biochem* 32:1773–1785. [https://doi.org/10.1016/S0038-0717\(00\)00096-1](https://doi.org/10.1016/S0038-0717(00)00096-1)

- Dill-Macky R, Jones RK (2000) The Effect of Previous Crop Residues and Tillage on Fusarium Head Blight of Wheat. *Plant Dis* 84:71–76. <https://doi.org/10.1094/PDIS.2000.84.1.71>
- Dixon GR (2009) *Plasmodiophora brassicae* in its environment. *J Plant Growth Regul* 28:212–228. <https://doi.org/10.1007/S00344-009-9098-3>
- Doehlemann G, Ökmen B, Zhu W et al (2017) Plant pathogenic fungi. *Microbiol Spectr*. <https://doi.org/10.1128/microbiolspec.FUNK-0023-2016>
- Donmez E, Heckelet T, Storm H (2025) Satellite remote sensing-based crop cover classification over Europe: accuracy of different methodological approaches. *Int J Remote Sens* 46:8251–8294. <https://doi.org/10.1080/01431161.2025.2565837>
- Douglas CL, Allmaras RR, Rasmussen PE et al (1980) Wheat straw composition and placement effects on decomposition in dryland agriculture of the Pacific Northwest. *Soil Sci Soc Am J* 44:833–837. <https://doi.org/10.2136/SSSAJ1980.03615995004400040035X>
- Duczek LJ, Jones-Flory LL, Reed SL et al (2011) Sporulation of *Bipolaris sorokiniana* on the crowns of crop plants grown in Saskatchewan. *Can J Plant Sci* 76:861–867. <https://doi.org/10.4141/cjps96-146>
- Duczek LJ, Sutherland KA, Reed SL et al (1999) Survival of leaf spot pathogens on crop residues of wheat and barley in Saskatchewan. *Can J Plant Pathol* 21:165–173. <https://doi.org/10.1080/07060669909501208>
- Dugan FM, Lupien SL, Hernandez-Bello M et al (2005) Fungi resident in chickpea debris and their suppression of growth and reproduction of *Didymella rabiei* under laboratory conditions. *J Phytopathol* 153:431–439. <https://doi.org/10.1111/j.1439-0434.2005.00996.x>
- Eisner SA (2025) Investigating use of experimental evolution to improve biological control of the wheat pathogen *Zymoseptoria tritici*. PhD Thesis, ETH Zürich
- Eisner SA, Fiegna F, McDonald BA et al (2023) Bacterial predation of a fungal wheat pathogen: prelude to experimental evolution of enhanced biocontrol agents. *Plant Pathol* 72:1059–1068. <https://doi.org/10.1111/PPA.13716>
- Erenstein O, Sayre K, Wall P et al (2012) Conservation Agriculture in Maize- and Wheat-Based Systems in the (Sub)tropics: Lessons from Adaptation Initiatives in South Asia, Mexico, and Southern Africa. *J Sustain Agric* 36:180–206. <https://doi.org/10.1080/10440046.2011.620230>
- Eriksen L, Shaw MW, Østergård H (2001) A model of the effect of pseudotechia on genetic recombination and epidemic development in populations of *Mycosphaerella graminicola*. *Phytopathology* 91:240–248. <https://doi.org/10.1094/PHYTO.2001.91.3.240>
- Estep LK, Torriani SFF, Zala M et al (2015) Emergence and early evolution of fungicide resistance in North American populations of *Zymoseptoria tritici*. *Plant Pathol* 64:961–971. <https://doi.org/10.1111/PPA.12314>
- FAO (2025) Land statistics 2001–2023 – Global, regional and country trends. FAOSTAT Analytical Briefs. <https://doi.org/10.4060/CD5765EN>
- FAO (2023) Agricultural production statistics 2000–2022. FAOSTAT Analytical Briefs 79. <https://doi.org/10.4060/CC9205EN>
- Fatima A, Zahid A, Ali S et al (2025) Microbial consortia-mediated rice residue decomposition for eco-friendly management. *Sci Rep* 15:32381. <https://doi.org/10.1038/s41598-025-99613-5>
- Felton W, Freebairn D, Fettell N et al (1987) Crop residue management
- Filho AB, Inoue-Nagata AK, Bassanezi RB et al (2016) The importance of primary inoculum and area-wide disease management to crop health and food security. *Food Secur* 8:221–238. <https://doi.org/10.1007/s12571-015-0544-8>
- Fininsa C, Yuen J (2002) Temporal progression of bean common bacterial blight (*Xanthomonas campestris* pv. *phaseoli*) in sole and intercropping systems. *Eur J Plant Pathol* 108:485–495. <https://doi.org/10.1023/A:1019970308576>
- Fitt BDL, Brun H, Barbetti MJ et al (2006) World-wide importance of phoma stem canker (*Leptosphaeria maculans* and *L. biglobosa*) on oilseed rape (*Brassica napus*). *Eur J Plant Pathol* 114:3–15. <https://doi.org/10.1007/s10658-005-2233-5>
- Fiyaz RA, Shivani D, Chaithanya K et al (2022) Genetic improvement of rice for bacterial blight resistance: present status and future prospects. *Rice Sci* 29:118–132. <https://doi.org/10.1016/J.RSCI.2021.08.002>
- Foley JL, Silburn DM (2002) Hydraulic properties of rain impact surface seals on three clay soils—influence of rainfall impact frequency and rainfall intensity during steady state. *Aust J Soil Res* 40:1069–1083. <https://doi.org/10.1071/SR01112>
- Fones H, Gurr S (2015) The impact of *Septoria tritici* blotch disease on wheat: an EU perspective. *Fungal Genet Biol* 79:3–7. <https://doi.org/10.1016/J.FGB.2015.04.004>
- Foresto E, Carezzano ME, Giordano W et al (2023) Ascochyta blight in chickpea: an update. *J Fungi* 9:203. <https://doi.org/10.3390/JOF9020203>
- Fortune JA, Qi A, Ritchie F et al (2021) Effects of cultivar resistance and fungicide application on stem canker of oilseed rape (*Brassica napus*) and potential interseasonal transmission of *Leptosphaeria* spp. inoculum. *Plant Pathol* 70:2115–2124. <https://doi.org/10.1111/ppa.13453>
- Fox NM, Hwang SF, Manolli VP et al (2022) Evaluation of lime products for clubroot (*Plasmodiophora brassicae*) management in canola (*Brassica napus*) cropping systems. *Can J Plant Pathol* 44:21–38. <https://doi.org/10.1080/07060661.2021.1940590>
- Fraaije BA, Bayon C, Atkins S et al (2012) Risk assessment studies on succinate dehydrogenase inhibitors, the new weapons in the battle to control *Septoria* leaf blotch in wheat. *Mol Plant Pathol* 13:263–275. <https://doi.org/10.1111/J.1364-3703.2011.00746.X>
- Freebairn DM, Boughton WC (1981) Surface runoff experiments on the eastern Darling Downs. *Aust J Soil Res* 19:133–146. <https://doi.org/10.1071/SR9810133>
- Frei M (2013) Lignin: characterization of a multifaceted crop component. *Sci World J* 2013:436517. <https://doi.org/10.1155/2013/436517>
- Friberg H, Lagerlöf J, Rämert B (2005) Influence of soil fauna on fungal plant pathogens in agricultural and horticultural systems. *Biocontrol Sci Technol* 15:641–658. <https://doi.org/10.1080/09583150500086979>
- Friedrich T, Derpsch R, Kassam A et al (2012) Overview of the Global Spread of Conservation Agriculture. *Field Actions Sci Rep*
- Fu B, Chen L, Huang H et al (2021) Impacts of crop residues on soil health: a review. *Environ Pollut Bioavailab* 33:164–173. <https://doi.org/10.1080/26395940.2021.1948354>
- Garrett SD (1972) Factors affecting saprophytic survival of six species of cereal foot-rot fungi. *Trans Br Mycol Soc* 59:445–452. [https://doi.org/10.1016/S0007-1536\(72\)80125-6](https://doi.org/10.1016/S0007-1536(72)80125-6)
- Gaudin ACM, Tolhurst TN, Ker AP et al (2015) Increasing crop diversity mitigates weather variations and improves yield stability. *PLoS ONE* 10:e0113261. <https://doi.org/10.1371/JOURNAL.PONE.0113261>
- Geffersa AG, Burdon JJ, Macfadyen S et al (2023) The socio-economic challenges of managing pathogen evolution in agriculture. *Philos Trans R Soc Lond B Biol Sci* 378. <https://doi.org/10.1098/RSTB.2022.0012>
- Gill BS, Jalota SK (1996) Evaporation from soil in relation to residue rate, mixing depth, soil texture and evaporativity. *Soil Technol* 8:293–301. [https://doi.org/10.1016/0933-3630\(95\)00026-7](https://doi.org/10.1016/0933-3630(95)00026-7)
