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Review

The Past, Present, and Future of Barley Yellow Dwarf Management

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Abstract: Barley yellow dwarf (BYD) has been described as the most devastating cereal grain disease worldwide causing between 11% and 33% yield loss in wheat fields. There has been little focus on management of the disease in the literature over the past twenty years, although much of the United States still suffers disease outbreaks. With this review, we provide the most up-to-date information on BYD management used currently in the USA. After a brief summary of the ecology of BYD viruses, vectors, and plant hosts with respect to their impact on disease management, we discuss historical management techniques that include insecticide seed treatment, planting date alteration, and foliar insecticide sprays. We then report interviews with grain disease specialists who indicated that these techniques are still used today and have varying impacts. Interestingly, it was also found that many places around the world that used to be highly impacted by the disease; i.e. the United Kingdom, Italy, and Australia, no longer consider the disease a problem due to the wide adoption of the aforementioned management techniques. Finally, we discuss the potential of using BYD and aphid population models in the literature, in combination with web-based decision-support systems, to correctly time management techniques.

Keywords: *Barley yellow dwarf virus*; winter wheat; decision-support system; aphids

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1. Introduction

Barley yellow dwarf (BYD), a disease of grasses (Poaceae) caused by a group of viruses in the family Luteoviridae is the most economically important viral disease of small grains worldwide. Global statistics are difficult to estimate due to lack of data and misdiagnoses [1]; however, individual wheat (*Triticum aestivum* L.) fields in areas prone to viral infection may experience average yield losses between 11% and 33% and sometimes up to 80% [1,2]. Viruses that cause BYD are commonly referred to as barley yellow dwarf virus (BYDV), maize yellow dwarf virus (MYDV) and cereal yellow dwarf virus (CYDV) and belong to different genera in the same family. These viruses can be transmitted by more than 25 species of aphids worldwide, but the most relevant aphid vectors of BYD viruses in temperate climates are: *Rhopalosiphum padi* (bird cherry-oat aphid), *Rhopalosiphum maidis* (corn leaf aphid), *Sitobion avenae* (English grain aphid), and *Schizaphis graminum* (greenbug). The aphids feed upon, and transmit the viruses to various grain crops such as wheat, barley, oats, rye, and corn, as well as over 150 non-crop grass species in the family Poaceae [1]. Due to its wide host range and to the complicated life-style of its vectors, the BYD disease syndrome is difficult to manage, and management strategies vary according to climate and location. While no comprehensive review has been published on BYD management since 1995 [3], in this review we briefly discuss the history, taxonomy, symptom development, vector biology, vector-virus interaction, and vector-plant host interaction of BYD viruses with implications for management. We also detail past, current, and future management strategies for BYD that include artificial intelligence applications.

1.1. History of BYD

Today BYD occurs in most regions of the world [3] and periodically causes epidemics, usually associated with vector population dynamics. BYD viruses are thought to have evolved in North America [4]. The viruses likely originated in grasses native to North America, but are more virulent in exotic grasses (including grain crops) that expand the reservoir for the virus, which in turn increases incidence in native grasses [5]. Under optimal conditions virus populations will rise to epidemic levels to cause disease in crop and non-crop hosts.

BYD was first recognized as a problem in the United States in 1890 when the disease reached epidemic proportions in oats and was widespread throughout the Midwest [6]. The "greenbug" vector, now known as *S. graminum* (Aphididae) is thought to have been introduced to the United States from England in 1882 [6], which coincides with the rise of BYD outbreaks. Another epidemic occurred in 1907 after which T.F. Manns of Ohio published the first report of the disease in the world [7]. At first the disease was restricted to the Midwest and Eastern United States and was not believed to extend farther west than Illinois [7]. The disease was initially thought to affect oats alone, but later it was discovered to affect wheat, rye, barley, and other cereal species. The disease was believed to be caused by a symbiotic association of two bacterial species and partially transmitted by "plant lice", which later came to be known as aphids. It was also believed that the bacteria were soil-borne and could persist in infested fields. These beliefs prevailed for nearly 50 years until 1951, another epidemic year, when the disease spread to barley crops in California. During this outbreak Oswald and Houston [8] were the first to describe the causal agent of the disease as a virus persistently transmitted by multiple aphid species. This paper was seminal and formed the basis for future studies of BYD ecology.

