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Management of aphid and BYDV risk in winter cereals

S. White[1], S. Telling[1], H. G. Griffiths[2], D. J. Skirvin[3], M. Williamson[4], S. Ellis[5], T. Schaare[6], R. E. Granger[7] and O. Potter[8]

[1]ADAS Boxworth, Battle Gate Road Boxworth, Cambridge CB23 4NN

[2]ADAS, 10 Stillhouse Lane, Bristol BS3 4EB

[3]ADAS Wolverhampton, Unit 14, Newton Court, Pendeford Business Park, Pendeford, Wolverhampton WV9 5HB

[4]Rothamsted Research, Harpenden, Herts, AL5 2JQ

[5]ADAS Starcross, Starcross Environment Agency Building, Devon, Exeter EX6 8PF

[6]BASF Digital Farming GmbH, Im Zollhafen 24, 50678 Köln, Germany

[7]Limagrain UK, Rothwell, Market Rasen, Lincolnshire LN7 6DT

[8]KWS UK Limited, 56 Church Street, Thriplow, Royston, Hertfordshire SG8 7RE

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1. Abstract

Barley yellow dwarf virus (BYDV) is the main virus disease of cereals in the UK, capable of causing yield losses of up to 80% in winter barley and 84% in winter wheat. It is transmitted primarily by bird cherry-oat aphid (*Rhopalosiphum padi*) and grain aphid (*Sitobion avenae*). Control of these aphids has changed dramatically in recent years, with the loss of neonicotinoid seed treatments and the appearance of moderate levels of pyrethroid resistance in *S. avenae*. Control now relies on foliar applications of pyrethroid insecticides, meaning management has progressed little in forty years. Increased use of pyrethroids risks stronger or new forms resistance appearing in BYDV vectors. Concerns over the optimal timing of foliar insecticides, overuse of insecticides and insecticide resistance mean that the development of integrated pest management (IPM) for BYDV is critically important. This project aims to 1) optimise monitoring of BYDV risk, and 2) develop decision support systems (DSS) for guiding the use of insecticides and non-chemical control of BYDV. Monitoring will be improved by understanding the relevance of suction trap data for surrounding farms, identifying effective in-field monitoring methods and comparing the cost-effectiveness of different monitoring methods. New DSS will be developed from previously published models by updating and improving them, before being validating in field surveys and trials.

Crop surveys showed that suction trap data on aphid numbers was reliable over a smaller area than previously thought, though data on the percentage of aphids carrying BYDV (% viruliferous) was reliable over a greater area. Water traps were found to be the most effective method of monitoring *R. padi* within crops, though plant inspection may be the only effective means of monitoring *S. avenae*. A BYDV monitoring scheme is proposed. *R. padi* were found far more frequently than *S. avenae* in all regions. The % viruliferous aphids was notably higher than in previous surveys, especially the RPV serotype, which has implications for varietal tolerance and resistance.

The ACroBAT DSS developed in this work predicts aphid population dynamics, BYDV epidemiology and risk. It has two functions: 1) a spray support DSS, for use once the crop has been sown to provide guidance on the need for sprays and their optimal timing, and 2) a cultural control DSS, for use as far in advance of drilling as desired, to assist in making choices that can reduce risk, such as field selection, drill date and varietal choice. The model accounts for a range of important variables relevant to BYDV management, such as drill date, aphid pressure, % viruliferous aphids, varietal tolerance and crop economics, with spray decisions calculated based on whether an insecticide is economically worthwhile to prevent the predicted yield loss. ACroBAT was able to accurately predict BYDV symptoms in surveys of untreated crops. In trials, BYDV control was as good as, if not better than, the T-sum tool, but with fewer insecticide applications, and provided yield benefits where BYDV was present. However, BYDV was generally low in these trials.

2. Introduction

Barley yellow dwarf virus (BYDV) is the main virus disease of cereals in the UK (O'Driscoll et al., 2019). It is spread by several aphid species, the control of which has changed dramatically in recent years, moving from a reliance on neonicotinoid seed treatments to the use of foliar insecticides. However, concerns over the optimal timing of foliar insecticides, overuse of insecticides and insecticide resistance mean that the development of integrated pest management (IPM) for BYDV is critically important.

2.1. Barley yellow dwarf virus (BYDV)

BYDV is a circulatively and persistently transmitted *Luteovirus* affecting wheat, barley, oat, rye and triticale crops worldwide. It was first reported in the UK in 1957 (Watson & Mulligan, 1957) and was recently estimated to affect 82% of winter wheat and 81% of winter barley crops based on the proportion of crops treated with insecticides (Clarke et al., 2009). However, the actual area affected is generally much lower and fluctuates widely between years; surveys found 38%, 10%, 45%, 0%, <1%, 0% and 4% of fields contained BYDV-infected plants in 1996, 1997, 1998, 2009, 2010, 2011 and 2012 respectively (Foster et al., 2004; Flint, 2015). The virus is transmitted by all three main aphid pests of UK cereals; grain aphid (*Sitobion avenae*), bird cherry-oat aphid (*Rhopalosiphum padi*) and rose-grain aphid (*Metopolophium dirhodum*). However, in winter cereals only *R. padi* and *S. avenae* are considered important vectors because *M. dirhodum* is rarely seen in crops in the winter, overwintering on roses instead (McGrath & Bale, 1989; Dewar et al., 2016).

Several serotypes of the virus are known globally but three predominate in the UK: MAV, PAV and RPV (Plumb, 1974). PAV is considered the most virulent and is transmitted primarily by *R. padi* and less efficiently by *S. avenae* (Rochow, 1969a; Plumb, 1974; Barker, 1990). MAV causes relatively mild infections and is transmitted primarily by *S. avenae*, less efficiently by *M. dirhodum* and rarely by *R. padi* (Rochow, 1969a; Plumb, 1974). RPV is transmitted by *R. padi* and reports of its virulence vary from the weak (Rochow, 1969a; Rochow, 1969b; Almasi *et al*., 2015) to severe (Smith, 1967; Plumb, 1974). It should be noted that RPV has since been reclassified as *Cereal yellow dwarf virus*-RPV (CYDV-RPV) based on differences in nucleotide sequences but is otherwise similar to BYDV (Miller et al., 2002; Almasi et al., 2015).

Aphids can acquire the virus from an infected plant in as little as 15 minutes to four hours, but acquisition is more likely when aphids feed for 20 or more hours (Carrigan et al., 1983; Gray et al., 1991; Power et al., 1991). Infected aphids are able to transmit the virus to uninfected plants when feeding for as little as two hours but the likelihood of infection increases as the duration of feeding increases (Van der Broek & Gill, 1980; Gray et al., 1991; Lowles et al., 1996). The BYDV serotype, aphid species and temperature all affect this inoculation efficiency (Van der Broek & Gill, 1980; Gray et al., 1991; Lowles et al., 1996). For instance, PAV is more efficiently transmitted than MAV (Van der Broek & Gill, 1980; Lowles et al., 1996), *R. padi* transmits more efficiently than *S. avenae* (Gray et al., 1991; Power et al., 1991) and infection efficiency drops between 12°C and 6°C (Lowles et al., 1996). The latter means that small changes in autumn and winter temperatures can have important impacts on infection efficiency. Adult and nymph *R. padi* and *S. avenae* are equally efficient vectors (Gill, 1970).

The virus affects yield formation in several ways, including reducing plant height, grains per m^2, tillers per plant, grains per ear and thousand grain weight (Yount et al., 1985; McKirdy & Jones, 2002). Yield losses of up to 80% in winter barley (Dedryver et al., 2010) and 84% in winter wheat (Nancarrow et al., 2021) have been reported, though such cases are rare. A linear relationship between the percent of plants infected and yield loss has been shown (Smith & Sward, 1982; Perry et al., 2000). While work from elsewhere in the world has shown that yield impacts in wheat can be as bad, or worse, than in barley (Yount et al., 1985; Nancarrow et al., 2021), trial work and crop observations in the UK have tended to indicate that barley is more severely affected in this country (Doodson & Saunders, 1970; Bassett, 1985; Foster et al., 2004).

In winter cereals, infections tend to appear from April onwards as discoloured and/or stunted patches or foci, which represent areas where aphids have introduced the virus to plants in the centre of the patch and subsequently spread to neighbouring plants, carrying the virus with them. Symptoms of the virus differ between crops, with wheat tending to exhibit red and yellowing of leaves (Fig. 1). In barley, leaves turn a striking chrome yellow (Fig. 1). In oats, symptoms appear as a reddish purpling. Discolouration of leaves in all these crops starts from the leaf tip and margins before progressing across the rest of the leaf.