- Giller KE, Tittonell P, Rufino MC et al (2011) Communicating complexity: integrated assessment of trade-offs concerning soil

- fertility management within African farming systems to support innovation and development. *Agric Syst* 104:191–203. <https://doi.org/10.1016/J.AGSY.2010.07.002>
- Gilpatrick JD (1969) Role of ammonia in the control of avocado root rot with alfalfa meal soil amendment. *Phytopathology* 59:973–978
- Goncharov AA, Glebova AA, Tiunov AV (2020) Trophic interactions between *Fusarium* species and soil fauna: a meta-analysis of experimental studies. *Appl Soil Ecol* 145:103302. <https://doi.org/10.1016/J.APSOIL.2019.06.005>
- Gosende S, Penaud A, Aubertot JN et al (2003) Evolution of soil surface oilseed rape stubbles and their ability to produce spores of *Leptosphaeria maculans*: preliminary results. In: 11th International Rapeseed Congress, Proceedings, pp 1166–1168
- GRDC (2024) SDHI fungicide resistance detected in the blackleg fungus. Paddock Practices, Grains Research and Development Corporation. <https://grdc.com.au/resources-and-publications/all-publications/paddock-practices/2024/southern/december/sdhi-fungicide-resistance-detected-in-the-blackleg-fungus>. Accessed on 15 Sep 2026
- Gregory PJ, Simmonds LP, Pilbeam CJ (2000) Soil type, climatic regime, and the response of water use efficiency to crop management. *Agron J* 92:814–820. <https://doi.org/10.2134/AGRONJ2000.925814X>
- Gruber N, Galloway JN (2008) An Earth-system perspective of the global nitrogen cycle. *Nature* 451:293–296. <https://doi.org/10.1038/nature06592>
- Guo XW, Fernando WGD, Bullock P et al (2010) Quantifying cropping practices in relation to inoculum levels of *Fusarium graminearum* on crop stubble. *Plant Pathol* 59:1107–1113. <https://doi.org/10.1111/J.1365-3059.2010.02353.x>
- Gutteridge RJ, Hornby D, Hollins TW et al (1993) Take-all in autumn-sown wheat, barley, triticale and rye grown with high and low inputs. *Plant Pathol* 42:425–431. <https://doi.org/10.1111/J.1365-3059.1993.TB01521.X>
- Hall R (1992) Epidemiology of blackleg of oilseed rape. *Can J Plant Pathol* 14:46–55. <https://doi.org/10.1080/0706069209500905>
- Hardison JR (1974) Fire and disease. In: Proceedings, Annual Tall Timbers Fire Ecology Conference, pp 223–224
- He Z, Zhao W, Liu H et al (2012) The response of soil moisture to rainfall event size in subalpine grassland and meadows in a semi-arid mountain range: a case study in northwestern China's Qilian Mountains. *J Hydrol (Amst)* 420–421:183–190. <https://doi.org/10.1016/j.jhydrol.2011.11.056>
- Hershman DE, Perkins DM (1995) Etiology of canola blackleg in Kentucky and seasonal discharge patterns of *Leptosphaeria maculans* ascospores from infested canola stubble. *Plant Dis* 79:1225–1229. <https://doi.org/10.1094/PD-79-1225>
- Holland EA, Coleman DC (1987) Litter placement effects on microbial and organic matter dynamics in an agroecosystem. *Ecology* 68:425–433. <https://doi.org/10.2307/1939274>
- Holzleitner C, Gawlik T (2022) Carbon farming in the EU. *Food Sci Technol* 36:36–39. https://doi.org/10.1002/FSAT.3601_10.X
- Holzworth DP, Huth NI, deVoil PG et al (2014) APSIM – evolution towards a new generation of agricultural systems simulation. *Environ Model Softw* 62:327–350. <https://doi.org/10.1016/J.ENVSOFT.2014.07.009>
- Hosford RM Jr, Larez CR, Hammond JJ (1987) Interaction of wet period and temperature on *Pyrenophora tritici-repentis* infection and development in wheats of differing resistance. *Phytopathology* 77:1021–1027. <https://doi.org/10.1094/Phyto-77-1021>
- Howlett BJ (2004) Current knowledge of the interaction between *Brassica napus* and *Leptosphaeria maculans*. *Can J Plant Pathol* 26:245–252. <https://doi.org/10.1080/07060660409507141>
- Huang YJ, Mitrousis GK, Sidique SNM et al (2018) Combining R gene and quantitative resistance increases effectiveness of cultivar resistance against *Leptosphaeria maculans* in *Brassica napus* in different environments. *PLoS ONE* 13:e0197752. <https://doi.org/10.1371/JOURNAL.PONE.0197752>
- Hubbard VC, Jordan D (1996) Nitrogen recovery by corn from nitrogen-15 labeled wheat residues and intact roots and soil. *Soil Sci Soc Am J* 60:1405–1410. <https://doi.org/10.2136/sssaj1996.03615995006000050016x>
- Huber DM, Watson RD (1970) Effect of organic amendment on soil-borne plant pathogens. *Phytopathology* 60:22–26. <https://doi.org/10.1094/Phyto-60-22>
- Humpherson-Jones FM, Burchill RT (1982) Chemical suppression of the sexual stage of *Leptosphaeria maculans* on oil-seed rape and turnip seed crop straw. *Ann Appl Biol* 100:281–288. <https://doi.org/10.1111/J.1744-7348.1982.TB01940.X>
- Hunt JR, Browne C, McBeath TM et al (2013) Summer fallow weed control and residue management impacts on winter crop yield though soil water and N accumulation in a winter-dominant, low rainfall region of southern Australia. *Crop Pasture Sci* 64:922–934. <https://doi.org/10.1071/CP13237>
- Hunt JR, Lilley JM, Trevaskis B et al (2019) Early sowing systems can boost Australian wheat yields despite recent climate change. *Nat Clim Chang* 9:244–247. <https://doi.org/10.1038/s41558-019-0417-9>
- Hunter T, Coker RR, Royle DJ (1999) The teleomorph stage, *Mycosphaerella graminicola*, in epidemics of septoria tritici blotch on winter wheat in the UK. *Plant Pathol* 48:51–57. <https://doi.org/10.1046/j.1365-3059.1999.00310.x>
- Inch S, Gilbert J (2003) The incidence of *Fusarium* species recovered from inflorescences of wild grasses in southern Manitoba. *Can J Plant Pathol* 25:379–383. <https://doi.org/10.1080/07060660309507093>
- Innocenti G, Sabatini MA (2018) Collembola and plant pathogenic, antagonistic and arbuscular mycorrhizal fungi: a review. *Bull Insectol* 71:71–76
- Jones JP, Woltz SS (1969) *Fusarium* wilt (race 2) of tomato: calcium, pH, and micronutrient effects on disease development. *Plant Dis Rep* 53:276–279
- Ju C, Jiang F, Gao Y et al (2023) Effects of Fungicides and Nontarget Pesticides on Accumulation of the Mycotoxin Deoxynivalenol in Wheat. *Toxics* 11:768. <https://doi.org/10.3390/toxics11090768>
- Kabbage M, Bockus WW (2002) Effect of placement of inoculum of *Gaeumannomyces graminis* var. *tritici* on severity of take-all in winter wheat. *Plant Dis* 86:298–303. <https://doi.org/10.1094/PDIS.2002.86.3.298>
- Kaiser WJ (1973) Factors affecting growth, sporulation, pathogenicity, and survival of *Ascochyta rabiei*. *Mycologia* 65:444–457. <https://doi.org/10.1080/00275514.1973.12019452>
- Kara T, Sahin AD (2023) Implications of Climate Change on Wind Energy Potential. *Sustainability (Basel)* 15:14822. <https://doi.org/10.3390/SU152014822>
- Karlsson I, Friberg H, Steinberg C et al (2014) Fungicide Effects on Fungal Community Composition in the Wheat Phyllosphere. *PLoS ONE* 9:e111786. <https://doi.org/10.1371/JOURNAL.PONE.0111786>
- Kassam A, Friedrich T, Derpsch R (2019) Global spread of conservation agriculture. *Int J Environ Stud* 76:29–51. <https://doi.org/10.1080/00207233.2018.1494927>
- Kassam A, Friedrich T, Shaxson F et al (2009) The spread of conservation agriculture: justification, sustainability and uptake. *Int J Agric Sustain* 7:292–320. <https://doi.org/10.3763/IJAS.2009.0477>
- Kaur H (2019) Maintaining access to EU markets for Australian canola. CSIRO. https://www.csiro.au/-/media/About/Files/Impact-case-studies/Full-Reports/CSIRO_Aus-Canola---EU-market-access---Impact-Assessment-Jul-18_Final.pdf. Accessed on 15 Sep 2026