1.2. BYD Virus Taxonomy

Using traditional transmission assays and injections of virions directly into the hemocoel, Rochow [9] described four species of BYD viruses uniquely based on vector specificity. Molecular analysis shows that all of these viral genomes are composed of a single linear molecule of positive-sense, single stranded RNA ranging from 5.7 to 6.0 kb in size [1,10,11]. Using these analyses the International Committee on Taxonomy of Viruses lists ten virus species that cause the disease syndrome known as barley yellow dwarf. All of these species belong to the family Luteoviridae. Within the Luteoviridae these species are classified into the genera *Luteovirus*, *Polerovirus*, or are unassigned. The species in the genus *Luteovirus* are barley yellow dwarf virus (BYDV-PAV, BYDV-MAV, BYDV-PAS, BYDV-kerII, BYDV-kerIII) [12,13]. The species in the genus *Polerovirus* are cereal yellow dwarf virus (CYDV-RPV, CYDV-RPS) [11,12]. The species yet to be assigned to a genus are maize yellow dwarf virus (MYDV-RMV; Domier 2011), BYDV-SGV, and BYDV-GPV [12]. In 1999 the species formerly known as BYDV-RPV was reclassified into the *Polerovirus* and renamed cereal yellow dwarf virus [11,12]. Later CYDV-RPS and MYDV-RMV were added to this genus. For simplicity henceforth the viruses causing the BYD disease syndrome will be referred to as BYD viruses.

The transmission efficiency of each virus species depends, in part, on the vector species [9,14]. BYDV-PAV is transmitted most efficiently by *R. padi* and *S. avenae*, BYDV-MAV specifically by *S. avenae*, CYDV-RPV specifically by *R. padi*, MYDV-RMV by *R. maidis*, and BYDV-SGV most efficiently, but not specifically, by *S. graminum* [9,14].

1.3. BYD Symptom Development

Understanding the biology and the organisms involved in the disease cycle is fundamental in developing an appropriate disease management plan. Disease management often begins with symptom identification so that preventative measures may be taken the following season as once symptoms are present it is usually too late to manage the virus. Plants infected with BYD viruses often exhibit symptoms of stunted growth and discoloration due to chlorosis of the leaves. Severe infections of BYD viruses in wheat can cause up to a 66% reduction in plant size, decreased heading, and an obvious yellow coloring due to chlorosis [8]. Chlorosis in BYD virus-infected plants is associated with an accumulation of soluble carbohydrates and a decrease in the nitrogen, calcium, and magnesium concentrations in the infected leaf tissues [15,16]. BYD virus infection causes approximately a 45% total reduction in photosynthesis per plant, or a 25% reduction when comparing equal masses of healthy and infected plant tissues [17]. This 25% reduction in photosynthesis is accompanied by a 65% reduction in chloroplasts [17] and by distinct yellowing. These symptoms progress the most when temperatures hover around 25 °C and higher, whereas lower temperatures inhibit infection and symptom development [18,19].

Susceptible species of Poaceae may become infected with the virus at any time throughout their life cycle, but winter wheat is most susceptible and damaged during its seedling stages in the fall, especially when inoculated before Growth Stage 31 (GS 31), the beginning of stem elongation [8,20,21]. When inoculated after tillering or during stem elongation, yield losses are dramatically decreased [20]. Various species of BYD virus often differ in the symptom severity. Plumb [22] generally classified BYDV-PAV and CYDV-RPV as "severe" and BYDV-MAV as "mild"