Yield loss is strongly affected by the growth stage at infection, with the highest impacts tending to occur with infection at earliest growth stages followed by a gradual decrease in yield loss with later growth stages up until growth stage 31/32 (Smith, 1967, Doodson & Saunders, 1970). New infections beyond growth stage 31/32 have negligible yield impact (Smith, 1967, Doodson & Saunders, 1970). Evidence regarding the effect of viral load (i.e. the number of aphids transmitting the virus to a single plant) is mixed, with some reporting that an increased numbers of viruliferous aphids per plant produce greater yield impacts (Smith, 1967; Burnett et al., 1975) while others report some increased symptoms but no effect on yield or plant virus content (Boulton & Catherall, 1980; Skaria et al., 1984). Overall, it seems that yield impact is primarily a function of the proportion of the crop infected and timing of infection (ie. the growth stage at infection). The factors that are likely to have the greatest impact on this is the duration of autumn aphid migration, the percentage of aphids carrying the virus, the viral serotype, sow date and autumn/winter conditions, which affect crop emergence, aphid flight into crops and the spread of aphids within crops.

Figure 1. Typical BYDV symptoms in wheat (left) and barley (right). Images copyright of ADAS.

2.2. Biology of BYDV vectors

The three main aphid pests of UK cereals (*R. padi, S. avenae* and *M. dirhodum*) differ in their life cycles and host selection. Their prevalence in crops also varies throughout the year and so affects their risk of infecting crops with BYDV. As mentioned above, *M. dirhodum* is not considered to be an important BYDV vector in winter cereals and so is not covered here.

In the UK, *R. padi* exists in both a holocyclic, host-alternating form and an anholocyclic form. In the holocyclic form, *R. padi* migrate from bird cherry trees (the primary and overwintering host) to grasses and cereal crops (their secondary hosts) in the spring as viviparous females (those that give birth to live young through parthenogenesis). These then persist and multiply throughout the spring and summer, causing direct feeding damage, until cereals begin to senesce. Senescence in cereals lowers their nutritional value, triggering the formation of winged (alate) viviparous females which move to other secondary hosts in mid-summer, primarily grasses and cereal volunteers (Dixon, 1971; Leather & Dixon, 1981). In autumn, the increase of natural enemies and diminishing nutritional value of grasses encourage the production of winged gynoparae (viviparous females that produce sexual offspring) and the migration back to the primary host (Way & Banks, 1965; Dixon, 1985). Oviparous females (sexual) and males mate on the primary host and then lay eggs which overwinter until emerging as fundatrix (viviparous females produced from sexual reproduction) the following spring. Fundatrix produce alate viviparous females which move from bird cherry trees to grasses or cereals, beginning the cycle again. As BYDV is not passed between parent and offspring, aphids moving from bird cherry in the spring must feed on an infected plant to be inoculated with, and subsequently spread, the virus.

In the anholocyclic form, *R. padi* is entirely parthenogenic (producing live young asexually) and non-host alternating, existing solely on grasses and cereals throughout the year. This form is most common where the primary host, bird cherry, is scarce (Dewar *et al*., 2016) and where winter conditions are mild (Harrington et al., 2012). The live young are much less able to tolerate cold winter conditions than the eggs laid on bird cherry trees. As the anholocyclic form migrates to winter cereals in the autumn, rather than bird cherry trees, it is this form that poses the threat of carrying BYDV to winter cereals.

S. avenae is a non-host-alternating species with a host range primarily consisting of grasses, including cereals. It is almost entirely parthenogenic in the UK but sexual forms can occur rarely, a tendency more common in the north, likely due to colder winters resulting in higher mortality of the parthenogenic forms (Llewellyn et al., 2003). *S. avenae* populations increase rapidly in the spring and is the main aphid pest of wheat in the summer, causing direct feeding damage. When winter crops senesce *S. avenae* move to other grasses, cereal crops and volunteers before migrating from these to winter cereals in the autumn.

In the summer, the increase in population density of both aphid species in wild grasses can create a sink for BYDV which in turn can act as a source for infection once the aphids move to cereals (Van den Eynde et al., 2020). The main factor affecting the risk of these aphids transmitting BYDV to winter cereals is autumn and winter weather, primarily temperature. Neither species fly at temperatures at or below 10°C, while the flight threshold for 50% of individuals was 19°C and 17.5°C for *S. avenae* and *R. padi* respectively (Walters & Dixon, 1984). *S. avenae* can tolerate very cold winter conditions, with adults shown to survive at -8°C (Alford et al., 2014), although survival at -12°C has been recorded when aphids are acclimated to the cold (Powell & Bale, 2005). *R. padi* is less cold-hardy (Williams, 1980), with significant adult mortality seen at -4°C, although this may be mitigated by behavioural responses that increase low temperature survival (Alford et al., 2014), e.g. moving below the soil surface to feed on plant roots where temperatures are less cold. Temperature also affects development, reproduction and movement in both species (Dean, 1974; Williams, 1987; Smyrnioudis et al., 2000; Wiest et al., 2021), affecting the build-up of populations and movement between plants within a crop.

2.3. Chemical control

For decades, management of BYDV has relied on chemical control of the aphid vectors. Prior to 2019, most winter cereal growers in areas at risk from BYDV depended on neonicotinoid seed treatments (NSTs) for BYDV control. These provided protection for 6-8 weeks post drilling (Perry et al., 2000) and often removed the need for foliar insecticides (Holland et al., 2019b). NSTs were first available for use in winter cereals around 20 years ago. In 2000, 8% of winter wheat and <1% of winter barley was treated with NSTs (Garthwaite & Thomas, 2003). Their use soon increased so that by 2018, 48% of winter wheat crops and 35% of winter barley had NSTs (Garthwaite et al., 2019). However, a European Union ban on these seed treatments meant that they could not be used on winter cereals from 2019. A survey of farmers in 2018 found that >75% of farmers and >85% of agronomists commonly used at least one foliar insecticide and/or seed treatments for BYDV management (Holland et al., 2019b). Control of BYDV vectors now relies almost completely on foliar insecticides, with only pyrethroids registered for use. The prevailing guidance is that a foliar spray should be considered if aphids are seen (Ramsden et al., 2017a). This means that recommendations for control of BYDV has not changed substantially in decades. Given the low cost of pyrethroids relative to the potential yield impacts of BYDV infection, there is a risk of widespread prophylactic use of pyrethroids that is not related to BYDV risk. In addition to unnecessary environmental impacts, the disproportionate use of pyrethroids would increase the risk of insecticide resistance.

Resistance to pyrethroids in *S. avenae* has been present in the UK since 2011 (Foster et al., 2014). Surveys in 2019 and 2020 found the resistance to be widespread, although there were regional differences, with just 2% of individuals resistant in Devon compared to 71% in Yorkshire in 2020 (IRAG, 2021a). The mechanism of resistance is knockdown (kdr) target-site resistance (Foster et al., 2014), however resistant *S. avenae* have only been found in the heterozygous form so that the level of tolerance it confers to pyrethroids is intermediate. In terms of management, this means that applications of pyrethroids at their full label rate should still be effective (IRAG, 2021a). No resistance has been detected in UK populations of *R. padi* (Foster & Leybourne, 2021), although reduced sensitivity to pyrethroids has been detected in Ireland (Walsh et al., 2020) and high levels of pyrethroid resistance (super-kdr) have been detected in China (Wang et al., 2020; Gong *et al.*, 2021), demonstrating the ability for such resistance to arise in the UK. As pyrethroids are the only group of insecticides currently available for use against BYDV vectors, their widespread use, with no option to rotate insecticide mode of action, represents a high risk of stronger forms of resistance appearing in *S. avenae* and novel resistance appearing in *R. padi* (IRAG, 2021b).

Knowing if and when to apply foliar insecticides to control BYDV is not straightforward. During the autumn, migrating aphids flying into cereals are responsible for most BYDV infections (the alternative route is via the 'green bridge', see Section 2.4). These aphids settle on and infect a relatively small number of plants in a crop with BYDV, referred to as primary infection. As the aphids reproduce, they begin to move away from the initially colonised plants to neighbouring plants and causing secondary spread of the virus. Primary infection is thought to be the main cause of infections in cold winters, while secondary spread is associated with the greatest yield impacts in mild winters (Halbert & Pike, 1985; Teulon et al., 1999). As it is very difficult to prevent primary infection, targeting aphids to prevent or slow secondary spread is thought to be the most effective way to minimise losses to BYDV with foliar insecticides (HGCA, 2003). In an effort to help growers with timing of sprays, AHDB made a T-sum decision support system (DSS) available online (AHDB, 2023b). This model predicts the appearance of the second wingless (apterous) generation of aphids in the crop, which are the aphids thought to be associated with the start of secondary spread (HGCA, 2003). This generation begins to appear after 170 'degree days' (DD) have accumulated, above a baseline temperature of 3°C. For locations across the country and using weather forecasts, the DSS carries out the calculation for the user and indicates when the second wingless generation of aphids are likely to appear, recommending a crop inspection and for an insecticide to be considered (monitoring is discussed further in Section 3). The T-sum tool is also available through other providers, e.g. Syngenta. However, there are several concerns regarding the T-sum tool. These, and other DSS, are considered further in Section 4.