- Kaur M, Hüberli D, Bayliss KL (2020) Cold plasma: exploring a new option for management of postharvest fungal pathogens,

- mycotoxins and insect pests in Australian stored cereal grain. *Crop Pasture Sci* 71:715–724. <https://doi.org/10.1071/CP20078>
- Kaur M, Hüberli D, Bayliss KL (2022) A protocol for the use of cold plasma treatment to inhibit in vitro growth of *Fusarium graminearum*. *bioRxiv* 2022.05.23.493010. <https://doi.org/10.1101/2022.05.23.493010>
- Kaur M, Kowalczyk M, Hüberli D et al (2024) Postharvest blown-arc plasma treatment did not reduce *Fusarium graminearum* or its mycotoxins in field-infested wheat grain. *J Stored Prod Res* 108:102402. <https://doi.org/10.1016/j.jspr.2024.102402>
- Keating BA, Carberry PS, Hammer GL et al (2003) An overview of APSIM, a model designed for farming systems simulation. *Eur J Agron* 18:267–288. [https://doi.org/10.1016/S1161-0301\(02\)00108-9](https://doi.org/10.1016/S1161-0301(02)00108-9)
- Keck M, Hung DT (2018) Burn or bury? A comparative cost–benefit analysis of crop residue management practices among small-holder rice farmers in northern Vietnam. *Sustain Sci* 14:375–389. <https://doi.org/10.1007/S11625-018-0592-Z>
- Keller MD, Thomason WE, Schmale DG (2011) The spread of a released clone of *Gibberella zeae* from different amounts of infested corn residue. *Plant Dis* 95:1458–1464. <https://doi.org/10.1094/PDIS-03-11-0218>
- Keller MD, Waxman KD, Bergstrom GC et al (2010) Local distance of wheat spike infection by released clones of *Gibberella zeae* disseminated from infested corn residue. *Plant Dis* 94:1151–1155. <https://doi.org/10.1094/PDIS-94-9-1151>
- Kelly LA, Tan YP, Ryley MJ et al (2017) *Fusarium* species associated with stalk rot and head blight of grain sorghum in Queensland and New South Wales, Australia. *Plant Pathol* 66:1413–1423. <https://doi.org/10.1111/PPA.12697>
- Kerdraon L, Balesdent MH, Barret M et al (2019a) Crop residues in wheat–oilseed rape rotation system: a pivotal, shifting platform for microbial meetings. *Microb Ecol* 77:931–945. <https://doi.org/10.1007/S00248-019-01340-8>
- Kerdraon L, Barret M, Balesdent MH et al (2020) Impact of a resistance gene against a fungal pathogen on the plant host residue microbiome: the case of the *Leptosphaeria maculans*–*Brassica napus* pathosystem. *Mol Plant Pathol* 21:1545–1558. <https://doi.org/10.1111/MPP.12994>
- Kerdraon L, Barret M, Laval V et al (2019b) Differential dynamics of microbial community networks help identify microorganisms interacting with residue-borne pathogens: the case of *Zymoseptoria tritici* in wheat. *Microbiome* 7:1–17. <https://doi.org/10.1186/S40168-019-0736-0>
- Kerdraon L, Laval V, Suffert F (2019c) Microbiomes and pathogen survival in crop residues, an ecotone between plant and soil. *Phytobiomes J* 3:246–255. <https://doi.org/10.1094/PBIOMES-02-19-0010-RVV>
- Khalil I, Fanning J, Melloy P et al (2020) The role of conidia in the dispersal of *Ascochyta rabiei*. *Eur J Plant Pathol* 158:911–924. <https://doi.org/10.1007/s10658-020-02126-2>
- Khangura R, Speijers J, Barbetti MJ et al (2007) Epidemiology of blackleg (*Leptosphaeria maculans*) of canola (*Brassica napus*) in relation to maturation of pseudothecia and discharge of ascospores in Western Australia. *Phytopathology* 97:1011–1021. <https://doi.org/10.1094/PHYTO-97-8-1011>
- Khanna S, Mahajan K, Ramanujam S (2025) Are crop residue burning bans effective? Evidence from India. https://www.lse.ac.uk/granthaminstitute/wp-content/uploads/2025/07/working-paper_428_Khanna-et-al.pdf. Accessed on 15 Sep 2026
- Kirkby CA, Kirkegaard JA, Richardson AE et al (2011) Stable soil organic matter: a comparison of C:N:P:S ratios in Australian and other world soils. *Geoderma* 163:197–208. <https://doi.org/10.1016/J.GEODERMA.2011.04.010>
- Kirkby CA, Richardson AE, Wade LJ et al (2013) Carbon–nutrient stoichiometry to increase soil carbon sequestration. *Soil Biol Biochem* 60:77–86. <https://doi.org/10.1016/j.soilbio.2013.01.011>
- Kirkby CA, Richardson AE, Wade LJ et al (2016) Inorganic nutrients increase humification efficiency and C-sequestration in an annually cropped soil. *PLoS ONE* 11:e0153698. <https://doi.org/10.1371/JOURNAL.PONE.0153698>
- Kirkby CA, Richardson AE, Wade LJ et al (2014) Nutrient availability limits carbon sequestration in arable soils. *Soil Biol Biochem* 68:402–409. <https://doi.org/10.1016/j.soilbio.2013.09.032>
- 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. *Aust J Agric Res* 55:321–334. <https://doi.org/10.1071/AR03178>
- Kladivko EJ, Unger PW (1994) Residue effects on soil physical properties. In: Unger PW (ed) *Managing Agricultural Residues*. Lewis Publishers, Boca Raton, USA, pp 123–141
- Klein TA, Summerell BA, Burgess LW (1988) Influence of stubble-management practices on crown rot of wheat. *Plant Prot Q* 3:10–11
- Klinner WE, Neale MA, Arnold RE et al (1987) A new concept in combine harvester headers. *J Agric Eng Res* 38:37–45. [https://doi.org/10.1016/0021-8634\(87\)90137-5](https://doi.org/10.1016/0021-8634(87)90137-5)
- Klopp HW, Blanco-Canqui H (2022) Implications of crop residue removal on soil physical properties: a review. *Soil Sci Soc Am J* 86:979–1001. <https://doi.org/10.1002/SAJ2.20418>
- Knight NL, Sutherland MW (2017) Assessment of *Fusarium pseudograminearum* and *F. culmorum* biomass in seedlings of potential host cereal species. *Plant Dis* 101:2116–2122. <https://doi.org/10.1094/PDIS-12-16-1739-RE>
- Knorr K, Jørgensen LN, Nicolaisen M (2019) Fungicides have complex effects on the wheat phyllosphere microbiome. *PLoS ONE* 14:e0213176. <https://doi.org/10.1371/JOURNAL.PONE.0213176>
- Ko WH, Hora FK, Herlicska E (1974) Isolation and identification of a volatile fungistatic substance from alkaline soil. *Phytopathology* 64:1398–1400. <https://doi.org/10.1094/Phyto-64-1398>
- Krakowsky MD, Lee M, Coors JG (2005) Quantitative trait loci for cell wall components in recombinant inbred lines of maize (*Zea mays* L.) II: leaf sheath tissue. *Theor Appl Genet* 112:717–726. <https://doi.org/10.1007/S00122-005-0175-0>
- Krupinsky JM, Bailey KL, McMullen MP et al (2002) Managing plant disease risk in diversified cropping systems. *Agron J* 94:198–209. <https://doi.org/10.2134/AGRONJ2002.1980>
- Kutcher HR, Malhi SS (2010) Residue burning and tillage effects on diseases and yield of barley (*Hordeum vulgare*) and canola (*Brassica napus*). *Soil Tillage Res* 109:153–160. <https://doi.org/10.1016/j.still.2010.06.001>
- Kuzyakov Y, Xu X (2013) Competition between roots and microorganisms for nitrogen: mechanisms and ecological relevance. *New Phytol* 198:656–669. <https://doi.org/10.1111/NPH.12235>
- Kwak YS, Weller DM (2013) Take-all of wheat and natural disease suppression: a review. *Plant Pathol J* 29:125. <https://doi.org/10.5423/PPJ.SI.07.2012.0112>
- Lakshar DPS, Backhouse D, Kristiansen P (2010) Nutritional constraints on displacement of *Fusarium pseudograminearum* from cereal straw by antagonists. *Biol Control* 55:241–247. <https://doi.org/10.1016/j.biocontrol.2010.09.002>
- Lal R (2005) World crop residues production and implications of its use as a biofuel. *Environ Int* 31:575–584. <https://doi.org/10.1016/J.ENVINT.2004.09.005>
- Lavrukaitė K, Almodad M, Ramanauskienė J et al (2024) Sensitivity of Lithuanian *Zymoseptoria tritici* to Quinone Outside Inhibitor and Succinate Dehydrogenase Inhibitor Fungicides.