1.4. Vector Biology

BYD viruses are persistently transmitted by aphids, and thus control of aphids means control of BYD. The aphid vectors of BYD viruses are greatly impacted by abiotic factors, such as temperature, that affect their growth, development, and migration, and therefore management of BYD. The phenologies of aphid vectors are cyclic, may have one or more migratory phases, and occur at relatively regular intervals year to year [23]. Aphid migrations are preceded by the production of alatae that, under the right conditions, will take flight and migrate to new locations. In addition, aphid species may occupy many hosts and not all of these alternate hosts are virus hosts. Migratory patterns are a species-specific trait that has been studied extensively. *R. padi* and *R. maidis*, the most economically important vectors, have two distinct migratory periods in most cropping areas with a temperate climate one in late spring and another in autumn [23,24]. These migratory peaks often coincide with the sowing and emergence of cereal grains during the time in which they are the most susceptible [20,25]. *S. avenae* has a single migratory peak in late spring, but only a very small migration in autumn [23,26,27]. Proportions of viruliferous migrants in a given migration can range from 0% to over 10% [23,26]. In Italy, the average percentages of viruliferous migrant caught in suction traps from 1992–2002 were 11.22, 0.71, 7.71, and 1.85 for *R. padi*, *S. avenae*, *R. maidis*, and *S. Graminum*, respectively [23]. As low as these percentages may seem, considering a migration may consist of millions of aphids, the actual number of viruliferous aphids is quite high.

Temperature and rainfall/moisture are significant factors in predicting onset of BYD virus aphid vector migrations [25,28,29]. Alate aphids have a threshold ambient temperature at which internal body temperature is high enough to allow flight muscles to function. The temperature threshold at which 50% of *R. padi* and *S. avenae* take flight is 15 °C and 19 °C, respectively [30]. These temperatures may vary, however, based on other variables such as substrate and wind speed [31], so it is difficult to interpret these results in the context of the single temperature variable. Concerning the fall migration of these aphids, overnight temperatures will usually be much lower than the maximums, so it is likely that migration flight occurs during specific parts of the day similar to other aphid species [32]. However, other factors, such as light intensity, affect take-off as well [32]. Thus, simply because the temperature threshold is met does not necessarily mean the aphids will immediately take flight. Wind speed also affects the take-off of aphid alatae. Aphids are poor fliers and have difficulty flying in strong winds, so when strong winds are present flight take-off is often delayed. Time to take-off is positively correlated with wind speed, thus, the greater the wind speed the longer individual aphids will delay flight [32].

1.5. Vector–Virus Interaction

BYD viruses are transmitted in a circulative, persistent manner by aphids [1]. The acquisition of viral particles by the aphid vector alters the aphid's behavior to promote the spread of the virus. Aphids viruliferous for BYD viruses prefer healthy plants, whereas non-viruliferous aphids prefer diseased plants [33]. Virions are acquired during feeding from infected phloem cells. A readthrough protein encoded by the open reading frames 3 and 5 of the virus enhances the efficiency of transmission, though it is not required [34]. Once the virions are ingested by the aphid, they must pass through the midgut and/or hindgut wall into the hemocoel. Hindgut epithelium recognition of virus particles is *Luteovirus* specific, but not virus species-specific, as any of the virus species can pass to the hemocoel of any vector, even if the vector is unable to transmit that specific species [1]. Virions contain structural proteins needed for transport through the midgut into the hemocoel (coat proteins). Once in the hemocoel virions are bound by GroEL-like proteins synthesized by symbiotic bacteria, *Buchnera* spp. [35]. The N terminal of the readthrough domain of the *Luteovirus* coat protein binds specifically to the GroEL protein to prevent degradation in the aphid hemocoel and promotes the persistent transmission of the virus [36].

From the hemocoel, the virions are then actively transported to the salivary glands through the accessory salivary glands in vesicles obtained from the gut [1,37,38]. Transport into the salivary glands requires virus species-specific minor read-through proteins, and these proteins, together with various vector proteins, are responsible for vector specificity [39–43]. Host plant proteins also likely play a role in vector specificity through binding with virions and subsequent uptake by the aphid vectors [44,45]. An infected aphid remains viruliferous for the rest of its life. Aphids require a minimum acquisition access period for BYD virus transmission that ranges between 15 minutes and 3 hours [46]. The acquisition access period and transmission efficiency is dependent on virus titer, age of the plant, and infection stage [46].