As aphids tend to arrive first at the crop margins, it has been suggested that selective spraying could target the crop headlands, but this would have to happen before the start of secondary spread (Holland et al., 2019b). Such an approach would also need to consider the restrictions associated with spraying near field boundaries and the risks to invertebrates in field margins. These could be mitigated by spraying only in very low wind conditions and using low-drift nozzles (Holland et al., 2019b).

Whether sprays decisions are based on the T-sum DSS or the mere presence of aphids, a key consideration that is lacking is the proportion of aphids carrying the virus (Gillet et al., 1990; Harrington et al., 1999; Dedryver et al., 2010). Currently, any *S. avenae* or *R. padi* are assumed to be carrying BYDV but previous work has shown that only a small proportion typically do (Plumb, 1976; Torrance et al., 1986; McGrath & Bale, 1989; Holland et al; 2019b). Developments in molecular testing mean it is now feasible to generate data on the proportion of aphids carrying the virus relatively quickly and affordably.

2.4. Non-chemical control

Risk factors: In their comprehensive study, Foster et al. (2004) identified several risk factors for BYDV. The presence of aphids in the autumn was a key risk, for obvious reasons. Sow date was one of the most important indicators of risk and is discussed further below. The most important of the remaining risk factors were proximity to the sea (especially the south, south west and west coasts), the presence of permanent grassland in the vicinity, and field aspect. Proximity to the sea is likely important due to the associated mild winter temperatures, which increase aphid activity. Permanent grassland provides a source of aphids and BYDV. Holland et al. (2019b) also found significantly more aphids in crops where the proportion of grass in the landscape was high, and that aphid numbers tend to be higher adjacent to woodland and treelines. *R. padi* and PAV were found more often in fields with a south-western aspect, while *S. avenae*, MAV and RPV were found more commonly in eastern and southern aspect fields. These associations were attributed to effects on the arrival of migrating aphids and crop microclimates. See Foster et al. (2004) for further details of other, less important risk factors.

Sowing date: The date of crop emergence is possibly the most important factor determining risk from BYDV. A survey by Foster et al. (2004) found that crops sown before mid-September had almost five times as many infected leaves as those sown after mid-October. Trials have consistently shown that delaying drilling reduces BYDV infection and yield loss (McGrath & Bale, 1990; McKirdy & Jones, 1997; Kennedy & Connery, 2001; Royer et al., 2005), for example plots sown at the start of September had 11% of plants infected while this was close to nil for plots sown in mid or late September (McGrath & Bale, 1990). This was due to the reduced number of aphids and plants infested with aphids found in later drilled plots (McGrath & Bale, 1990; McKirdy & Jones, 1997; Kennedy & Connery, 2001; Royer et al., 2005), for example plots sown at the start of September had 21% of plants infested while this was 6% and 3% for plots sown in mid or late September respectively (McGrath & Bale, 1990). Essentially, delayed sowing avoids the bulk of aphid migration and can experience less secondary spread due to cooler conditions. There are trade-offs with delayed drilling in that deteriorating weather can reduce the ability to drill crops and yields can be reduced if BYDV pressure is low (Plumb, 1983; McKirdy & Jones, 1997; Spink et al., 2000), however yield reductions are not always seen (McGrath & Bale, 1990; McKirdy & Jones, 1997; Royer et al., 2005).

Green bridge: Crops can become infested with aphids that are already present in the field, living on grass weeds or cereal volunteers. Any grass weeds pose a risk but crops following permanent grass or grass leys are at greatest risk. Control options include destroying the weeds using cultivation or an effective herbicide. However, as unpublished ADAS work has shown that *R. padi* can survive, reproduce and feed when buried 20 cm deep before emerging at the surface six weeks later (Bassett, 1984), weeds ought to be controlled suitably in advance of drilling. Guidance in the 1980s recommended ploughing 4-6 weeks before drilling but that the interval could be shorter if glyphosate was used (Plumb, 1983). Current guidance is to destroy any weeds (especially volunteers and annual meadow grass), leaving five weeks before cultivating and sowing (AHDB, 2023c).

Ploughing is much less employed currently compared with the 1980s, usually by those with serious blackgrass problems and even then, no more than every three years (L. Tatnell, pers. comm.). Grass weed control in winter cereals now focuses on the monitoring and management of weed resistance, with an emphasis on a sterile seedbed approach in which the field is given a shallow cultivation after harvest to encourage grass weeds and volunteers to chit then, once there is a good flush of weeds, treated with glyphosate (Cook & Tatnell, 2018). This cycle usually happens once but some growers repeat the process if time and conditions allow. If glyphosate is used, care should be taken to ensure that dying weeds do not coincide with the emerging crop as this will encourage the aphids to move across to colonise the crop rapidly, potentially infecting it with BYDV at a very damaging early stage. If glyphosate were to be banned or its use restricted this would have serious implications for weed and 'green bridge' management, with approaches used in organic farming (e.g. using crimper rollers) being more widely used.

The current approaches to weed management mean that 'green bridges' are more likely to be present for BYDV vectors, and so their implications for BYDV management should be given careful consideration, especially in areas at high risk from BYDV. In situations in which a 'green bridge' is present it is suggested that monitoring of BYDV vectors happens in weeds and volunteers prior to drilling and in crops soon after emergence. If wingless aphids (apterae) are found in crops soon after emergence an insecticide is likely needed.

Tillage: Multiple trials have shown that minimum tillage reduces aphid numbers and BYDV infection compared to conventional tillage (Kendall et al., 1991; Kennedy et al., 2010; Kennedy & Connery 2012). Kendall et al. (1991) found direct drilled and non-inversion tilled plots suffered <3% and 9-24% BYDV compared to >40% BYDV in ploughed plots, and that direct drilling provided equivalent BYDV reductions to that in the insecticide treated discard areas. Kennedy et al. (2010) found that minimum tillage (shallow tine cultivation without soil inversion) resulted in up to 71% less BYDV than ploughing. Incorporating straw into the soil also reduced BYDV (Kendall et al., 1991; Kennedy et al., 2010). The effect has been attributed to increased natural enemy activity and/or an interference with the ability of migrating aphids to find the crop. Kendall et al. (1991) found the greatest number of aphid predators in direct drilled plots and the least in ploughed plots. Other work has shown that minimum tillage increases the abundance and activity of aphid predators and parasitoids (Kennedy et al., 2013; Tamburini et al., 2016). It has been suggested that, by reducing the contrast of the green foliage against the dark soil, minimum tillage affects the visual cues used by flying BYDV vectors (Kendall et al., 1991; Kennedy et al., 2010; Kennedy & Connery 2012) and while this has not been proven for BYDV vectors, work has shown that summer *R. padi* morphs do prefer artificial targets with a high percentage of light in long (green-yellow) wavelengths (Schröder et al., 2014) and autumn *R. padi* morphs (gynoparae and oviparae) prefer green foliage (Archetti & Leather, 2005), while other aphid species are known to use the contrast between brown and green as a visual cue (Kennedy et al., 1961). However, the effect of tillage has not always been apparent; Foster et al. (2004) found no effect on risk and Holland et al. (2019b) found no effect on migration or natural enemies. Further work is needed to determine the potential benefits of minimum tillage.

Natural enemies: Cereal aphids have a range of natural enemies, including rove beetles, ground beetles, spiders, hoverflies, ladybirds, parasitic wasps and entomopathogenic fungi (Holland & Oakley, 2007). The role of these for controlling cereal aphids in the summer has been well demonstrated (e.g. Plantegenest et al., 2001; Ramsden et al., 2017b) but their importance in the autumn is poorly understood, although it has been shown that *R. padi* carrying BYDV are attacked more often by parasitic wasps (de Oliveira et al., 2014). Modifying habitats surrounding fields has great potential to support and enhance natural enemy activity in crops (Olson & Wäckers, 2007; Greenop et al., 2019). Further work is needed to understand which natural enemies are present in the autumn and ways to improve their activity.