- Agronomy (Basel) 14:813. <https://doi.org/10.3390/AGRONOMY14040813>
- Lawes RA, Roche R, Darbyshire RO et al (2025) Contrasting trends in wheat production exist across Australia in response to climate. *Eur J Agron* 171:127785. <https://doi.org/10.1016/J.EJA.2025.127785>
- Lazarovits G, Conn KL, Potter J (1999) Reduction of potato scab, verticillium wilt, and nematodes by soymeal and meat and bone meal in two Ontario potato fields. *Can J Plant Pathol* 21:345–353. <https://doi.org/10.1080/07060669909501170>
- Leplat J, Friberg H, Abid M et al (2013) Survival of *Fusarium graminearum*, the causal agent of *Fusarium* head blight. A Review. *Agron Sustain Dev* 33:97–111. <https://doi.org/10.1007/S13593-012-0098-5>
- Leslie J, Pearson C, Nelson P et al (1990) *Fusarium* spp. from corn, sorghum, and soybean fields in the central and eastern United States. *Phytopathology* 80:343–350. <https://doi.org/10.1094/Phyto-80-343>
- Levy Y, Pataky JK (1992) Epidemiology of northern leaf blight on sweet corn. *Phytoparasitica* 20:53–66. <https://doi.org/10.1007/BF02995636>
- Lewis WJ, Van Lenteren JC, Phatak SC et al (1997) A total system approach to sustainable pest management. *Proc Natl Acad Sci U S A* 94:12243–12248. <https://doi.org/10.1073/PNAS.94.23.12243>
- Li H, Sivasithamparam K, Barbetti MJ (2007) Soilborne ascospores and pycnidiospores of *Leptosphaeria maculans* can contribute significantly to blackleg disease epidemiology in oilseed rape (*Brassica napus*) in Western Australia. *Australas Plant Pathol* 36:439–444. <https://doi.org/10.1071/AP07048>
- Li Y, Li Z, Chang SX et al (2020) Residue retention promotes soil carbon accumulation in minimum tillage systems: implications for conservation agriculture. *Sci Total Environ* 740:140147. <https://doi.org/10.1016/j.scitotenv.2020.140147>
- Li Z, Shen Y, Zhang W et al (2023) Effects of long-term straw returning on rice yield and soil properties and bacterial community in a rice-wheat rotation system. *Field Crops Res* 291:108800. <https://doi.org/10.1016/J.FCR.2022.108800>
- Lin M, Begho T (2022) Crop residue burning in South Asia: a review of the scale, effect, and solutions with a focus on reducing reactive nitrogen losses. *J Environ Manage* 314:115104. <https://doi.org/10.1016/J.JENVMAN.2022.115104>
- Lô-Pelzer E, Aubertot JN, David O et al (2009) Relationship between severity of blackleg (*Leptosphaeria maculans*/L. *biglobosa* species complex) and subsequent primary inoculum production on oilseed rape stubble. *Plant Pathol* 58:61–70. <https://doi.org/10.1111/J.1365-3059.2008.01931.X>
- Lukas S, Abbas SJ, Karlovsky P et al (2014) Substrate use and survival of fungal plant pathogens on maize residues at winter temperatures around freezing point. *Soil Biol Biochem* 77:141–149. <https://doi.org/10.1016/J.SOILBIO.2014.06.023>
- Lupwayi NZ, Clayton GW, O'Donovan JT et al (2004) Decomposition of crop residues under conventional and zero tillage. *Can J Soil Sci* 84:403–410. <https://doi.org/10.4141/S03-082>
- Lupwayi NZ, Turkington TK, Tidemann BD et al (2024) Crop rotation and fungicides impact microbial biomass, diversity and enzyme activities in the wheat rhizosphere. *Front Agron* 6:1455448. <https://doi.org/10.3389/FAGRO.2024.1455448>
- Lutsko NJ (2021) The relative contributions of temperature and moisture to heat stress changes under warming. *J Clim* 34:901–917. <https://doi.org/10.1175/JCLI-D-20-0262.1>
- Macmillan A (1956) The entry of ammonia into fungal cells. *J Exp Bot* 7:113–126. <https://doi.org/10.1093/JXB/7.1.113>
- Mahaffee WF, Margairaz F, Ulmer L et al (2023) Catching spores: linking epidemiology, pathogen biology, and physics to ground-based airborne inoculum monitoring. *Plant Dis* 107:13–33. <https://doi.org/10.1094/PDIS-11-21-2570-FE>
- Marcroft SJ, Sprague SJ, Pymmer SJ et al (2004a) Crop isolation, not extended rotation length, reduces blackleg (*Leptosphaeria maculans*) severity of canola (*Brassica napus*) in south-eastern Australia. *Aust J Exp Agric* 44:601–606. <https://doi.org/10.1071/EA03087>
- Marcroft SJ, Sprague SJ, Pymmer SJ et al (2003) Factors affecting production of inoculum of the blackleg fungus (*Leptosphaeria maculans*) in south-eastern Australia. *Aust J Exp Agric* 43:1231–1236. <https://doi.org/10.1071/EA02117>
- Marcroft SJ, Sprague SJ, Salisbury PA et al (2004b) Potential for using host resistance to reduce production of pseudothecia and ascospores of *Leptosphaeria maculans*, the blackleg pathogen of *Brassica napus*. *Plant Pathol* 53:468–474. <https://doi.org/10.1111/J.1365-3059.2004.01050.X>
- Mariani RO, Cadotte MW, Isaac ME et al (2021) National-scale changes in crop diversity through the Anthropocene. *Sci Rep* 11:20361. <https://doi.org/10.1038/s41598-021-99728-5>
- Martin AR, Cadotte MW, Isaac ME et al (2019) Regional and global shifts in crop diversity through the Anthropocene. *PLoS ONE* 14:e0209788. <https://doi.org/10.1371/JOURNAL.PONE.0209788>
- Mathre DE (ed) (1997) Compendium of Barley Diseases, 2nd edn. APS Press, St Paul, MN
- Mawalagedera SMMR, Fanning JP, Fromm MR et al (2022) Lower severity of ascochyta blight and higher grain yields from chickpeas sown into standing cereal stubble compared to slashed stubble. In: Proceedings of the 20th Agronomy Australia Conference, Toowoomba, QLD
- McCarty JL (2011) Remote sensing-based estimates of annual and seasonal emissions from crop residue burning in the contiguous United States. *J Air Waste Manage Assoc* 61:22–34. <https://doi.org/10.3155/1047-3289.61.1.22>
- McCool DK, Pannkuk CD, Kennedy AC et al (2008) Effects of burn/low-till on erosion and soil quality. *Soil Tillage Res* 101:2–9. <https://doi.org/10.1016/J.STILL.2008.05.007>
- McCredden J, Cowley RB, Marcroft SJ et al (2018) Changes in farming practices impact on spore release patterns of the blackleg pathogen, *Leptosphaeria maculans*. *Crop Pasture Sci* 69:1–8. <https://doi.org/10.1071/CP16404>
- McDonald BA, Linde C (2002) Pathogen population genetics, evolutionary potential, and durable resistance. *Annu Rev Phytopathol* 40:349–379. <https://doi.org/10.1146/ANNUREV.PHYTO.40.120501.101443>
- McDonald BA, Suffert F, Bernasconi A et al (2022) How large and diverse are field populations of fungal plant pathogens? The case of *Zymoseptoria tritici*. *Evol Appl* 15:1360–1373. <https://doi.org/10.1111/eva.13434>
- McGee DC (1977) Black leg (*Leptosphaeria maculans* (Desm.) Ces. de Not.) of rapeseed in Victoria: sources of infection and relationships between inoculum, environmental factors and disease severity. *Aust J Agric Res* 28:53–62. <https://doi.org/10.1071/AR9770053>
- McGuire KL, Bent E, Borneman J et al (2010) Functional diversity in resource use by fungi. *Ecology* 91:2324–2332. <https://doi.org/10.1890/09-0654.1>
- Meng X, Meng F, Chen P et al (2024) A meta-analysis of conservation tillage management effects on soil organic carbon sequestration and soil greenhouse gas flux. *Sci Total Environ* 954:176315. <https://doi.org/10.1016/J.SCITOTENV.2024.176315>
- Messéan A, Viguier L, Paresys L et al (2021) Enabling crop diversification to support transitions toward more sustainable European agrifood systems. *Front Agric Sci Eng* 8:474. <https://doi.org/10.15302/J-FASE-2021406>

- Meyer C, Jeanbille M, Breuil MC et al (2024) Soil microbial community fragmentation reveals indirect effects of fungicide exposure mediated by biotic interactions between microorganisms. *J Hazard Mater* 470:134231. <https://doi.org/10.1016/j.jhazmat.2024.134231>
- Meyer M, Diehl D, Schaumann GE et al (2021) Agricultural mulching and fungicides—impacts on fungal biomass, mycotoxin occurrence, and soil organic matter decomposition. *Environ Sci Pollut Res Int* 28:36535. <https://doi.org/10.1007/s11356-021-13280-3>
- Mian IH, Rodriguez-Kabana R (1982) Organic amendments with high tannin and phenolic contents for control of *Meloidogyne arenaria* in infested soil. *Nematropica* 12:221–234
- Miller JD, Culley J, Fraser K et al (1998) Effect of tillage practice on fusarium head blight of wheat. *Can J Plant Pathol* 20:95–103. <https://doi.org/10.1080/07060669809500450>