1.6. Vector-Plant Host Interaction

Aphid vectors of BYD viruses have complex interactions with their wild and crop hosts that affect BYD virus distribution. The primary hosts, the hosts on which aphids lay their sexually-produced eggs, are the bird cherry (*Prunus padus*) for *R. padi*, and grasses in general for *S. graminum* and *S. avenae*, while *R. maidis* do not sexually reproduce. [47,48]. Knowledge of the primary host is important because it is where genetic diversity may arise. *R. padi*, *R. maidis*, *S. graminum*, and *S. avenae* therefore do not feed specifically on wheat, though it is one of the alternative hosts [49,50]. A secondary or alternative host is a plant on which the aphids may feed on and reproduce parthogenetically. *R. maidis*, for instance, will feed on wheat but generally prefers barley [51] and the preferred secondary host of *R. padi* is *Lolium perenne*, or perennial ryegrass, where aphids are highly attracted and perform well [49]. For all these species, when the primary hosts are not present, the vectors persist year-round only on the secondary hosts.

These four aphid species have different fecundities based on many variables. *S. avenae* and *R. maidis* have much higher reproductive rates in wheat fields than *R. padi* or *S. graminum* [23]. This is especially apparent in seedling wheat plants when *R. padi* and *S. avenae* colonize the same plant [52]. Pre-colonization by *R. padi* of infected plants facilitates the subsequent foraging of conspecifics and *R. maidis*, while the order of species arrival dictates the colonization pattern on uninfected plants [53]. On a heading plant, *S. avenae* prefer the head, whereas *R. padi* prefer lower parts of the plant such as the stalk or leaves [52,54]. Although *S. avenae* and *R. maidis* may be stronger competitors once a field is colonized, *R. padi* and *S. graminum* produce more migrants [23]. This is apparent in the two major migrations and number of individuals of *R. padi* and *R. maidis* caught in suction traps compared with the single migration of *S. avenae* [23].

In temperate climates direct feeding damage from aphids is actually quite rare in the autumn. Yield losses may occur in the spring, generally from *S. avenae* due to the large spring migration, but only under extreme infestation [55]. However, these yield losses cannot be considered direct because most of the damage comes from a fungal pathogen in the aphid honeydew [54]. In fact, one of the most devastating outcomes of aphid infestation is due to the transmission of BYD viruses in the autumn. Thus, managing the autumn migration of aphids is more important in preventing yield loss than managing spring migration of aphids.

2. Management of BYD

2.1. History of BYD Management

BYD has historically been managed through selection of resistant cultivars, planting date alteration, insecticidal seed treatments, and foliar insecticide sprays. As previously described, there exists an array of complex interactions among virus, vector, and host making disease epidemics and outbreaks extremely difficult to predict. Management has remained relatively consistent throughout the years, but the difficulty in tracking the disease adds uncertainty to timing and necessity of management tactics.

Optimizing planting date can be important in managing aphid vectors of BYD viruses. Planting later in the fall decreases BYD virus infections because it delays winter-cereal emergence dates after aphid migration [23,56–59]. However, there is a trade-off between late planting to decrease yield loss due to BYD and winter kill. Wheat that is planted too late in the season may experience much higher rates of winter kill due to immaturity when entering the cold season [60,61]. Generally planting after the Hessian fly-free dates is useful for avoiding the aphid migration [62].

Insecticide-treated seeds can be used to offset early planting susceptibility to aphids [63–65]. Imidicloprid, a neonicotinoid, seed treatments can be used to protect the crop for approximately three to five weeks after emergence to reduce primary infection [66–68], but success also depends on the chemical and the method used to coat the seeds. However, since the treatment loses efficacy after a few weeks further management may be needed later in the season [65,69]. However, using treated seeds has drawbacks. They are more expensive than untreated seeds, can leave significant insecticide residuals in the soil, can disrupt the natural soil and aquatic ecosystems, and being systemic, can have non-target effects on pollinators and other beneficial arthropods [70,71]. For instance, bees that visited maize, another wind-pollinated crop that had been seed-treated with neonicotinoids, showed high mortality with neonicotinoids in their systems [71]. Bees use cereal crops, such as wheat, to collect pollen, thus the presence of neonicotinoid seed-treatment is likely to have a similar effect. These non-target effects can be alleviated to increase agricultural sustainability by only using seed treatment when other measures are likely to be ineffective.

