BATTLEFIELD TACTICS FOR THE MANAGEMENT OF *ZYMOSEPTORIA TRITICI*

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Abstract

Zymoseptoria tritici, often known as Septoria Tritici Blotch or STB, is a major disease of wheat which can cause yield reductions of 30-50% by reducing the photosynthetic area of the crop. A range of cultural techniques can be employed but in isolation these have limited success for control. Z. tritici control is still heavily reliant on fungicides which is becoming ever more challenging due to increasing fungicide resistance. This paper discusses how Z. tritici can be controlled by a series the military battlefield strategy through shaping, decisive and sustaining actions, underpinned by a constantly refreshed understanding of the operating environment. Decisive actions are those actions that, without which, the mission (in this case achieving a good yield from a wheat crop) could not be achieved. Shaping actions are those actions that set conditions for a successful decisive action. Sustaining actions are those which sustain the ability to deliver shaping and decisive actions Considering Z. tritici management using this range of strategies will effectively help severe yield loss from disease infection.

Keywords

Septoria, Leaf Blotch, wheat, disease, *Zymoseptoria tritici*, battlefield

Introduction

Septoria Tritici Blotch (STB) (*Zymoseptoria tritici)* is a foliar disease of wheat, rye, and triticale (AHDB, 2020a). It is the most ubiquitous wheat disease globally (Suffert et al., 2010) causing significant yield losses, especially in temperate regions (Dean, et al., 2012). Z. tritici is characterised by brown necrotic lesions on the leaves and stems of the infected plant, which surround dark fruiting bodies (Ponomarenko et al., 2011 (Quaedvlieg, et al., 2011)). Z. tritici epidemics have two district phases.

<u>Phase 1</u>

Early Epidemic Phase: This phase begins during leaf emergence and tillering, with the initial infection of the crop by the spores of the Z. tritici fungus (Suffert et al., 2010). These spores come in two forms. Ascospores are dispersed aerially from pseudothecia, a dark fruiting body which contains spore producing organs, and are characterised by reproducing sexually and their double cell wall which absorbs water to violently expels spores (Wyatt et al., 2013). Pycnidiospores are dispersed either aquatically or by direct contact and emanate from pycnidia, a dark fruiting body which contains spore producing organs. They are characterised by asexual reproduction and oozing their spores (Emlab, 2022).

Initial Infection: 70% of initial infection occurs through aerial transmission of ascospores (AHDB, 2020a) with 30% occurring through splashing of pycnidiospores (Suffert et al., 2010). The most significant source of spores is external wheat debris, followed by internal wheat debris (especially in second wheats), infected volunteers, and infected grass margins (Suffert et al., 2010).

Latent Phase: Within 24 hours of landing on a leaf spores germinate and produce hyphae which bypass the protective epidermis of the leaf by entering stomatal cavities (Steinberg, 2015). The hyphae colonise the mesophyll of the leaf, linking up stomatal cavities in a network in up to 15 days post infection (Shetty, et al., 2003). Concurrently, colonised stomal cavities fill with pre-pycnidia which begin to develop (Kema et al., 1996). If the colonised areas of two different strains of *Z. tritici*, that are of opposite mating types meet they will reproduce sexually resulting in pseudothecia (Suffert et al., 2010). During the latent phase identification of infection by visual inspection will prove difficult (Bayer, 2022).

<u>Phase 2</u>

Necrotic Phase: 14 to 28 DPI pycnidia and pseudothecia reach maturity and the infection enters the necrotic phase characterised by lesions and exposed dark fruiting bodies on the leaf (AHDB, 2020a).

Secondary Infection: During leaf emergence and tillering, interleaf transfer of pycnidiospores occurs by rain splash and physical contact. This expands the number of infected leaves within the crop (Ponomarenko et al., 2011) and the latent, necrotic and secondary infection phases cycle. Lower temperatures during the winter suppress fungal activity and slower plant growth reduces availability of new host leaves, further suppressing the expansion of infection within the crop (Suffert et al., 2010).

Late Epidemic Phase: Fungal activity resumes in the spring, as increased temperatures and plant growth enable further infection (Ponomarenko et al., 2011). The primary driver of disease spread during the late epidemic phase is secondary infection via the transition of pycnidiospores, from infected lower leaves to emerging upper leaves (AHDB, 2020a). Ascospores provide a second vector for infection enabling new primary infection (Suffert et al., 2010). As temperatures increase towards the fungus' optimal range of 15-20^{o}C, the latent period shortens (AHDB, 2020a) and the rate of infection increases (AHDB, 2021a). When the crop is harvested Z. tritici remains in the sources discussed above and the cycle begins again in the next harvest year.