- Minasny B, Malone BP, McBratney AB et al (2017) Soil carbon 4 per mille. *Geoderma* 292:59–86. <https://doi.org/10.1016/j.geoderma.2017.01.002>
- Mitrousis GK, Huang YJ, Qi A et al (2018) Effectiveness of Rlm7 resistance against *Leptosphaeria maculans* (phoma stem canker) in UK winter oilseed rape cultivars. *Plant Pathol* 67:1339–1353. <https://doi.org/10.1111/PPA.12845>
- Monzon JP, Sadras VO, Andrade FH (2006) Fallow soil evaporation and water storage as affected by stubble in sub-humid (Argentina) and semi-arid (Australia) environments. *Field Crops Res* 98:83–90. <https://doi.org/10.1016/J.FCR.2005.12.010>
- Moore KJ, Cook RJ (1984) Increased take-all of wheat with direct drilling in the Pacific Northwest. *Phytopathology* 74:1044–1049. <https://doi.org/10.1094/Phyto-74-1044>
- Morais D, Gélisse S, Laval V et al (2016a) Inferring the origin of primary inoculum of *Zymoseptoria tritici* from differential adaptation of resident and immigrant populations to wheat cultivars. *Eur J Plant Pathol* 145:393–404. <https://doi.org/10.1007/S10658-015-0853-Y>
- Morais D, Sache I, Suffert F et al (2016b) Is the onset of septoria tritici blotch epidemics related to the local pool of ascospores? *Plant Pathol* 65:250–260. <https://doi.org/10.1111/ppa.12408>
- Moritsuka N, Yanai J, Mori K et al (2004) Biotic and abiotic processes of nitrogen immobilization in the soil-residue interface. *Soil Biol Biochem* 36:1141–1148. <https://doi.org/10.1016/J.SOILBIO.2004.02.024>
- Mortensen DA, Smith RG (2020) Confronting barriers to cropping system diversification. *Front Sustain Food Syst* 4:564197. <https://doi.org/10.3389/FSUFS.2020.564197>
- Murphy RP, Montes-Molina JA, Govaerts B et al (2016) Crop residue retention enhances soil properties and nitrogen cycling in smallholder maize systems of Chiapas, Mexico. *Appl Soil Ecol* 103:110–116. <https://doi.org/10.1016/j.apsoil.2016.03.014>
- Murray GM, Brennan JP (2010) Estimating disease losses to the Australian barley industry. *Australas Plant Pathol* 39:85–96. <https://doi.org/10.1071/AP09064>
- Murray GM, Brennan JP (2009) Estimating disease losses to the Australian wheat industry. *Australas Plant Pathol* 38:558–570. <https://doi.org/10.1071/AP09053>
- Nalley L, Tsioboe F, Durand-Morat A et al (2016) Economic and Environmental Impact of Rice Blast Pathogen (*Magnaporthe oryzae*) Alleviation in the United States. *PLoS ONE* 11:e0167295. <https://doi.org/10.1371/JOURNAL.PONE.0167295>
- Natural Resources Conservation Service (2023) The Economics of Stripper Header and Disc Drill Adoption. <https://www.nrcs.usda.gov/sites/default/files/2023-11/Montana-Economics-of-Stripper-Header-and-Disc-Drill-Adoption.pdf>. Accessed on 15 Sep 2026
- Newlands NK (2018) Model-based forecasting of agricultural crop disease risk at the regional scale, integrating airborne inoculum, environmental, and satellite-based monitoring data. *Front Environ Sci* 6:356467. <https://doi.org/10.3389/fenvs.2018.00063>
- Nicolardot B, Bouziri L, Bastian F et al (2007) A microcosm experiment to evaluate the influence of location and quality of plant residues on residue decomposition and genetic structure of soil microbial communities. *Soil Biol Biochem* 39:1631–1644. <https://doi.org/10.1016/j.soilbio.2007.01.012>
- Niones JT, Sharp RT, Donayre DKM et al (2022) Dynamics of bacterial blight disease in resistant and susceptible rice varieties. *Eur J Plant Pathol* 163:1–17. <https://doi.org/10.1007/S10658-021-02452-Z>
- Niwa R, Nomura Y, Osaki M et al (2008) Suppression of clubroot disease under neutral pH caused by inhibition of spore germination of *Plasmodiophora brassicae* in the rhizosphere. *Plant Pathol* 57:445–452. <https://doi.org/10.1111/J.1365-3059.2007.01817.X>
- Nnadi NE, Carter DA (2021) Climate change and the emergence of fungal pathogens. *PLoS Pathog* 17:e1009503. <https://doi.org/10.1371/JOURNAL.PPAT.1009503>
- Norton R, Kirkegaard J, Angus J et al (1999) Canola in rotations. In: *GCIRC Proceedings*. <https://www.regional.org.au/au/gcirk/canola/p-06.htm>. Accessed on 15 Sep 2026
- Oerke EC (2006) Crop losses to pests. *J Agric Sci* 144:31–43. <https://doi.org/10.1017/S0021859605005708>
- Ogle SM, Alsaker C, Baldock J et al (2019) Climate and Soil Characteristics Determine Where No-Till Management Can Store Carbon in Soils and Mitigate Greenhouse Gas Emissions. *Sci Rep* 9:11665. <https://doi.org/10.1038/S41598-019-47861-7>
- O’Gorman PA (2015) Precipitation extremes under climate change. *Curr Clim Change Rep* 1:49–59. <https://doi.org/10.1007/s40641-015-0009-3>
- Orellana-Torrejon C, Vidal T, Gazeau G et al (2022a) Multiple scenarios for sexual crosses in the fungal pathogen *Zymoseptoria tritici* on wheat residues: potential consequences for virulence gene transmission. *Fungal Genet Biol* 163:103744. <https://doi.org/10.1016/j.fgb.2022.103744>
- Orellana-Torrejon C, Vidal T, Saint-Jean S et al (2022b) The impact of wheat cultivar mixtures on virulence dynamics in *Zymoseptoria tritici* populations persists after interseason sexual reproduction. *Plant Pathol* 71:1537–1549. <https://doi.org/10.1111/ppa.13577>
- Osono T (2007) Ecology of ligninolytic fungi associated with leaf litter decomposition. *Ecol Res* 22:955–974. <https://doi.org/10.1007/S11284-007-0390-Z>
- Ou SH (1985) *Rice Diseases*, 2nd edn. Commonwealth Mycological Institute, Kew. ISBN 978-0-85198-545-9
- Palm C, Blanco-Canqui H, DeClerck F et al (2014) Conservation agriculture and ecosystem services: an overview. *Agric Ecosyst Environ* 187:87–105. <https://doi.org/10.1016/j.agee.2013.10.010>
- Pan S, Qiao J, Wang R et al (2022) Intelligent diagnosis of northern corn leaf blight with deep learning model. *J Integr Agric* 21:1094–1105. [https://doi.org/10.1016/S2095-3119\(21\)63707-3](https://doi.org/10.1016/S2095-3119(21)63707-3)
- Pasut C, Li M, Armour B et al (2026) Integrating soil monitoring and machine learning to map historical tillage and stubble management across Australian cropping systems (2001–2023). *Comput Electron Agric* 243:111408. <https://doi.org/10.1016/j.compag.2026.111408>
- Paul PA, El-Allaf SM, Lipps PE et al (2005) Relationships between incidence and severity of *Fusarium* head blight on winter wheat in Ohio. *Phytopathology* 95:1049–1060. <https://doi.org/10.1094/PHYTO-95-1049>
- Peluola C, Fernando WGD, Huvenaars C et al (2013) Effect of flooding on the survival of *Leptosphaeria* spp. in canola stubble. *Plant Pathol* 62:1350–1356. <https://doi.org/10.1111/ppa.12036>
- Pepe M, Pompilio L, Ranghetti L et al (2023) Mapping spatial distribution of crop residues using PRISMA satellite imaging spectroscopy. *Eur J Remote Sens* 56:2122872. <https://doi.org/10.1080/22797254.2022.2122872>
- Pereyra SA, Dill-Macky R (2008) Colonization of the residues of diverse plant species by *Gibberella zeae* and their contribution

- to *Fusarium* head blight inoculum. *Plant Dis* 92:800–807. <https://doi.org/10.1094/PDIS-92-5-0800>
- Pereyra SA, Dill-Macky R, Sims AL (2004) Survival and inoculum production of *Gibberella zeae* in wheat residue. *Plant Dis* 88:724–730. <https://doi.org/10.1094/PDIS.2004.88.7.724>
- Petrie GA (1995) Long-term survival and sporulation of *Leptosphaeria maculans* (blackleg) on naturally-infected rapeseed/canola stubble in Saskatchewan. *Can Plant Dis Surv* 75:23–34
- Petronaitis T, Forknall C, Brodie G et al (2022a) “Killer joules”: spores of *Bipolaris sorokiniana* and *Fusarium* species are susceptible to microwave radiation. *Australas Plant Pathol* 51:433–440. <https://doi.org/10.1007/s13313-022-00872-X>
- Petronaitis T, Forknall C, Simpfendorfer S et al (2025) Taking shortcuts: lowering harvest height to restrict colonization of cereal stubble by *Fusarium pseudograminearum*. *Crop Pasture Sci* 76. <https://doi.org/10.1071/CP24365>
- Petronaitis T, Forknall C, Simpfendorfer S et al (2022b) Stubble trouble! Moisture, pathogen fitness and cereal type drive colonization of cereal stubble by three fungal pathogens. *Australas Plant Pathol* 51:363–368. <https://doi.org/10.1007/s13313-022-00860-1>