Plant breeding: Several sources of genetic resistance to BYDV or its vectors have been identified for breeding into commercial wheat and barley. In barley, four genes associated with resistance/tolerance to BYDV have been described: *Ryd1*, *Ryd2*, *Ryd3* and *Ryd4Hb* (Jarošová et al., 2016). Several barley varieties containing *Ryd2*, and so tolerant to BYDV, are commercially available in the UK (e.g. KWS Amistar and LG Rafaela). BYDV tolerance/resistance genes in wheat have been more difficult to identify, but several genes have been located in wheat and its relatives (Zhang et al., 2009; Jarošová et al., 2016; Aradottir & Crespo-Herrera, 2021). Commercial wheat varieties resistant to BYDV have recently become available in the UK (e.g. RGT Wolverine), and further varieties, with a wider range of traits, are due to market in 2023 (de la Pasture, 2022; CPM, 2023). There are no examples of cultivars resistant to *R. padi* or *S. avenae*, primarily because screening for resistance to these aphids is difficult and only moderate levels of resistance have been found so far (Jarošová et al., 2016; Aradottir & Crespo-Herrera, 2021). BYDV tolerance/resistance is now a recognised important genetic trait targeted by most cereal breeders, and further material is coming through the pipeline and will be recognised by the AHDB Recommended List panel as an important attribute for listing on future AHDB Recommended Lists (R. Granger, pers. comm.). Plant tolerance/resistance represents a welcome addition to the BYDV management toolbox, offering growers security, although, as with resistance/tolerance genes to other pathogens, the genetics will need protecting through gene pyramiding (Aradottir & Crespo-Herrera, 2021) and/or the use of other

BYDV management methods. Plant breeding for BYDV vector and BYDV tolerance/resistance is reviewed in detail in Jarošová et al. (2016) and Aradottir & Crespo-Herrera (2021).

Trap crops: There is some suggestion that in the autumn cereal aphids initially arrive at the crop border before central areas of the crop (Holland et al., 2019a). This behaviour has been used to investigate trap crops more attractive to these aphids that could be planted at crop borders (Schröder et al., 2014; Schröder et al., 2015), an approach which could draw them away from the cash crop and reduce virus spread. The use of heritage wheat varieties as a border trap crop for BYDV management is currently the subject of an AHDB-funded PhD studentship (Cunningham, 2021).

Companion/Intercropping: The use of companion or intercrops has the potential to reduce BYDV risk by interfering with the ability of migrating aphids to find the crop (e.g. by reducing the soil to plant contrast) and/or by increasing natural enemy activity. Most work in this area has focussed on growing winter wheat with white clover or oilseed rape and has consistently shown reductions in aphids and BYDV compared to conventional crops (Clements & Asteraki, 1993; Burke et al., 1998; Clements & Donaldson, 1998; Wang et al., 2011). Further work is needed to determine the potential for such an approach.

Biopesticides: Several biopesticides have shown promise for controlling cereal aphids. An aphid alarm pheromone has been shown to reduce aphid numbers, BYDV and yield loss (Dawson et al., 1988). Wheat supplemented with silicon was found to be less attractive to *R. padi* and more attractive to its parasitoids (de Oliveira et al., 2020). Cereals treated with methyl salicylate, a herbivore-induced plant volatile, have lower incidence of *S. avenae* and *R. padi* and higher natural enemy populations (Ninkovic et al., 2003; Wang et al., 2011; Wang et al., 2019). In other work, entomopathogenic fungi (Hsiao et al., 1992; Mahmood et al., 2019; Rasool et al., 2020) and botanical extracts (Ali et al., 2018) have also shown potential as control methods, although much of this work occurred in controlled environment conditions so the challenge remains whether effective control can be achieved in the field in the autumn. It should be noted that management of BYDV does not necessarily need to entail killing aphids. The focus of BYDV management is on slowing the rate at which plants become infected before winter conditions severely reduce aphid activity. Therefore, biopesticides that reduce the spread of aphids within the crop (e.g. by slowing development, fecundity or movement, or increasing natural enemy activity) may be effective for minimizing BYDV infection and yield loss.

2.5. Aims and objectives

The development of IPM is a priority in BYDV management. Potential components of an IPM programme include varietal resistance/tolerance, pest monitoring, cultural control, DSS, biopesticides and biological control. This project will focus on pest monitoring, DSS and resistant/tolerant varieties. The project primarily aims to develop improved methods for monitoring BYDV risk and decision support systems (DSS) to guide the use of insecticides and cultural controls. Specific objectives are:

Objective 1: Optimising monitoring of the risk from *Barley yellow dwarf virus*

Objective 1.1: Understanding the relevance of suction trap data on assessing BYDV risk for surrounding fields.

Objective 1.2: Determining the relationship between aphid numbers in crops and those in suction traps and in-field traps.

Objective 1.3: Investigating the potential of image analysis techniques for identifying BYDV vectors.

Objective 1.4: Comparing the cost-effectiveness of different BYDV vector monitoring methods.

Objective 2: Developing DSS for guiding the use of insecticides and non-chemical control of BYDV

Objective 2.1 Develop DSS for guiding spray decisions and cultural control.

Objective 2.2: Validate the DSS in surveys and trials.

3. Optimising monitoring of the risk from *Barley yellow dwarf virus*

3.1. Introduction

Objective 1 of this project focuses on improving monitoring of *R. padi* and *S. avenae* and the proportion of their populations that carry BYDV. Current guidance dictates that crops should be monitored for the presence of these aphids before the use of foliar aphicides is considered. Monitoring involves visually inspecting plants for the aphids, although other resources, such as the national network of suction traps that form part of the Rothamsted Insect Survey (RIS) and AHDB's T-sum tool (AHDB, 2023b), can help in timing monitoring effort. This work will assess the efficiency and reliability of current monitoring methods for BYDV vectors and investigate the potential of alternative monitoring methods.

3.1.1. Understanding the relevance of suction trap data for assessing BYDV risk in surrounding fields

The RIS suction trap network, developed and run by Rothamsted Research, generates data on the number of alate aphids present across the year for a range of agriculturally important species. Currently, there are 16 operational suction traps in England and Scotland, located in areas of agricultural importance. The 12.2 m high traps catch flying insects and are emptied approximately daily from spring until November/December. Weekly summary data on the numbers of a range of aphid species caught at each trap is made freely available in 'Aphid Bulletins' on the RIS web page. Additional comments on the presence of other pests and natural enemies are also made available through their 'RIS Remarks' bulletins. The 'Aphid Bulletins' and 'RIS Remarks' can be subscribed to via email. A free text service specifically providing information on the numbers of BYDV vectors and *Myzus persicae* (the vector of a number of viruses including Turnip yellows virus in oilseed rape) is also available from April until June and during the autumn.

Since 2019, the RIS data on aphid numbers has been complemented by data on the percent of cereal aphids carrying BYDV (% viruliferous) at a small number of suction traps. The % viruliferous data is generated using a novel RT-PCR assay developed by project partner, Rothamsted Research. Previously, this data could only be generated using infectivity assays or enzyme-linked immunosorbent assays (ELISA). However, infectivity assays are labour and resource intensive, and results take several weeks to generate (Catherall, 1963; Torrance et al., 1986; McGrath & Bale, 1989; Gillet et al., 1990). ELISA also has limited sensitivity (Fabre et al., 2003), though is more sensitive than infectivity assays (Torrance et al., 1986), so both methods can lead to false negative results. The novel RT-PCR approach is highly sensitive and presents the opportunity for rapid testing of aphids caught in traps to provide 'real time' data on % viruliferous aphids. It has previously been successfully used to test aphids caught on sticky traps for the presence of the virus (Bates et al., 2020).

The suction trap data on aphid numbers and % viruliferous aphids allows growers to use the nearest suction trap to determine when the migration of BYDV vectors is underway in their area, guide monitoring effort, evaluate the risk of BYDV and adjust their management decisions accordingly. It has also been demonstrated that this data can be used to predict crop infestation from both pea and cereal aphids (McVean et al., 1999; Harrington et al., 1999). However, some growers and agronomists have questioned the reliability of the data for their farms. The RIS web page states that each "trap is representative of what is flying over an area of radius approximately 80 km" (Rothamsted Research, 2023). The relationship between the number of aphids caught in the Rothamsted Tower suction trap and those caught in surrounding fields was investigated by Harrington et al. (1999). They found a significant correlation between *R. padi* numbers caught in the suction trap and those in fields up to 39 km away. However, it is unknown whether this relationship is applicable to traps in other areas of the country, with their different climates and topographies. The relationship between % viruliferous aphid data obtained from suction traps catches and that from surrounding fields is unknown.

This objective sought to expand on the work by Harrington et al. (1999) by evaluating the reliability of suction trap data for surrounding farms in several regions across England. The suction traps selected for this work were chosen as being in the main cereal growing regions and because they represented a range in cereal aphid and BYDV pressures. Farms around each suction trap were chosen at a range of distances and directions, and aphid numbers and % viruliferous aphid data were assessed in crops throughout the autumn. This data was then compared with that from the suction trap, with the aim being that the distance and direction from each suction trap at which the data remains reliable could be identified. This might then produce a zone around suction traps wherein growers can confidently rely on suction trap data. The work might also identify factors which increase or decrease the reliability of the suction trap data. Beyond this zone, growers would likely have to rely on in-field monitoring to determine BYDV risk.