The importance of Septoria Tritici Blotch

Z. tritici is considered a challenging disease because it can cause catastrophic yield losses in one of the most important cash crops and is highly adaptable making it difficult to manage (Dean, et al., 2012).

a. **Yield Loss**. Z. tritici can cause reductions in yield ranging from 30% to 50% (AHDB, 2020a). Yield loss is caused by lesions which reduce the leaf area available for photosynthesis. A 1% loss of photosynthesising surface of the flag leaf and second leaf will result in a 1% and 0.6% reduction in yield respectively (Bayer, 2022).

b. **Regional Significance**. Fones and Gurr (2015) assessed that yield losses caused by Z. tritici cost UK agriculture up to €240 million per annum, following a spend of c. €163 million per annum on crop protection, making Z. tritici the target of around 70% of fungicide applied. In the UK, Z. tritici is particularly significant in the South West because it experiences higher rainfall and fewer days below -2^{0}C (Met Office, 2013) which enables better survival overwinter (Gladders, et al., 2001) and easier transmission (AHDB, 2020a).

c. **Adaptability**. Z. tritici can reproduce sexually and undergo many cycles of reproduction during a growing season, resulting rapid evolution (Ponomarenko et al., 2011). It develops fungicide resistance and adapts to resistant genes in plants quickly. Up 90% of its genetic pool can be present in a single field (Zhan et al., 2003) and this diversity increases the likelihood of an effective strain of Z. tritici being present while the rapid sexual reproductive cycle enables the initial breakdown to be exploited (Orton et al., 2011). Z. tritici is not the only arable disease capable of developing and overcoming resistance, it is currently seen as the greatest risk (FRAG UK, 2020), so much so that in the 22/23 growing season, wheat received a

3 year resistance rating and a 1 year resistance rating on AHDB's Recommended List (RL) (AHDB, 2022a).

Historic Management of Z. tritici

Z. tritici has been an active pathogen since the domestication of wheat around 8000 BC and has co-evolved and spread around the world with wheat (Stukenbrock, et al., 2010). In the 1980's it overtook Septoria nodorum as the most endemic foliar disease, possibly due to a reduction in atmospheric SO_2 levels and the introduction of dwarf genes to wheat (Shaw et al., 2007).

Crop protection control measures can be broadly broken in to four categories; resistant cultivars, cultural controls, biological controls, and chemical controls (Back et al., 2021). Chemical and cultural controls dominated historic Z. tritici management as resistant cultivars did not emerge until the 1990's (Goodwin, 2007) and biological controls are still developing.

Loss of Controls to Fungicide Resistance. Continuous erosion of fungicide efficacy, and occasional total breakdown, due to poor fungicide resistance management has been the leading issue in Z. tritici management. Repeated use of the same fungicide, failure to combine modes of action, and over reliance on chemical controls have led to the loss of several products (Brent & Holloman, 2007). This historic loss of fungicides, particularly single-site fungicides, seriously restricts current management by reducing the pool of fungicides available for rotation to avoid resistance (FRAG UK, 2020).

1) *Methyl Benzimidazole Carbamates (MBCs),* were the main form of control up to the 1980s, but repeated single use and no combination of mode of action selected for a resistant allele (E198A) resulting in loss of control (Lucas et al., 2015).

2) *Quinone Outside Inhibitors (QoIs)/Strobilurin fungicides,* were introduced to the UK in 1997 with excellent efficacy. Resistance was identified in 2002 and control was lost at an unprecedented rate over the subsequent 3 seasons despite efforts to check the decline (Fraaijie, et al., 2005). As with MBCs, poor management practices selected for a resistant allele (G143A). To prevent further loss of control solo use of QoIs was abandoned in favor of pairing it with a product with a different mode of action and the number of uses within a season was reduced to two. Despite these efforts QoIs became largely ineffective in the UK and other countries by 2004 (Lucas et al., 2015).

3) *Demethylation Inhibitors (DMIs)/Azoles:* The loss of QoIs led to increased use of Chlorothalonil (CTL) and azoles to control Z. tritici. DMIs, a Group 3 Sterol Biosynthesis Inhibitor (SBI) (FRAC, 2022), have a varying efficacy on Z. tritici which has declined over time driven by target site changes (Leroux & Walker, 2011). AHDB trials have shown show that azole efficacy is below 50% with prothioconazole as low as 20%, but the newer mefentrifluconazole shows very high efficacy (AHDB, 2021b).