After planting, there is still the option to spray a foliar insecticide to manage the aphid vectors. Since aphids require time to acquire and inoculate BYD viruses, insecticide is a valid management strategy to decrease infection rate. Once it was recognized that BYD viruses are transmitted by aphids, the primary goal in management of BYD became reduction of the number of aphids. Thus, chemical insecticides or repellants have been commonly employed by growers. An economic threshold for BYD virus management has been estimated at 15 aphids per one foot row of plants during early post-emergence [72]. Typically, pyrethroid foliar sprays are better to manage aphids, but pirimicarb may also be used at a lower efficacy [73], especially in the case where *S. avenae* has developed resistance to pyrethroids [74]. Unfortunately, even with the known pollinator toxicity, neonicotinoids seem to be most effective [75].

2.2. BYD Virus Resistance

Tolerance and resistance to BYD can both occur. Tolerance describes an interaction in which the virus may still infect the host plant, but at lower titer or symptom development. Resistance provides a total protection against the virus. The mechanisms of resistance or tolerance to BYD described in this section are: introgression of dominant resistant or recessive genes, cross protection, and RNA interference (RNAi).

Tolerance to BYD viruses has been studied extensively in barley and wheat [76]. In barley, the genes conveying tolerance to BYD are *Ryd1*, *Ryd2*, *Ryd3*, and *Ryd4Hb* [76,77]. *Ryd1* was not found to be highly efficient and therefore not bred into commercial cultivars [78]. *Ryd2* has been introduced into commercial cultivars and is used often in traditional BYD resistance breeding programs [77,79]. However, this gene only conveys tolerance to BYD viruses in young plants by reducing virus titer but does not reduce titer in older plants [77,80]. This could be more detrimental to crops because plants are not dying and are acting as reservoirs for aphids to acquire the virus. Riedel et al. [80] studied the effects of pyramiding *Ryd2* and *Ryd3*. They found that these two genes together conveyed an effective resistance rather than tolerance. Thus, this seems to be the best option in barley for BYD resistance studies. The dominant *Ryd4Hb* gene conveys resistance to BYD viruses not through direct resistance to the virus, but by preventing inoculation through decreased time of salivation of the aphid vectors [81,82].

Host plant resistance to BYD viruses does not naturally occur in wheat; however there has been some work to identify a resistance gene found in other wild relatives, such as *Thinopyrum* spp. [83], and work on cross-protection against the viruses met with limited success. The *bdv2* gene found in plants in the genus *Thinopyrum* is the most widely used gene to evaluate resistance to BYD viruses [83–86]. It conveys a broad-spectrum resistance to BYD viruses [74]. This gene has been successfully introgressed from *T. intermedium* onto the 7DL chromosome of wheat [87,88]. The presence of the *bdv2* gene allows the resistant host to induce pathogen-associated molecular pattern-triggered immunity and up- and down-regulate many pathogenesis-related genes to reduce virus titer [89]. Unfortunately, the translocation of the *bdv2* gene also incorporates genes that cause the flour of wheat to turn yellow, which is undesirable in terms of marketing [90].

Other mechanisms of resistance have been studied, but have not been adopted. An attenuated strain of BYDV, PAV-P, may convey resistance to the more virulent wild-type strains [91,92]. However, there was low cross-protection between the PAV-P isolate and other species of BYD viruses [92]. Other attempts at achieving cross-protection have yielded similar results. A line of barley was developed that induced RNAi against BYDV-PAV by encoding for a hairpin loop of a section of the viral coat protein [93] and several lines of oat and barley to express the coat protein of BYDV-PAV, BYDV-MAV, and CYDV-RPV [94]. These lines were highly resistant to the respective viruses, but not to others. None of these resistant cultivars were readily adopted.