In-field monitoring currently involves visual inspection of plants for cereal aphids in the autumn, which is an onerous task. As even low numbers of aphids can present a risk of BYDV infection, especially when they begin to spread within the crop, sufficient plants need to be checked on a regular basis. Aphids can be difficult to spot on cereals in the autumn, especially in overcast, rainy or windy conditions. They can also move to the base of the plant, even below the soil surface, when conditions are poor. Multiply this by the number of winter cereal fields sown and it is understandable that such monitoring may be a daunting prospect. This work also investigated alternative in-field monitoring methods to identify the most effective means of monitoring BYDV risk in crops.

3.1.2. Determining the relationship between aphid numbers on plants and those in suction traps and in-field traps

Pest population models that form part of DSS to gauge BYDV risk often need the number of aphids per plant as an input variable (e.g. Kendall et al., 1992; Morgan, 2000; Thackray et al., 2009). It would be useful to be able to predict the numbers of aphids per plant from data on aphid numbers caught in suction, water or sticky traps to reduce the need for laborious visual assessments of aphids on plants. This would allow monitoring using traps to readily link with the DSS developed in Section 4.

3.1.3. Investigating the potential of image analysis techniques for identifying BYDV vectors

Ensuring that the relevant aphid species is present is crucial in determining BYDV risk, but the skills necessary to distinguish *S. avenae* and *R. padi* from other aphids may be lacking in many growers and advisors, an issue likely exacerbated by the lack of need for such skills while NSTs were available. This means growers/advisors either to have to improve their identification skills or send aphids to a specialist for identification, a costly and time-consuming process. Other factors such as low light, which make the aphids and their key distinguishing features difficult to spot, can increase the difficulty of identifying aphids the autumn. Image analysis of water or sticky trap contents to identify cereal aphids would help overcome these challenges. Image analysis of insects has improved markedly in recent years (Lima et al., 2020; Hansen et al., 2022). The development of pest recognition software, either integrated into camera phones or built into insect traps, could potentially be used for identifying cereal aphids when scouting the crop (Liu et al., 2016), visiting traps (Liu et al., 2019) or even remotely through use of camera-equipped traps that transfer images wirelessly, so reducing the need for field visits (Preti et al., 2021). To test this potential, photographs were taken of traps, which were sent to the project partners Syngenta and BASF Digital Farming, where image analysis approaches were used to attempt to identify aphids present. If successful, this would allow images taken on a smart phone to be analysed in-field or when phone signal improves. This approach would reduce the need for specialist identification skills and provide relatively rapid results.

3.1.4. Comparing the cost-effectiveness of different BYDV vector monitoring methods

There are several ways in which BYDV risk can be monitored. Traditionally this has focussed on simply assessing the presence and number of cereal aphids but recent developments have made the assessment of the proportion of aphids carrying BYDV/CYDV feasible. However, while this approach is relatively affordable and practical compared with other methods (see Section 3.1.1), deploying it on a national level may come with significant costs and limitations. An alternative is to use modelling to predict the percentage of viruliferous aphids. This has been done recently in France (Fabre et al., 2005) where it was demonstrated that the percentage of viruliferous aphids in a region can be estimated using information on regional land use and temperature; specifically, the ratio of area grown to small grain cereals and that for maize, and the accumulated degree days above 5°C from January to August.

This element of the project will review the various options for monitoring BYDV vectors and the proportion carrying the virus. This will include validating the Fabre et al. (2005) model in UK conditions. It will identify the strengths and weaknesses of the options, recommend the most appropriate BYDV monitoring method and suggest whether monitoring should remain the responsibility of individual farmers or be part of a wider service. Key to any monitoring scheme is that it provides reliable information in a timely manner so effective management decisions can be taken. The scheme also needs to be affordable, to deter the use of cheap prophylactic insecticide applications, and practical, so that all growers could employ it with minimal requirement for extra work, equipment or training. Lastly, it is important that any recommended monitoring programme is taken up by enough growers to facilitate change in the industry. The main outcome of this part of the project will be a report on the most cost-effective solution to monitoring, taking into account the results of Objectives 1.1, 1.2 and 1.3. This will include consideration of the effectiveness, practicality, and cost of each monitoring method. The approach will allow users of this report to compare methodologies and tailor their programme according to their needs.

3.2. Materials and methods

3.2.1. Understanding the relevance of suction trap data for assessing BYDV risk in surrounding fields

Aphid monitoring

Each year, 3-4 suction traps were chosen that gave a wide geographic spread and a variation in risk of potential BYDV infection. In the first year (2019) the suction traps selected were Starcross (Devon), Broom’s Barn (Suffolk) and Newcastle (Tyne and Wear). The suction traps selected in the second year (2020) were York (Yorkshire), Starcross, Rosemaund (Herefordshire) and Broom’s Barn. In the third year (2021) York, Starcross, Broom’s Barn and Rosemaund were chosen. At each suction trap, monitoring sites consisting of commercial winter wheat and barley fields were chosen and grouped into distance categories. These were approx. 10 km, 20 km and 40 km away from the suction trap. Fields were arranged along the four cardinal compass points (N, E, S, W) where possible, with sites that deviated from that being grouped to the nearest cardinal compass point by degrees. The aim was that 12 monitoring fields would be selected for each suction trap; three along each cardinal direction at approximately 10, 20 and 40 km from the suction trap. This was achieved for most suction traps, except for Newcastle in 2019 (two fields monitored) and Rosemaund in 2021 (ten fields monitored). In total, 106 fields were monitored across the three years of the project: 24 in 2019, 36 in 2020 and 46 in 2021 (Fig. 2). Further site details are given in Table 1 of the Appendix.

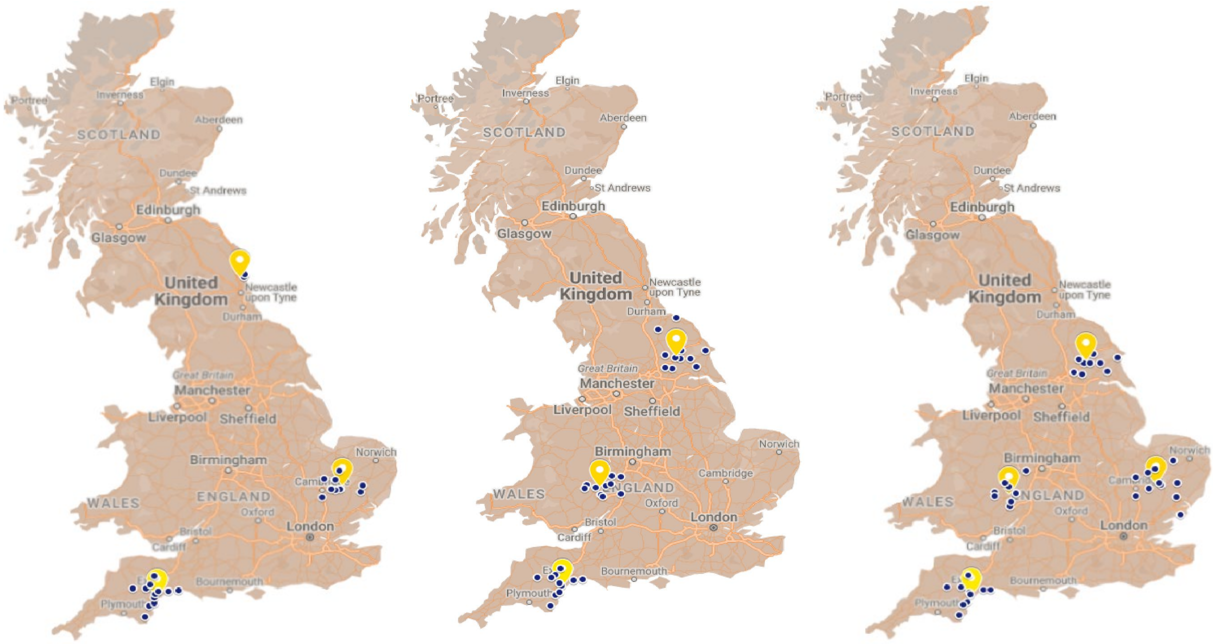

Figure 2. Monitoring sites visited in autumn 2019 (left), 2020 (middle) and 2021 (right). Yellow markers indicate the location of a suction trap, the blue dots are the monitored crops.