- Petronaitis T, Forknall C, Simpfendorfer S (2018) Microwave radiation reduces survival of *Fusarium pseudograminearum* in durum wheat stubble. *Australas Plant Pathol* 47:375–378. <https://doi.org/10.1007/s13313-018-0568-6>
- Petronaitis T, Geffersa AG, Zakeel MCM (2026) Innovations for sustainable crop protection: application of microwaves for stubble and soilborne disease management. *Eur J Plant Pathol*. <https://doi.org/10.1007/s10658-026-03182-w>
- Pfender WF, Wootke SL (1988) Microbial communities of Pyrenophora-infested wheat straw as examined by multivariate analysis. *Microb Ecol* 15:95–113. <https://doi.org/10.1007/BF02012954>
- Pook M, Lisson S, Risbey J et al (2009) The autumn break for cropping in southeast Australia: trends, synoptic influences and impacts on wheat yield. *Int J Climatol* 29:2012–2026. <https://doi.org/10.1002/JOC.1833>
- Poole GJ, Harries M, Hüberli D et al (2015) Predicting cereal root disease in Western Australia using soil DNA and environmental parameters. *Phytopathology* 105:1069–1079. <https://doi.org/10.1094/PHYTO-07-14-0203-R>
- Potapov P, Turubanova S, Hansen MC et al (2021) Global maps of cropland extent and change show accelerated cropland expansion in the twenty-first century. *Nat Food* 3:19–28. <https://doi.org/10.1038/s43016-021-00429-z>
- Prestele R, Hirsch AL, Davin EL et al (2018) A spatially explicit representation of conservation agriculture for application in global change studies. *Glob Chang Biol* 24:4038–4053. <https://doi.org/10.1111/GCB.14307>
- Probert ME, Dimes JP, Keating BA et al (1998) APSIM's water and nitrogen modules and simulation of the dynamics of water and nitrogen in fallow systems. *Agric Syst* 56:1–28. [https://doi.org/10.1016/S0308-521X\(97\)00028-0](https://doi.org/10.1016/S0308-521X(97)00028-0)
- Ranaivoson L, Naudin K, Ripoche A et al (2017) Agro-ecological functions of crop residues under conservation agriculture. A Review. *Agron Sustain Dev* 37:26. <https://doi.org/10.1007/S13593-017-0432-Z>
- Reddy PN, Kumari JA, Mounika C et al (2026) Characterization and dynamics of lignocellulosic components, enzyme activities and microbial populations in diverse crop residues during decomposition. *Sci Rep* 16:6560. <https://doi.org/10.1038/s41598-026-37886-0>
- Rees RG, Platz GJ (1979) The occurrence and control of yellow spot of wheat in north-eastern Australia. *Aust J Exp Agric Anim Husbandry* 19:369–372. <https://doi.org/10.1071/EA9790369>
- Rhoton FE, Shipitalo MJ, Lindbo DL (2002) Runoff and soil loss from Midwestern and Southeastern US silt loam soils as affected by tillage practice and soil organic matter content. *Soil Tillage Res* 66:1–11. [https://doi.org/10.1016/S0167-1987\(02\)00005-3](https://doi.org/10.1016/S0167-1987(02)00005-3)
- Riedo J, Yokota A, Walther B et al (2023) Temporal dynamics of total and bioavailable fungicide concentrations in soil and their effect upon nine soil microbial markers. *Sci Total Environ* 878. <https://doi.org/10.1016/j.scitotenv.2023.162995>
- Rimbaud L, Fabre F, Papaix J et al (2021) Models of plant resistance deployment. *Annu Rev Phytopathol* 59:125–152. <https://doi.org/10.1146/ANNUREV-PHYTO-020620-122134>
- Rimbaud L, Papaix J, Rey JF et al (2018) Assessing the durability and efficiency of landscape-based strategies to deploy plant resistance to pathogens. *PLoS Comput Biol* 14:e1006067. <https://doi.org/10.1371/JOURNAL.PCBL.1006067>
- Rogers CDW, Ting M, Li C et al (2021) Recent Increases in Exposure to Extreme Humid-Heat Events Disproportionately Affect Populated Regions. *Geophys Res Lett* 48. <https://doi.org/10.1029/2021GL094183>
- Rothrock CS, Kirkpatrick TL, Frans RE et al (1995) The influence of winter legume cover crops on soilborne plant pathogens and cotton seedling diseases. *Plant Dis* 79:167–171. <https://doi.org/10.1094/PD-79-0167>
- Rowińska P, Gutarowska B, Janas R et al (2024) Biopreparations for the decomposition of crop residues. *Microb Biotechnol* 17:e14534. <https://doi.org/10.1111/1751-7915.14534>
- Rush CM, Lyda SD (1982) The effects of anhydrous ammonia on membrane stability of *P.hymatotrichum omnivorum*. *Mycopathologia* 79:147–152. <https://doi.org/10.1007/BF01837194>
- Salmon S, Vittier T, Barot S et al (2021) Responses of Collembola communities to mixtures of wheat varieties: a trait-based approach. *Pedobiologia* (Jena) 87–88:150755. <https://doi.org/10.1016/J.PEDOB.2021.150755>
- Sato H, Ando I, Hirabayashi H et al (2008) QTL analysis of brown spot resistance in rice (*Oryza sativa* L.). *Breed Sci* 58:93–96. <https://doi.org/10.1270/JSBBS.58.93>
- Savary S, Willocquet L, Elazegui FA et al (2000) Rice pest constraints in tropical Asia: characterization of injury profiles in relation to production situations. *Plant Dis* 84:341–356. <https://doi.org/10.1094/PDIS.2000.84.3.341>
- Savary S, Willocquet L, Pethybridge SJ et al (2019) The global burden of pathogens and pests on major food crops. *Nat Ecol Evol* 3:430–439. <https://doi.org/10.1038/s41559-018-0793-y>
- Schippers B, Meijer JW, Liem JI (1982) Effect of ammonia and other soil volatiles on germination and growth of soil fungi. *Trans Br Mycol Soc* 79:253–259. [https://doi.org/10.1016/S0007-1536\(82\)80111-3](https://doi.org/10.1016/S0007-1536(82)80111-3)
- Schlatter D, Kinkel L, Thomashow L et al (2017) Disease suppressive soils: new insights from the soil microbiome. *Phytopathology* 107:1284–1297. <https://doi.org/10.1094/PHYTO-03-17-0111-RVW>
- Schlegel A, Haag L, Assefa Y et al (2023) Wheat stubble height effects on subsequent corn and grain sorghum crops. *Crop Sci* 63:1494–1507. <https://doi.org/10.1002/CSC2.20890>
- Schoeny A, Jumel S, Rouault F et al (2010) Effect and underlying mechanisms of pea-cereal intercropping on the epidemic development of ascochyta blight. *Eur J Plant Pathol* 126:317–331. <https://doi.org/10.1007/S10658-009-9548-6>
- Scott BJ, Eberbach PL, Evans J et al (2010) Stubble retention in cropping systems in southern Australia: benefits and challenges. Industry and Investment NSW, Orange, NSW
- Secretaría de Agricultura Ganadería y Pesca Datos Agricultura, Ganadería y Pesca. <https://datos.magyp.gob.ar/>. Accessed on 18 Sep 2025

- Seneviratne SI, Zhang X, Adnan M et al (2021) Weather and climate extreme events in a changing climate. In: Climate Change 2021: The Physical Science Basis. Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp 1513–1766. <https://doi.org/10.1017/9781009157896.013>
- Sherman J, Burke JM, Gent DH (2019) Cooperation and Coordination in Plant Disease Management. *Phytopathology* 109:1720–1731. <https://doi.org/10.1094/PHYTO-01-19-0010-R>
- Shiau FL, Chung WC, Huang JW et al (1999) Organic amendment of commercial culture media for improving control of *Rhizoctonia* damping-off of cabbage. *Can J Plant Pathol* 21:368–374. <https://doi.org/10.1080/07060669909501173>
- Sidique SNM (2016) Effects of Host Resistance on Colonisation of *Brassica napus* (Oilseed Rape) by *Leptosphaeria maculans* and *Leptosphaeria biglobosa* (Phoma Stem Canker). PhD Thesis, University of Hertfordshire. <https://uhra.herts.ac.uk/handle/2299/17221>
- Simpfendorfer S, McKay A, Ophel-Keller K (2020) New approaches to crop disease management in conservation agriculture. *Australian agriculture in 2020: from conservation to automation*. Agronomy Australia, pp 173–188
- Singh R, Kumar K, Purayannur S et al (2022) *Ascochyta rabiei*: a threat to global chickpea production. *Mol Plant Pathol* 23:1241–1261. <https://doi.org/10.1111/MPP.13235>
- Smil V (1999) Crop residues: agriculture's largest harvest. *Biosci* 49:299–308. <https://doi.org/10.2307/1313613>
- Smiley RW, Gourlie JA, Easley SA et al (2005) Crop damage estimates for crown rot of wheat and barley in the Pacific Northwest. *Plant Dis* 89:595–604. <https://doi.org/10.1094/PD-89-0595>
- Smiley RW, Machado S (2019) *Fusarium* crown rot of winter wheat influenced by resource competition near a tree windbreak. *Plant Dis* 104:348–357. <https://doi.org/10.1094/PDIS-01-19-0213-RE>