A winter wheat cultivar, Everest, that is moderately resistant to BYD, was bred by Kansas State University [95]. This cultivar does not contain the *bdv1* or *bdv2* gene, and it is not known what causes this moderate tolerance [96]. Since this is not a line introgressed with the *T. intermedium* 7 dL chromosome there is no yellow flour phenotype. The Everest cultivar is also moderately tolerant to *Fusarium* head blight, which is a huge plus in marketing to growers. However, the cultivar is highly susceptible to *Magnaporthe oryzae*, though this pathogen has not been introduced into wheat in the U.S. [97].

Resistance to BYD in oats and maize, two other crops in which BYD has a major impact, has been less well studied. No single genes have been explored for resistance to BYD in these crops [77].

2.3. Current Management of BYD

Informal email interviews with grain disease specialists were done during the spring and summer of 2017. The comments of the experts who responded to our request are summarized in the following sections. Thus, inferences are drawn on BYD incidence and management approaches in winter cereals for U.S. and international regions.

2.3.1. Northeast United States

In recent years BYD has been managed in the Northeast U.S. mainly through delayed planting. Planting after the Hessian fly free date (the date after which planting of winter cereals is suggested to reduce pest pressure; especially from Hessian flies, but can be expanded to other pests such as aphids) has been successful in reducing the incidence of disease. Imidicloprid seed treatments are available, but the expense of buying treated seeds often does not outweigh the risk of BYD because epidemics have been rare in recent years. With that said BYD is still present, but at low incidence and with seemingly low impact. There has been some work to develop resistant oat varieties, but not so much with wheat and barley [98].

2.3.2. Southeast United States

While sporadic, BYD still causes major losses in wheat in the Southeast U.S. Unfortunately, changing the planting date is not as successful in managing the disease in this region mainly due to the impact on yield from other pests, diseases, and abiotic factors. There is generally a two week period of suggested planting, before which planting will cause loss from BYD, Hessian fly, and other pests; but after which winter kill will cause damage and yield potential will be reduced. Neonicotinoid seed treatment is often used, especially in oats where fall inoculation is the most significant. Pyrethroid foliar sprays are generally used at various times throughout the fall, winter, and early spring to control the aphids vectoring the virus. Resistant cultivars are not used in BYD management in this region because they have reduced overall performance compared to susceptible cultivars [99,100].

2.3.3. Pacific Northwest United States

In the Northern U.S. the disease pressure from BYD has been relatively high and the most severe problems have been associated with early-planted fields. Thus, here it is regularly suggested to use both insecticide-treated seeds and delayed planting. However, due to the difficulties of tracking aphid migrations these are general, not targeted, management techniques. Another recommendation that has been found to be effective is to remove weeds and volunteer crops several weeks before planting to reduce refuge for aphid vectors and virus reservoirs [101].

2.3.4. Midwest United States

The winter wheat cultivar Everest has become the most used cultivar in Kansas for five years in a row [102]. As stated above this cultivar has moderate resistance to BYD and FHB making it a desirable crop to plant. In 2011 and 2012, Kansas saw the highest yield losses due to BYD in 10 years at 2.7% and 2.3%, respectively [103]. These numbers are extremely low compared to the potential to lose up to 80% in a given field [1,2].

2.3.5. United Kingdom

In the U.K. BYD is of most concern in early-sown autumn cereals. Insecticide seed treatments are nearly ubiquitous here and likely in most of Europe. The seed treatments, along with not planting too early (not necessarily delayed planting) have worked well in managing the disease. Thus, BYD has been of little concern in the U.K. in recent years [104].

2.3.6. Italy

In Italy growers are no longer concerned with BYD. The disease has been so sporadic in recent years that it does not cause any major losses. Thus, there are no management tactics frequently taken by growers. Interestingly, neonicotinoid seed treatment is banned in Italy, so this is not an option for management there [105].