Aphid numbers were recorded in each field using three separate methods: on-plant observations, yellow water traps and yellow sticky traps. These methods are ones that are currently used by some growers for cereal aphid monitoring or are regularly used for monitoring other pests, and so would be simple to incorporate into BYDV vector monitoring on farms. The use of different in-field monitoring methods allowed for direct comparison to identify which is the most effective in terms of monitoring and cost. Two yellow water traps and two yellow sticky traps were placed in each site at two timings, once in October and once in November. These were placed at least 1 m from any tramline and 20 m and 70 m from the field boundary. Incidence of BYDV vectors often differs between the field edge and further into the crop (Holland et al., 2019a), so having two monitoring positions in the field allowed this to be investigated and for the optimal trap position to be identified. Trap contents were collected after 3-4 days so as to minimise reductions in the detectability of viral RNA in subsequent testing (Bates et al., 2020). Water trap contents were emptied into a sieve lined with muslin cloth, large insects that were not aphids (e.g. butterflies, large bees and wasps) were discarded, the muslin folded and placed into a screw top plastic container filled with 96% ethanol. Sticky traps were rolled with the sticky side on the inside and stapled to prevent unravelling in transit.

These were then sent to the ADAS Pest Evaluation Services at ADAS High Mowthorpe where the aphid species were identified and counted. All aphid species, including non-BYDV vectors, were identified. Aphids were then removed from the traps and placed into 7 ml screw top polystyrene pots, with different species of aphids from different traps placed into separate pots. Aphids were removed from sticky traps using a commercial alkane solvent formulation of 60% aliphatic hydrocarbon and 40% glycol ether (Mykal 'De-Solv-It Sticky Stuff Remover'®, Zep UK Ltd, Cheshire, UK). Aphids were then sent to Rothamsted Research for testing for the presence of the virus (see below).

On-plant counts took place at the time of the traps being placed in field and occurred on 100 plants. Plants were assessed in batches of 20 at five equidistant points between the two trapping locations (20 m and 70 m from the field boundary). Numbers of *R. padi*, *S. avenae* and *M. dirhodum* were recorded separately. Any other aphids found were identified to at least genus. Data on aphids caught in the suction traps was kindly provided by RIS.

Virus monitoring

The percent of viruliferous aphids in the population were ascertained from both suction traps and in-field monitoring sites. Sub samples of cereal aphids from select suction traps were tested fortnightly in summer and weekly between September until the end of suction trap sampling in December. In year 1 (2019) the selected suctions traps were Newcastle (Tyne and Wear), Starcross (Devon), Broom's Barn (Suffolk), Kirton (Lincolnshire) and Writtle (Essex). In year 2 (2020) the suction traps were York (Yorkshire), Starcross, Rosemaund (Herefordshire) and Broom's Barn, and in year 3 (2021) they were York, Starcross, Broom's Barn, Rosemaund and Edinburgh. On each occasion, up to twenty individuals of both *S. avenae* and *R. padi* were tested from each suction trap, depending on the availability of each species and up to a maximum of 96 aphids per week. Testing of aphids from in-field monitoring sites concentrated on those sites where at least ten *S. avenae* or *R. padi* were caught, so that a representative estimate of % viruliferous aphids could be calculated. All assays to detect BYDV in aphids were performed using RT-PCR by Rothamsted Research. Each assay was conducted on a single aphid and identified whether the aphid carried the MAV or PAV serotypes (but did not discriminate between the two) and/or the RPV serotype, now known as CYDV. Note the RPV assay did not start being used until September 2019, whereas the MAV/PAV assay began use in May 2019.

Data analysis

To effectively make comparisons between in-field and suction trap data on aphid numbers, both datasets were log transformed (x +1) so that skewed data approximately conformed to normality. Much of the *R. padi* migrating in the autumn is the host-alternating holocyclic form, which seek their primary host, bird cherry trees (*Prunus padus*), to complete the sexual phase of their life cycle. The remainder of the population is anholocyclic and seeks to remain on cereals and other grasses in the autumn. The only means of determining whether an individual *R. padi* is the holocyclic or anholocyclic form is by introducing it to a suitable host (e.g. a barley seedling) and observing whether it feeds and reproduces, which is not possible if it has been caught in a suction trap, or using the 'squash blot method', which involves laborious dissection (Lowles, 1995). For this reason, RIS only identify whether an aphid is *R. padi* and does not determine whether it is the holocyclic or anholocyclic form. This is problematic because we are attempting to identify a relationship between the number of aphids caught in crops, which we assume to be the anholocyclic form, and the anholocyclic aphids caught in the suction traps, which are not distinguished from the holocyclic form. Fortunately, in an analysis of 48 years of RIS data from the Rothamsted suction trap, Harrington et al. (2012) identified a relationship between the proportion of anholocyclic forms in the autumn and the mean temperature throughout the previous winter. We used a simplified version of this relationship to estimate the proportion of the total *R. padi* caught in a suction trap that are the anholocyclic form, whereby the proportion remains constant at or below a mean previous winter temperature of 4.5°C but where the mean temperature the previous winter is above 4.5°C, it increases linearly with temperature. The reason for this relationship is that, as the mobile anholocyclic aphids are less tolerant to cold winters than the eggs laid by the holocyclic forms on bird cherry trees, milder winter temperatures allow for a greater survival of the anholocyclic forms, resulting in a larger population of these forms in the following spring, summer and autumn. The equation used is given below, but see Section 4.2.4 for further details:

If the previous winter temperature (pwt) <= 4.5°C then proportion of cereal colonisers = 0.05
If the pwt >4.5°C then proportion of cereal colonisers = (0.1375 * pwt) - 0.5303
If the proportion of cereal colonisers > 0.5 then = 0.5

Temperature data for the suction traps was obtained using the ADAS IRRIGUIDE model (Silgram et al. 2007), which estimates weather for a specific site by interpolating weather data from UK Met Office weather stations.

Suction trap data on *S. avenae* and anholocyclic *R. padi* numbers and the % viruliferous aphids was compared with that from the surrounding monitoring sites. Included in this analysis is data on the percent viruliferous aphids from untreated strips used in Objective 1.2 (see Section 3.2.2). Comparisons and identification of variables that influence aphid numbers and % viruliferous aphids was analysed using analysis of variance (ANOVA). A post-hoc Duncan's Multiple Range test identified the significance of differences between individual variables. The relationship between data on aphid numbers and percent viruliferous aphids from in-field monitoring and the same data from nearby suction traps over the same time period was analysed using linear regression, where the intercept was fitted to 0. Explanatory variables investigated included distance from suction trap (sites were allocated to the nearest 10, 20 and 40 km), direction from suction trap (sites were allocated to the nearest cardinal direction), in-field monitoring method (on-plant observations, yellow water traps or yellow sticky traps), distance of trap from the field boundary and month. As the trapping data for the in-field traps and suction traps occurs over different timespans (four days and seven days respectively) the aphid count data from both sources was converted into a mean daily figure. The raw data for in-field and suction traps was transformed to monthly means for the regression analysis. Further transformation involved analysing subsets of the data according to variables such as distance, direction, month of collection, and aphid species, to identify the impact of these variables on the strength of the correlation between in-field traps and suction traps.

3.2.2. Determining the relationship between aphid numbers on plants and those in suction traps and in-field traps

Aphid monitoring

Growers were asked to leave unsprayed strips in winter wheat or barley crops at 24 sites across the three years of the project. In 2019, 12 sites were split evenly between Devon, Herefordshire, Suffolk and Yorkshire (Fig. 3). In the following years, six sites were split evenly between the Yorkshire and Devon. The areas selected in 2019 were chosen to represent the major cereal production areas in England. In 2020 and 2021 the areas were selected to represent those at high BYDV risk but are also considered to suffer contrasting aphid pressures, with *R. padi* thought to be the main vector of BYDV in the South West (Plumb, 1976) and *S. avenae* the main vector in Yorkshire (McGrath & Bale, 1989).

At each site, monitoring was performed in the unsprayed strips using on-plant counts and trapping. On-plant counts involved visually assessing 100 plants for the presence of aphids, which were identified as *S. avenae*, *R. padi*, *M. dirhodum* or other, and counted. Two yellow water traps and two yellow sticky traps were placed at each site, once in October and once in November. One of each trap type was placed approximately 10 m from the field edge and the second set of traps were placed at least 10 m away in the insecticide untreated area. All traps were placed at least 1 m from any tramline. Traps were left for 3-4 days before collection. Water trap contents were emptied into a sieve lined with muslin cloth, large insects that were not aphids (e.g. butterflies, large bees and wasps) were discarded and the muslin folded and placed into a screw top plastic container filled with 96% ethanol. Sticky traps were rolled with the sticky side on the inside and stapled to prevent unravelling in transit. These were then sent to the ADAS Pest Evaluation Services at ADAS High Mowthorpe where the aphids were identified to species and counted.