- Smith EG, Kutcher HR, Brandt SA et al (2013) The profitability of short-duration canola and pea rotations in western Canada. *Can J Plant Sci* 93:933–940. <https://doi.org/10.4141/CJPS2013-021>
- Smith ME, Vico G, Costa A et al (2023) Increasing crop rotational diversity can enhance cereal yields. *Commun Earth Environ* 4:89. <https://doi.org/10.1038/s43247-023-00746-0>
- Smith R, Adams M, Maier S et al (2007) Estimating the area of stubble burning from the number of active fires detected by satellite. *Remote Sens Environ* 109:95–106. <https://doi.org/10.1016/j.rse.2006.12.011>
- Soane BD, Ball BC, Arvidsson J et al (2012) No-till in northern, western and south-western Europe: a review of problems and opportunities for crop production and the environment. *Soil Tillage Res* 118:66–87. <https://doi.org/10.1016/J.STILL.2011.10.015>
- Sommerhalder RJ, McDonald BA, Mascher F et al (2011) Effect of hosts on competition among clones and evidence of differential selection between pathogenic and saprophytic phases in experimental populations of the wheat pathogen *Phaeosphaeria nodorum*. *BMC Evol Biol* 11:188. <https://doi.org/10.1186/1471-2148-11-188>
- Sørensen MB, Faurdal D, Schiesaro G et al (2025) Exploring crop health and its associations with fungal soil microbiome composition using machine learning applied to remote sensing data. *Commun Earth Environ* 6:355. <https://doi.org/10.1038/s43247-025-02330-0>
- Soussi A, Zero E, Sacile R et al (2024) Smart sensors and smart data for precision agriculture: a review. *Sensors (Basel)* 24:2647. <https://doi.org/10.3390/s24082647>
- Sprague SJ, Balesdent MH, Brun H et al (2006) Major gene resistance in *Brassica napus* (oilseed rape) is overcome by changes in virulence of populations of *Leptosphaeria maculans* in France and Australia. *Eur J Plant Pathol* 114:33–40. <https://doi.org/10.1007/s10658-005-3683-5>
- Sprague SJ, Marcroft SJ, Lindbeck K et al (2025) Influence of crop and stubble management practices on blackleg disease of canola (*Brassica napus*) in Australia. *Crop Pasture Sci* 76:. <https://doi.org/10.1071/CP24385>
- Srivastava RK (2025) Conservation tillage practices on GHG emissions, soil health and overall agricultural sustainability. *Soil Use Manag* 41:e70096. <https://doi.org/10.1111/SUM.70096>
- Storkey J, Bruce TJA, McMillan VE et al (2019) The future of sustainable crop protection relies on increased diversity of cropping systems and landscapes. In: *Agroecosystem Diversity: Reconciling Contemporary Agriculture and Environmental Quality*. Academic Press, London, pp 199–209. <https://doi.org/10.1016/B978-0-12-811050-8.00012-1>
- Suffert F, Delanoue M, Le Prieur S et al (2025) Off-season sex in *Zymoseptoria tritici*: little room for late encounters. *Fungal Genet Biol* 181:104043. <https://doi.org/10.1016/j.fgb.2025.104043>
- Suffert F, Delestre G, Gélisse S (2018a) Sexual Reproduction in the Fungal Foliar Pathogen *Zymoseptoria tritici* Is Driven by Antagonistic Density Dependence Mechanisms. *Microb Ecol* 77:110–123. <https://doi.org/10.1007/s00248-018-1211-3>
- Suffert F, Goyeau H, Sache I et al (2018b) Epidemiological trade-off between intra- and interannual scales in the evolution of aggressiveness in a local plant pathogen population. *Evol Appl* 11:768. <https://doi.org/10.1111/EVA.12588>
- Suffert F, Sache I (2011) Relative importance of different types of inoculum to the establishment of *Mycosphaerella graminicola* in wheat crops in north-west Europe. *Plant Pathol* 60:878–889. <https://doi.org/10.1111/j.1365-3059.2011.02455.x>
- Suffert F, Sache I, Lannou C (2011) Early stages of septoria tritici blotch epidemics of winter wheat: Build-up, overseasoning, and release of primary inoculum. *Plant Pathol* 60:166–177. <https://doi.org/10.1111/j.1365-3059.2010.02369.x>
- Summerell BA, Burgess LW (1988) Saprophytic colonization of wheat and barley by *Pyrenophora tritici-repentis* in the field. *Trans Br Mycol Soc* 90:551–556. [https://doi.org/10.1016/s0007-1536\(88\)80058-5](https://doi.org/10.1016/s0007-1536(88)80058-5)
- Summerell BA, Burgess LW, Klein TA (1989) The impact of stubble management on the incidence of crown rot of wheat. *Aust J Exp Agric* 29:91–98. <https://doi.org/10.1071/EA9890091>
- Suttie JM (2000) Hay and Straw Conservation for Small-Scale Farming and Pastoral Conditions, FAO Plant Production and Protection Paper 29. Food and Agriculture Organization, Rome
- Swan LJ, Backhouse D, Burgess LW (2000) Surface soil moisture and stubble management practice effects on the progress of infection of wheat by *Fusarium pseudograminearum*. *Aust J Exp Agric* 40:693–698. <https://doi.org/10.1071/EA99106>
- Swan T, Kirkegaard J, Dunn M et al (2023) Managing heavy stubble loads without compromising the “big things” – weeds, disease, pests, timeliness and profit! Experience from a decade of farming systems experiments. GRDC Update Papers, Grains Research and Development Corporation. <https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2023/07/managing-heavy-stubble-loads-without-compromising-the-big-things-weeds,-disease,-pests,-timeliness-and-profit!-experience-from-a-decade-of-farming-systems-experiments>. Accessed on 15 Sep 2026
- Sykes EM, Sackett KE, Severns PM et al (2018) Sensitivity variation and cross-resistance of *Zymoseptoria tritici* to azole fungicides in North America. *Eur J Plant Pathol* 151:269–274. <https://doi.org/10.1007/S10658-017-1370-Y>
- Tado CJM, Wacker P, Kutzbach HD et al (1998) Development of stripper harvesters: a review. *J Agric Eng Res* 71:103–112. <https://doi.org/10.1006/JAER.1998.0318>
- Talbot JM, Yelle DJ, Nowick J et al (2011) Litter decay rates are determined by lignin chemistry. *Biogeochemistry* 108:279–295. <https://doi.org/10.1007/S10533-011-9599-6>

- Taylor NP, Cuniffe NJ (2023) Optimal resistance management for mixtures of high-risk fungicides: robustness to the initial frequency of resistance and pathogen sexual reproduction. *Phytopathology* 113:55–69. <https://doi.org/10.1094/PHYTO-02-22-0050-R>
- Thompson SM, Tan YP, Shivas RG et al (2015) Green and brown bridges between weeds and crops reveal novel *Diaporthe* species in Australia. *Persoonia* 35:39–49. <https://doi.org/10.3767/003158515X687506>
- Thorburn PJ, Probert ME, Robertson FA (2001) Modelling decomposition of sugar cane surface residues with APSIM–Residue. *Field Crops Res* 70:223–232. [https://doi.org/10.1016/S0378-4290\(01\)00141-1](https://doi.org/10.1016/S0378-4290(01)00141-1)
- Torriani SFF, Melichar JPE, Mills C et al (2015) *Zymoseptoria tritici*: a major threat to wheat production, integrated approaches to control. *Fungal Genet Biol* 79:8–12. <https://doi.org/10.1016/j.FGB.2015.04.010>
- Tsao PH, Oster JJ (1981) Relation of ammonia and nitrous acid to suppression of *Phytophthora* in soils amended with nitrogenous organic substances. *Phytopathology* 71:53–59. <https://doi.org/10.1094/Phyto-71-53>
- Tsolakidou MD, Stringlis IA, Fanega-Sleziak N et al (2019) Rhizosphere-enriched microbes as a pool to design synthetic communities for reproducible beneficial outputs. *FEMS Microbiol Ecol* 95. <https://doi.org/10.1093/femsec/fiz138>
- Ueki A, Kaku N, Ueki K (2018) Role of anaerobic bacteria in biological soil disinfection for elimination of soil-borne plant pathogens in agriculture. *Appl Microbiol Biotechnol* 102:6309–6318. <https://doi.org/10.1007/S00253-018-9119-X>
- Vaish SS, Bilal Ahmed S, Prakash K (2011) First documentation on status of barley diseases from the high altitude cold arid Trans-Himalayan Ladakh region of India. *Crop Prot* 30:1129–1137. <https://doi.org/10.1016/J.CROPRO.2011.04.015>
- Van der Heyden H, Dutilleul P, Charron JB et al (2021) Monitoring airborne inoculum for improved plant disease management. A Review. *Agron Sustain Dev* 41:40. <https://doi.org/10.1007/s13593-021-00694-z>
- Vera DI, Murray TD (2016) Occurrence and survival of apothecia of the eyespot pathogens *Oculimacula aciformis* and *O. yallundae* on wheat stubble in the U.S. Pacific Northwest. *Plant Dis* 100:991–995. <https://doi.org/10.1094/PDIS-09-15-1056-RE>