2.3.7. Australia

Barley yellow dwarf used to be a much more significant problem in Australia (especially Western Australia), however ~15 years ago it was discovered that two early pyrethroid sprays greatly reduced the impact of the disease. This tactic was widely adopted in Western Australia and reduced the need for other control measures, even if the disease remains a large problem in the high rainfall areas of

Western Australia, Victoria, and Tasmania. Delayed planting and insecticide seed treatments are also occasionally used, but they are not as common as the pyrethroid sprays [106]

2.4. The Future of BYD Management

The management of BYD viruses, as well as other pathogens, is trending towards precision agriculture techniques using statistical models, expert decision-support systems (DSSs), and automation of management techniques. As justified above, historical management techniques are often only effective if applied at specific times during the field season and vector life cycles. There is a lack of communication of in-field data between farmers and researchers that could be used to optimize management timing [107]. Platforms which aid in merging research on management strategies with real time data obtained by farmers to give management recommendations exist as DSSs. In order to design a DSS the builder of the platform must have a method to infer the outcome of a management technique.

There are several available published models that can track aphid populations and BYD disease conditions to optimize timing of management strategies. The statistical model built by Thackray et al. [25] uses data gathered in Western Australia to synthesize a complex model that incorporates many environmental parameters to calculate aphid population and development. These include soil moisture and drainage, temperature, rainfall, evaporation, etc... The authors were able to use a plethora of previously published interactions to incorporate into their models of population development which are then used to calculate virus transmission via migration and in-field transmission. Ultimately the model can be used to estimate yield loss due to BYD and it explains 65% of variation in yield in Western Australia. Since all factors involved in BYD virus transmission (plant, aphid, and virus) are highly dependent upon climate, the model may only be applicable in Mediterranean climates, such as Western Australia.

A model developed in France [28] represents a statistical model available for more temperate climates. Using Bayesian statistical inference this model describes the population dynamics of *R. padi*, and therefore the potential dynamics of the virus itself. It simply uses an early season aphid count and temperature to model the spatial and temporal spread of the aphids with high accuracy. The use of Bayesian statistics seems to be the best method since there is so much uncertainty in the inputs and outputs, and this model seems to be the best in its risk assessment for temperate climates such as the United States.

Another model [108] uses vector preference and disease incidence to predict the expansion of the disease front within a field. Once a BYD virus is established in a field this model can be used to predict the spread to neighboring plants. It is not, however, useful in tracking large scale disease dynamics. This model also has to make assumptions of vector preference, so it would be difficult to use it alone to manage BYD. However, it could be used in conjunction with the model by Fabre et al. [28] giving data on a larger scale. These two models could potentially be in temperate climates.

There are other statistical models for BYD viruses, but most of them are not predictive. For instance, a model was designed [109] to fit a quadratic regression to the proportion of BYD virus-infected plants for individual years. Looking at individual years does not give a model that would be predictive of how virus spread would work. However, if the proportion of plants infected in all years were combined it may give a better model on the virus population dynamics.

Decision-support systems are computerized methods of taking unstructured data from a user to allow a broader analysis of the impacts of his or her actions [110,111]. There are several ways DSSs can be used to manage crops including, but not limited to, diagnosis or pest identification, projection of yield loss, disease front tracking, and management recommendations. Expert DSSs utilize expert knowledge in a field to gauge the impacts of actions and to track and provide suggestions on important management decisions a grower makes. Expert DSSs can incorporate statistical model outputs as well as expert heuristics.

Decision-support systems in conjunction with web-based platforms for tracking pest and disease presence are an increasingly used component of precision agriculture. The utility of DSS programs has been shown through a variety of systems. Fabre et al. [112] synthesized a model predicting BYD outbreaks to aid in planning foliar insecticide sprays. They showed their model reduced BYD control input costs by up to 36%. As described above, Thackray et al. [25] published a model that could predict yield loss from BYD outbreaks with an R^2 of 65%. This may not seem like a high R^2, but considering the complexity of the disease cycle, it is one of the better models for BYD prediction.