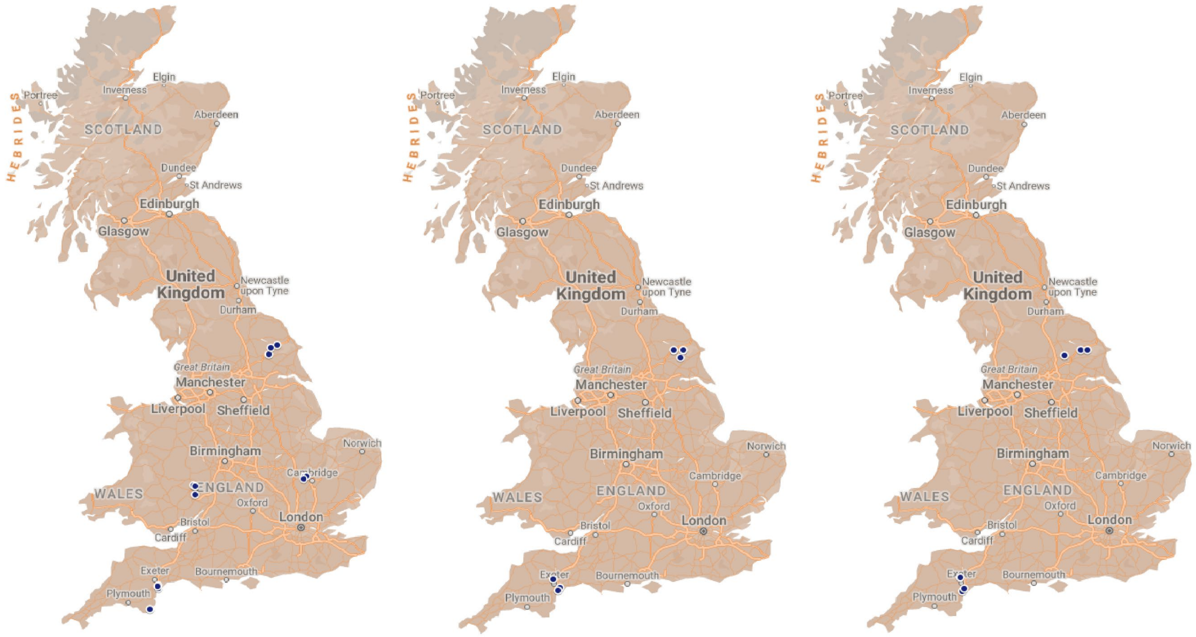

Figure 3. Untreated strips monitored in autumn 2019 (left), 2020 (middle) and 2021 (right)

Virus monitoring

The percentage of viruliferous aphids in the population were determined from aphids caught in in-field traps at four selected sites in each year using the collection and viral assay approach described in Section 3.2.1. Samples were tested for the presence of the virus if a total of 10 aphids, made up of either *R. padi* or *S. avenae*, were collected from a trap.

Data analysis

To assess the accuracy of trapping methods in determining the number of aphids that are likely to have infested a crop, comparisons between plant counts and trapping methods (suction traps and in-field traps) were performed using linear regression, where the intercept was fitted to 0. Prior to analysis, the aphid count data for all monitoring methods were log transformed (x +1) and the suction trap count data were adjusted to estimate the proportion of anholocyclic (cereal colonising) aphids using the method described in Section 3.2.1. Data on aphid numbers from monitoring sites assessed in Section 3.2.1 were included in this analysis where it had been confirmed that the host farmer had not applied an insecticide prior to an assessment timing (64 sites in total). Data on aphids caught in the suction traps was kindly provided by RIS. Data on % viruliferous aphids in untreated strips was included in the analysis of the relationship between this and the % viruliferous aphids caught at the same time in local suction traps (see Section 3.2.1).

3.2.3. Investigating the potential of image analysis techniques for identifying BYDV vectors

Images were taken of trap contents during visits to sites for monitoring work (Sections 3.2.1 and 3.2.2) or field trials carried out in Section 4. Photographs of the traps were taken in situ in the field with a smartphone camera. In years 1 and 2, guidance was simply to ensure the trap occupied the majority of the image, was in focus, well lit (so using a flash if necessary and avoiding shadow) and, if the subject was a water trap, to minimise disturbing any mud in the water that could cloud the image. Feedback from the project partners produced some minor additions in the final year; these were to take multiple photos of traps, gently stirring water traps to reduce a tendency for aphids to clump together, and pouring the contents of water traps into a white tray. Labelled photographs (in the form of files) of traps with and without aphids were then sent to BASF Digital Farming and Syngenta for image analysis.

3.2.4. Comparing the cost-effectiveness of different BYDV vector monitoring methods

Analysis of cost-effectiveness

All the monitoring methods described in Objectives 1.1 to 1.3 were considered, including quantification of their relative effectiveness, resource costs, time required and level of expertise needed. Time taken to achieve return of results was considered. Each monitoring method was broken down into its constituent tasks, with each task given a cost based on the time needed to complete it, the expertise level required plus any resource costs (e.g. for the purchase of equipment). The estimated time needed to complete the in-field tasks only includes the time needed within the crop. Travel time to the field is not included in this analysis as this will vary widely between fields and farms. The times taken for each task were estimated based on the opinions of ADAS staff and project partners experienced with the relevant task.

The value of the labour time is based on the expertise required (Table 1). The hourly rate at a basic level of expertise is based on the minimum median labour costs (Redman, 2019) with a slight adjustment to account for increases to minimum wages. The value at a low level of expertise reflects that of a farm worker with a slightly higher level of experience. The value at a medium level of expertise is based on an estimated average hourly rate for an agronomist (M. Cox, pers. comm.) or highly experienced farm worker. The value at a high level of expertise reflects the need for a high degree of proficiency in laboratory skills. The values for these hourly rates are estimates and do not represent the staff costs for ADAS or partner organisations. These hourly rates may vary widely depending on the organisation and individual and so should be treated with caution. Nevertheless, they are sufficient for the purpose of comparing these monitoring methods.

Table 1: Description of each level of expertise and associated costs.

Expertise	Cost per hour (£)	Description of expertise
Basic	15	No requirement for knowledge on aphids and basic knowledge of monitoring methods
Low	25	Ability to recognise aphids and good knowledge on monitoring methods
Medium	50	Moderate level of identification skills
High	70	High level of identification skills and/or experience with the use of molecular assays to quantify viral presence

The different monitoring methods considered are listed below. Note that for all methods of monitoring aphid numbers, it is assumed that information on aphid migration in a region is used to inform the timing of monitoring (e.g. by consulting the RIS website or signing up to text alerts). Time and expertise to do this is not included below as it used in all the monitoring methods considered. The estimated cost for each assessment method at each visit or assessment timing was calculated by:

Cost per visit = (cost per hour*time) + resource cost

Aphid monitoring methods

Method 1: Monitoring aphids using on-plant counts

This method involves manually checking 100 plants for aphids. These are identified to species and counted. The costs associated with this method are given in Table 2.

Table 2: Outline of stages and costs involved in performing on-plant counts to assess cereal aphids.

Activity	Expertise level	Time (hours)	Cost per activity (£)
Counting cereal aphids within the crop	Medium	1	50

Method 2: Monitoring aphids using water traps where aphids are identified on-farm (in situ)

This method involves putting out one yellow water trap. The trap is inspected after several days. Aphids caught are identified and counted on-farm by an individual able to identify cereal aphids to species. The costs associated with this method are given in Table 3. The price of water traps varies widely but a good quality trap is approximately £12. However, as these traps can be reused for several years, determining a cost per use is difficult (e.g. in comparison to sticky traps that are used once) so, rather than incorporate their cost at this stage, their cost will be considered later in the cost-benefit analysis.

Table 3: Outline of stages and costs involved in yellow water trap monitoring where trap samples are assessed on-farm.

Activity	Expertise level	Time (hours)	Cost per activity (£)
Setting out and collecting trap in field	Basic	0.5	7.5
Identifying trap contents	Medium	0.75	37.5

Method 3: Monitoring aphids using water traps where aphids are sent away for identification (ex situ)

This method involves putting out one yellow water trap. The trap is inspected after several days. Aphids caught are sent to an external laboratory for identification and counting, with results reported back to the farmer/advisor. The costs associated with this method are given in Table 4.

Table 4: Outline of stages and costs involved in yellow water trap monitoring where trap contents are sent away for identification.