4) *Succinate Dehydrogenase Inhibitors* (SDHIs). The new generation of SDHIs were introduced after resistance management was better understood and practiced. Their use for managing Z. tritici has become widespread in Europe and up to 2015 no reduction in efficacy had been found (Lucas, Hawkins, & Fraaije, 2015). Recently there has been a gradual reduction in the level of control provided but resistance management techniques appear to be effective in reducing the speed of control loss (AHDB, 2021b).

Loss of Controls to Legislation: CTL had been a vital element of resistance management strategies as it provided a highly effective, low cost, multisite action with a low risk of resistance development that reduced the pressure on the higher risk fungicides. Its approval for use in the EU was withdrawn in 2019. Folpet and mancozeb (legal in the UK but withdrawn in the EU (HSE, 2022) are both alternative multisites but have a higher cost and lower efficacy making them poor replacements (AHDB, 2022b). The recent loss of this vital control measure is a defining feature of current and Z. tritici management strategies.

Current Management practices

Integrated Pest Management (IPM) is a systemic approach to crop protection aimed at using non-chemical controls to manage pest incidence to a level where chemical controls can be used economically and sustainably (AHDB, 2019). IPM can be best understood through the lens of the Operational Framework, an effective method for articulating how actions contribute to achieving a desired outcome (Land Warfare Development Centre, 2017). This framework divides activity into, shaping, decisive and sustaining actions, underpinned by a constantly refreshed understanding of the operating environment. Decisive actions are those actions that, without which, the mission (in this case achieving a good yield from a wheat crop) could not be achieved. Shaping actions are those actions that set conditions for a successful decisive action. Sustaining actions are those which sustain the ability to deliver shaping and decisive actions (Land Warfare Development Centre, 2017).

a. *Understanding the Environment*: Regional variations in weather patterns influence disease pressure (Gladders, et al., 2001). For example an area which experiences mild wet conditions are likely to experience high levels of disease pressure and plans should reflect the forecast elevated level of risk by adopting more robust shaping activities. In year weather should be used to revise the plan, a cooler dry spell will reduce the threat (Gladders, et al., 2001) and wet weather during peak growing conditions would increase the threat (AHDB, 2019). Understanding the real time disease burden within crops by crop walking will enable refinement of the crop protection plan to correctly allocate resources, maximising margin by reducing expenditure or increasing yield (Finch et al., 2014). Crop walking will also enable effective timing of applications based on the crop growth stage (AHDB, 2019). Finally, understanding the level of threat posed by other foliar fungal diseases will also impact spraying decisions as other diseases may present a greater threat.

b. *Shaping Actions*: Three shaping actions set the conditions for the decisive action by keeping disease pressure at a level which can be economically managed.

1) *Varietal resistance selection*: The key shaping action is selecting a variety of wheat with high Z. tritici resistance from the varieties available. Resistant varieties reduce the severity of Z. tritici I epidemics, enabling a greater yield response from fungicide applications (Morgan, et al., 2021). While there have been recent breakdowns in varietal resistance, especially in the decedents of Cougar 8 (AHDB, 2021c), varieties such as KWS Extase (AHDB, 2022a) still restrict Z. tritici to a manageable level. It could be argued that in the south west selecting for varietal resistance is the decisive action as without selecting a high resistance variety Z. tritici could be unmanageable, however no variety on the RL gives complete resistance (AHDB, 2022a) and even with the selection of the highest resistance varieties the application of fungicide will still be necessary in a normal year. Mixtures of varieties with resistance provided by different genes can also help in reducing the disease pressure within a crop (Orellana-Torrejonet al., 2022).

2) *Sowing date:* The second most important shaping action is sowing date (AHDB, 2019). Reducing the period of exposure by later drilling shortens the window for primary infection especially where there are long growing seasons in temperate regions, reducing disease levels. Drilling slightly later rather can reduce disease levels by 6% in high threat regions (Morgan, et al., 2021) but can result in yield reductions where disease pressures are low.

3) *Establishment technique:* Reduced seed rates and cultivation techniques which bury infected debris can have some effect on disease burden. Lower seed rates can lead to lower-than-expected levels of disease by reducing humidity and temperature within the canopy. However reduced seed rates can also negatively impact final yield so there needs to be a fine balance to between the two (Morgan, et al., 2021). Cultivation methods can bury localised infected trash, reducing infection from pycnidiospores, but as ascospores are the driving force behind primary infection in the early growth stages, it will only have a limited effect (Suffert et al., 2010).

c. *Decisive Actions:* In wheat the flag leaf and second leave provide c. 40% and 25% of total yield respectively (AHDB, 2019). Protecting the flag leaf and leaf 2's ability to photosynthesise at maximum efficiency are both decisive actions, but as the flag leaf contributes more to yield protecting it is the main effort. The effectiveness of fungicides in protecting these leaves is a function of timing, product choice and product dose. As fungicides are more effective in prevention rather than in eradication (NIAB TAG, 2019) they need to be applied before spores arrive on the upper leaves.