- Verburg K, Bond WJ, Hunt JR (2012) Fallow management in dryland agriculture: explaining soil water accumulation using a pulse paradigm. *Field Crops Res* 130:68–79. <https://doi.org/10.1016/j.fcr.2012.02.016>
- Verburg K, Pasley HR, Biggs JS et al (2025) Review of APSIM's soil nitrogen modelling capability for agricultural systems analyses. *Agric Syst* 224. <https://doi.org/10.1016/j.agsy.2024.104213>
- 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 Res* 165:16–22. <https://doi.org/10.1016/j.still.2016.07.005>
- Wang B, Liu DL, Asseng S et al (2017) Modelling wheat yield change under CO₂ increase, heat and water stress in relation to plant available water capacity in eastern Australia. *Eur J Agron* 90:152–161. <https://doi.org/10.1016/J.EJA.2017.08.005>
- Wang J, Chang Y, Cao S et al (2025a) Explanatory framework of typhoon extreme wind speed predictions integrating the effects of climate changes. *Clim Dyn* 63:142. <https://doi.org/10.1007/S00382-025-07608-9>
- Wang J, Zhu B, Zhang J et al (2015) Mechanisms of soil N dynamics following long-term application of organic fertilizers to subtropical rain-fed purple soil in China. *Soil Biol Biochem* 91:222–231. <https://doi.org/10.1016/J.SOILBIO.2015.08.039>
- Wang P, Wang L, Liu K et al (2025b) Application of difenoconazole and *Trichoderma* broth combination for synergistic control of corn leaf blight and stalk rot in straw-returned fields in Liaoning Province, China. *Appl Sci (Basel)*. <https://doi.org/10.3390/app15147834>
- Wang X, Lu Z, Miller H et al (2020) Fungicide azoxystrobin induced changes on the soil microbiome. *Appl Soil Ecol* 145:103343. <https://doi.org/10.1016/J.APSSOIL.2019.08.005>
- Wegulo SN, Baenziger PS, Hernandez Nopsa J et al (2015) Management of *Fusarium* head blight of wheat and barley. *Crop Prot* 73:100–107. <https://doi.org/10.1016/J.CROPRO.2015.02.025>
- Weil RR, Magdoff F (2004) Significance of soil organic matter to soil quality and health. In: Magdoff F, Weil RR (eds) *Soil Organic Matter in Sustainable Agriculture*. CRC Press, Boca Raton, USA, pp 1–43
- West JS, Balesdent MH, Rouxel T et al (2002) Colonization of winter oilseed rape tissues by A/Tox+ and B/Tox0 *Leptosphaeria maculans* (phoma stem canker) in France and England. *Plant Pathol* 51:311–321. <https://doi.org/10.1046/J.1365-3059.2002.00689.X>
- Wherrett AD, Sivasithamparan K, Barbetti MJ (2003) Chemical manipulation of *Leptosphaeria maculans* (blackleg disease) pseudothecial development and timing of ascospore discharge from canola (*Brassic napus*) residues. *Aust J Agric Res* 54:837–848. <https://doi.org/10.1071/AR03056>
- Whitbread AM, Blair GJ, Lefroy RDB (2000) Managing legume leys, residues and fertilizers to enhance the sustainability of wheat cropping systems in Australia: 2. Soil physical fertility and carbon. *Soil Tillage Res* 54:77–89. [https://doi.org/10.1016/S0167-1987\(99\)00113-0](https://doi.org/10.1016/S0167-1987(99)00113-0)
- White EV, Roy DP (2015) A contemporary decennial examination of changing agricultural field sizes using Landsat time series data. *Geo Geogr Environ* 2:33–54. <https://doi.org/10.1002/GEO2.4>
- Wildermuth GB, McNamara RB (1987) Susceptibility of winter and summer crops to root and crown infection by *Bipolaris sorokiniana*. *Plant Pathol* 36:481–491. <https://doi.org/10.1111/J.1365-3059.1987.TB02265.X>
- 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 Res* 44:211–224. [https://doi.org/10.1016/S0167-1987\(97\)00054-8](https://doi.org/10.1016/S0167-1987(97)00054-8)
- Wilhelm S (1951) The inoculum potential of *Verticillium albo-atrum* as affected by soil amendments. *Phytopathology* 40:970
- Wolcast Broberg Å (2002) Evaporation from a clay soil covered with a surface mulch - three lysimeter studies. *Acta Agric Scand B Soil Plant Sci* 52:121–126. <https://doi.org/10.1080/090647103100004807>
- Wong PTW, Mead JA, Croft MC (2002) Effect of temperature, moisture, soil type and *Trichoderma* species on the. *Australas Plant Pathol* 31:253–257. <https://doi.org/10.1071/AP02020>
- Wood CW, Edwards JH (1992) Agroecosystem management effects on soil carbon and nitrogen. *Agric Ecosyst Environ* 39:123–138. [https://doi.org/10.1016/0167-8809\(92\)90048-G](https://doi.org/10.1016/0167-8809(92)90048-G)
- Wood SA, Tirfessa D, Baudron F (2018) Soil organic matter underlies crop nutritional quality and productivity in smallholder agriculture. *Agric Ecosyst Environ* 266:100–108. <https://doi.org/10.1016/J.AGEE.2018.07.025>
- Wu P, Zhao G, Huang H et al (2023) Optimizing soil and fertilizer management strategy to facilitate sustainable development of wheat production in a semi-arid area: a 12-year in-situ study

- on the Loess Plateau. *Field Crops Res* 302:109084. <https://doi.org/10.1016/J.FCR.2023.109084>
- Wyckhuys KAG, Tang FHM, Hadi BAR (2023) Pest management science often disregards farming system complexities. *Commun Earth Environ* 4:223. <https://doi.org/10.1038/s43247-023-00894-3>
- Xing Y, Liu X, Wang X (2026) Integrating UAVs, satellite remote sensing, and machine learning in precision agriculture: pathways to sustainable food production, resource efficiency, and scalable innovation. *Front Agron* 7:1670380. <https://doi.org/10.3389/fagro.2025.1670380>
- Xu C, Han X, Zhuge Y et al (2021) Crop straw incorporation alleviates overall fertilizer-N losses and mitigates N₂O emissions per unit applied N from intensively farmed soils: an in situ ¹⁵N tracing study. *Sci Total Environ* 764:142884. <https://doi.org/10.1016/j.scitotenv.2020.142884>
- Xu R, Du C, Gao Y et al (2023) Watering Shapes a Robust and Stable Microbial Community under Fusarium Crown Rot Infection. *Agronomy (Basel)* 13:. <https://doi.org/10.3390/AGRONOMY13051356>
- Xue H, Fan Y, Dong G et al (2024) Crop classification in the middle reaches of the Hei River based on model transfer. *Sci Rep* 14:28964. <https://doi.org/10.1038/s41598-024-80327-z>
- Yang T, Liu K, Poppy L et al (2021) Minimizing lentil harvest loss through improved agronomic practices in sustainable agro-systems. *Sustainability (Basel)* 13:1–13. <https://doi.org/10.3390/SU13041896>
- Yang Y, Guan H, Long D et al (2015) Estimation of surface soil moisture from thermal infrared remote sensing using an improved trapezoid method. *Remote Sens (Basel)* 7:8250–8270. <https://doi.org/10.3390/RS70708250>
- Ye S, Cao P, Lu C (2024) Annual time-series 1 km maps of crop area and types in the conterminous US (CropAT-US): cropping diversity changes during 1850–2021. *Earth Syst Sci Data* 16:3453–3470. <https://doi.org/10.5194/ESSD-16-3453-2024>
- Yi C, Kaul H-P, Kübler E et al (2002) Populations of *Fusarium graminearum* on crop residues as affected by incorporation depth, nitrogen and fungicide application / Populationen von *Fusarium graminearum* auf Ernterückständen beeinflusst durch Einarbeitungstiefe, Stickstoff- und Fungizidbehandlungen. *Z Pflanzenschutz* 109:252–263
- Yin S, Yi K, Zhang X et al (2024) Temporal and spatial dynamics of summer crop residue burning practices in North China: exploring the influence of climate change and anthropogenic factors. *Remote Sens* 16:4763. <https://doi.org/10.3390/RS16244763>
- Yinglan A, Wang G, Sun W et al (2018) Stratification response of soil water content during rainfall events under different rainfall patterns. *Hydrol Process* 32:3128. <https://doi.org/10.1002/hyp.13250>
- Zhan J (2016) Population Genetics of Plant Pathogens. *Encyclopedia of Life Sciences* 1–7. <https://doi.org/10.1002/9780470015902.a0021269.pub2>
- Zhang X, Fernando WGD (2018) Insights into fighting against blackleg disease of *Brassica napus* in Canada. *Crop Pasture Sci* 69:40–47. <https://doi.org/10.1071/CP16401>
- Zhou J, Zhang X, Qu Z et al (2024) Progress in research on prevention and control of crop fungal diseases in the context of climate change. *Agriculture (Basel)* 14:1108. <https://doi.org/10.3390/AGRICULTURE14071108>
- Zhou Y, Chen C, Franck WL et al (2023) Intercropping chickpea–flax for yield and disease management. *Agron J* 115:726–743. <https://doi.org/10.1002/AGJ2.21280>

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.