One of the most successful DSS platforms is the Integrated Pest Management Pest Information Platform for Extension and Education (soybean PIPE). This platform was designed for the soybean rust invasion of 2004 [113]. It was, and is, responsible for up to $299 million in annual fungicide savings since 2005, the year it was implemented [114,115]. The PIPE arose from a dire need of an early warning system for a disease devastating soybean crops as it moved from its origins in China through Africa and South America. The appearance of the disease in the U.S. in 2004 prompted the development and deployment of the soybean PIPE, and it was quickly adopted and still remains a widely accepted tool for soybean rust, and now other diseases and crops [116] The Integrated Pest Management PIPE (ipmPIPE) is the predecessor of the current Integrated Pest Information Platform for Extension and Education (iPIPE).

In the future, management could be regulated through platforms such as the iPIPE. Walls et al. [117] developed a method to capture expert management recommendations for BYD that is to be integrated into the iPIPE delivery platform. This method is beneficial in that it can normalize the management of the disease. It was also designed to accept input data from predictive models discussed previously. Available weather engines have the ability to take these models reported in literature and measure the parameters to give a forecast of aphid movement and virus transmission. The combination of models and decision support systems are going to become increasingly valuable and effective in disease management [107]

Although there are many benefits to using DSSs in disease management, in the past there have been barriers in the adoption of such programs. Most never even reach the hands of the grower because they either do not work, are not finished, or are never used [118]. The reasons for this may be due to technical, professional, economic, social, and psychological barriers [107]. In the future the technical as well as psychological barriers to implementing DSSs will become increasingly easier to overcome. Technical barriers will become less important because the computing power available to the general public is rapidly growing. The main psychological barrier to adopting DSSs is the hesitancy of the user to take advice from a computer [107]. This will decrease as our dependency on computers increases. The other factors are also likely to decrease as time goes on and production of DSSs becomes more streamlined.

Our work [117] suggests that given the trend towards automation in agriculture, models that can be utilized in disease management will become necessary to incorporate into algorithms of the machines controlling farm management. Huge amounts of data will need to be processed by these machines, and it will be necessary to analyze these data in a cloud-based platform [119,120]. The incorporation of statistical models and expert DSSs will allow interpretation of these data simpler and allow the machines to make decisions like a human expert, but without human error. BYD could be managed through the incorporation of the statistical models available in literature and the implementation of the DSS in these machines in the future [117].

3. Conclusions

Barley yellow dwarf can be a devastating disease of cereals. The biology of the aphid vector, plant host, and BYD viruses are quite complex and have made prediction of disease difficult. The control of the disease has evolved over the years since it first became a problem. Management tactics conducted often include insecticide spray and insecticide treated seeds to control vectors, and altering planting date of the crop to avoid aphid migration. However, management tactics are often conducted that are not necessary, such as planting winter wheat later in the season when there will be a low incidence of disease.

Barley yellow dwarf causes such sporadic damage that its impact range has changed over the years. In many places where it used to cause significant yield losses, such as Italy, the U.K., and Australia, it is no longer a problem. This change in incidence may be due to successful management practices taken by the growers. However, the disease is becoming a more substantial problem in areas such as the northern United States, and areas such as these are in need of more successful management techniques. Due to recent concerns on the safety of neonicotinoids as sprays and seed coating in agriculture and in particular for pollinators' health, the use of these chemicals is becoming less popular worldwide. For instance, they were banned in Montreal in 2015, and temporarily in the EU since 2013. This change in cultural practices and in policies could mean a new shift in management tactics for BYD.

In order to more precisely manage BYD, DSSs that track the status of disease risk on a field to field basis will be likely employed in the future. As can be seen from the current management techniques used in BYD affected areas, there is an impact of location and climate on disease severity and utility of management tactics, thus DSSs that use a combination of geographic information, simulation models, and decision rules to track disease will be particularly useful [107]. A decision system that can accommodate existing BYD simulation models e.g., [27,29,109] has been developed to input into a DSS platform for BY [117]. This and similar DSS platforms will likely lead to more efficient agricultural practices and reduce unnecessary monetary and environmental costs, linked to the management of pests and diseases in agriculture.

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