1) *T2 application* is critical for providing protection to the flag leaf as it is timed to coincide with GS39 which is the earliest application timing which can be used to directly protect the full surface of the flag leaf (AHDB, 2021a). If leaf 2 is infected it will still be early in the latent phase and T2 application will provide some eradicative effect (AHDB, 2020b) see Figure 2. Product choice and dosage depend on the assessed disease pressure as the amount spent on protection needs to be proportional to the threat to maximise margin (NIAB TAG, 2019). Multiple modes of action should be used to achieve best control. Azoles and folpet are the baseline treatment for T2, providing protection and helping manage resistance, SDHIs or Quinone Inside Inhibitors (QiLs) should be added depending on

disease pressure (AHDB, 2020b) to provide protection to the flag leaf and have an eradicative effect on Z. tritici latent on leaf 2 (AHDB, 2021b), QiLs can only be used once in a season and should be used at T2 to benefit from their eradicant effect.

2) *T1 application* is timed to coincide with GS32 when leaf 3 is just emerged and is designed to protect leaf 3 from infection and in doing so protect leaf 2 from spore transfer from leaf 3 (AHDB, 2019). DMIs and folpet should be used with an SDHI but actives should be different to T2 to maximise effect and manage resistance (AHDB, 2021b).

d. *Sustaining Actions:* Consistently applied fungicide resistance management strategies are the principal sustaining action for Z. tritici management as they preserve our control of Z. tritici in wheat. The history of Z. tritici management clearly illustrates the importance of continued discipline in fungicide use. Breeding to create new Z. TRITICI resistant or tolerant varieties of wheat, and the creation of new biological and chemical controls are also vital sustaining actions.

Future Management of Z. tritici

There are several technologies under adoption or on the horizon for Z. tritici management that are incremental improvements to current practice but do not overhaul it. Accurate and automated disease detection with tools using rapid pathogen DNA recognition (Microgenetics, 2022) and remote infield spore traps networked with modern agricultural data management platforms will provide accurate, field level disease modelling, enabling better understanding of the environment. The approval of new fungicides such as the QiL fenpicoxamid in 2021 (Corteva, 2021) will replace lost controls and new application technologies will improve their delivery (Teagasc, 2021), maintaining or improving the decisive action but not fundamentally changing it. Gene editing will increase the speed with which resistant varieties of wheat can be created (DEFRA, 2022) providing farmers with more effective shaping actions but not negating the requirement for the application of chemical controls. Developments in biopesticides or bioprotectants may enable a strategic shift in Z. tritici management (Back et al., 2021). Bioprotectants are agents based on micro-organisms, semiochemicals or botanicals that can be used to manage disease epidemics (AHDB, 2022c). The biochemical Iodus, already approved for use in the UK, has provided similar levels of Z. tritici control to folpet when applied at T0 (Agrii, 2021) with no residue or buffer zones (UPL, 2022) and Lipoetides have been shown to reduce Z.

tritici levels by up to 82% under laboratory conditions (Mejri, et al., 2018). Currently, high costs, slow action, poor supply, and issues with application are restricting adoption (Fenibo et al. 2021). Increased funding and research driven by the need for greener and more sustainable solutions are likely to resolve many of the issues with bioprotectants but with widespread adoption will come widespread evolution of Z. tritici.

Conclusion

Von Clausewitz (1874) argues that the nature of war, a violent politically motivated contest between forces, is immutable, but the character of war, the ways and means by which the war is conducted, is ever changing. The same is true for Z. tritici management and crop protection in general. The nature of Z. tritici management, the contest between the pathogens drive to reproduce and managers drive to maximise margin, is immutable, but the character of Z. tritici management, the means by which both sides achieve their outcome, is constantly evolving. In the future crop managers and those supporting them will continue to create new resistant cultivars, chemical controls, cultural controls, and biological controls, which will be targeted and applied in novel and increasingly accurate ways. Z. tritici will continue to adapt to the evolutionary pressure these changes apply and become resistant to new controls and overcome the resistance of new cultivars. Both sides in this battle will run very hard and stay in the same place (Dyer, 2014). Its immutable nature makes the contest Sisyphean but does not denude its importance. Until a truly paradigm shifting technology emerges, IPM and the Operational Framework guided by the ultimate objective of maximising margin will remain the most helpful principles in STB management.

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