Activity	Expertise level	Time (hours)	Cost per activity (£)
Setting out and collecting a trap in field	Basic	0.5	7.5
Preparing sample and sending for identification (includes postage)	Basic	1	15
Identification of contents and reporting results to grower	Medium	0.5	25

Method 4: Monitoring aphids using sticky traps where aphids are identified on-farm (in situ)

This method involves putting out one yellow sticky trap. The trap is inspected after several days. Aphids caught are identified and counted on-farm by an individual able to identify cereal aphids to species. Sticky traps cost approximately £0.5 each. The costs associated with this method are given in Table 5.

Table 5: Outline of stages and costs involved in sticky trap monitoring where trap contents are identified on-farm

Activity	Expertise level	Time (hours)	Cost per activity (£)
Setting out and collecting trap in field (includes purchase of a trap)	Basic	0.5	8
Identifying trap contents	Medium	0.5	25

Method 5: Monitoring aphids using sticky traps where aphids are sent away for identification (ex situ)

This method involves putting out one yellow sticky trap. The trap is collected after several days and sent to an external laboratory for identification and counting, with results reported back to the farmer/advisor. The costs associated with this method are given in Table 6.

Table 6: Outline of stages and costs involved in sticky trap monitoring where trap contents are sent away for identification.

Activity	Expertise level	Time (hours)	Cost per activity (£)
Setting out and collecting trap in field (includes purchase of a trap)	Basic	0.5	8
Preparing sample and sending for identification (includes postage)	Basic	0.25	8.75
Identification of contents and reporting results to grower	Medium	0.5	25

Method 6. Determining in-field aphid pressure using pest recognition software

If image analysis software was available that could identify aphids from traps (as investigated in Obj. 1.3), the process of determining aphid numbers is simplified and the need for a high level of identification skills is unnecessary. Currently the software being developed aims to identify BYDV vectors from traps, the costs associated for water and sticky traps are in Tables 7 and 8 respectively. Alternative software aims to be able to identify aphids directly on the crop, this removes the need to set out traps but currently is also in development. The process and associated cost is in Table 9.

Table 7: Outline of stages and costs involved in water trap monitoring using pest recognition software.

Activity	Expertise level	Time (hours)	Cost per activity (£)
Setting out and collecting trap in field	Basic	0.5	7.5
Identifying contents with recognition software	Basic	0.25	3.75

Table 8: Table 8: Outline of stages and costs involved in sticky trap monitoring using pest recognition software.

Activity	Expertise level	Time (hours)	Cost per activity (£)
Setting out and collecting trap in field (includes purchase of a trap)	Basic	0.5	8
Identifying contents with recognition software	Basic	0.25	3.75

Table 9: Outline of stages involved in the identification of aphids on plants using pest recognition software.

Activity	Expertise level	Time (hours)	Cost per activity (£)
Checking crop for BYDV vectors using pest recognition software	Basic	0.75	11.25

Determining percentage of viruliferous aphids

Determining the percentage of viruliferous aphids involves sending aphids collected from a field to a laboratory where they are tested for the presence of BYDV/CYDV. Collected aphids should be placed in 5 ml screw top tube in alcohol, ideally at least 90% ethanol, before sending to a laboratory. At least 10 aphids are needed to generate a reliable estimate of the percent aphids carrying the virus, though ideally a higher number would be used. The method for the viral assays is as described in Section 3.2.1. Currently, the cost of testing a single aphid for BYDV/CYDV is approximately £10. Tests done in bulk may potentially decrease the costs, which may lead to a reduced fee for growers. The costs involved in collecting aphids for viral assays are not included as that is part of the monitoring process described above. Costs for preparing samples for dispatch are included, this refers to the removal of aphids from the trap and placing into ethanol prior to dispatch. The costs for the purchase of containers and ethanol are not included.

Method 1: Determining percent viruliferous aphids using aphids caught in water traps

Aphids identified as BYDV vectors are removed from the water trap and posted to a laboratory. The costs associated with this method are given in Table 10. A single charge is given for the cost of preparing and running the RT-PCR and reporting the results of the assay back to the grower.

Table 10: Outline of stages and costs involved in assessing % viruliferous aphids from water traps

Activity	Expertise level	Time (hours)	Cost per activity (£)
Preparation and dispatch of sample (includes postage)	Medium	0.25	17.5
Preparation of sample for molecular analysis, running of RT-PCR and reporting of results	High	N/A	100

Method 2: Determining percent viruliferous aphids using aphids caught in sticky traps

Aphids identified as BYDV vectors are removed from the sticky trap and posted to a laboratory. Extra time is afforded to the preparation and dispatch of the aphid sample because aphids need to be carefully removed from sticky traps using a commercial alkane solvent. Occasionally aphids can clump together which increases the time taken to separate them before sending. The costs associated with this method are given in Table 11. The cost for the purchase of a commercial alkane solvent is not included.

Table 11: Outline of stages and costs involved in assessing % viruliferous aphids from sticky traps

Activity	Expertise level	Time (hours)	Cost per activity (£)
Preparation and dispatch of sample (includes postage)	Medium	0.75	42.5
Preparation of sample for molecular analysis, running of RT-PCR and reporting of results	High	N/A	100

Method 3: Determining percent viruliferous aphids using aphids collected from plants

This method involves the collection of aphids from cereal plants. Collecting sufficient aphids is likely to take a long time. On only two occasions, out of more than 200 visits that occurred to sites monitored in Sections 3.2.1 and 3.2.2, were more than 10 aphids observed on plants. This illustrates the difficulty in collecting enough aphids to reliably determine the percentage of the population that are viruliferous and is reflected in the time taken to collect aphids. The costs associated with this method are given in Table 12.

Table 12: Outline of stages and costs involved in assessing % viruliferous aphids from aphids collected on plants.

Activity	Expertise level	Time (hours)	Cost per activity (£)
Collection of aphids, preparation, and dispatch of sample (includes postage)	Medium	3.25	167.5
Preparation of sample for molecular analysis, running of RT-PCR and reporting of results	High	N/A	100

Method effectiveness

The effectiveness of each method for monitoring aphids was calculated by comparing the number of cereal aphids found with each trapping method to visual assessments of aphids on plants. Data collected from Sections 3.2.1 and 3.2.2 were used and the following calculation employed:

Effectiveness = (aphids caught using each trap type/ aphids found using plant counts)

This calculation determines the relative frequency with which aphids are found using the two trap types. It may seem a crude method of establishing effectiveness but, given that risk assessments involving models use the arrival of aphids to trigger a DSS (AHDB, 2023b) and even the most basic means of determining BYDV risk depends on establishing whether BYDV vectors are present in the crop, knowing when aphids first arrive is key. Monitoring when aphid numbers are low and first entering the crop is difficult, so this calculation of effectiveness is useful to establish which method tends to detect the most aphids. The cost effectiveness for each method was estimated by:

Cost per aphid = (cost per occasion/method effectiveness)

Validating the Fabre et al. (2005) model

Data on the percentage of viruliferous aphids caught in suction traps generated as part of Section 3.2.1 was used to validate the Fabre et al. (2005) model. The accumulated day degrees above 5°C from January to August for each suction trap was generated using the ADAS IRRIGUIDE tool, which interpolates weather data between weather stations for any given location (Silgram et al., 2007). The land use area for maize and small grain cereals for 2019 – 2021 was acquired from the Agricultural Land Use in England and Land Structure in England dataset (Defra, 2022).

As in the Fabre et al. (2005) paper, the effect of 'Year' (2019, 2020, 2021), 'Trap' (Broom's Barn, Hereford, Starcross, York) and their interaction on % viruliferous aphids was considered first. A stepwise regression was used to identify the significant factors, followed by a chi-squared test to assess the level of significance and finally a pairwise comparison to evaluate the % viruliferous aphids according to the different levels of the selected factors. 'Temp' and 'Trap' were analysed in a generalised linear model (GLM) along with their interaction. Land use was represented as the square root of the area that was sown to maize relative to small grain cereals for the regions containing the relevant suction traps. Note that due to the COVID-19 pandemic, the national land use survey data did not provide regional information in 2020 and so data for England was used instead of that for region for 2020. The effect of land use on the % viruliferous aphids was analysed with a GLM with two factors: 'Land use' and 'Year' and their interaction.

3.3. Results

3.3.1. Understanding the relevance of suction trap data for assessing BYDV risk in surrounding fields

In-field aphid monitoring

In total 1382 cereal aphids were recorded in autumn in-field trapping and on-plant observations at the monitoring sites across 2019-2021, comprising 1321 (95.6%) *R. padi* and 61 (4.4%) *S. avenae*. Low numbers of both species were recorded in autumn 2019 and autumn 2020, with a significant increase in the number of *R. padi* recorded in 2021 (df = 2, F = 6.19, p = 0.002), there was no significant difference between years with *S. avenae* (P <0.05) (Fig. 4).

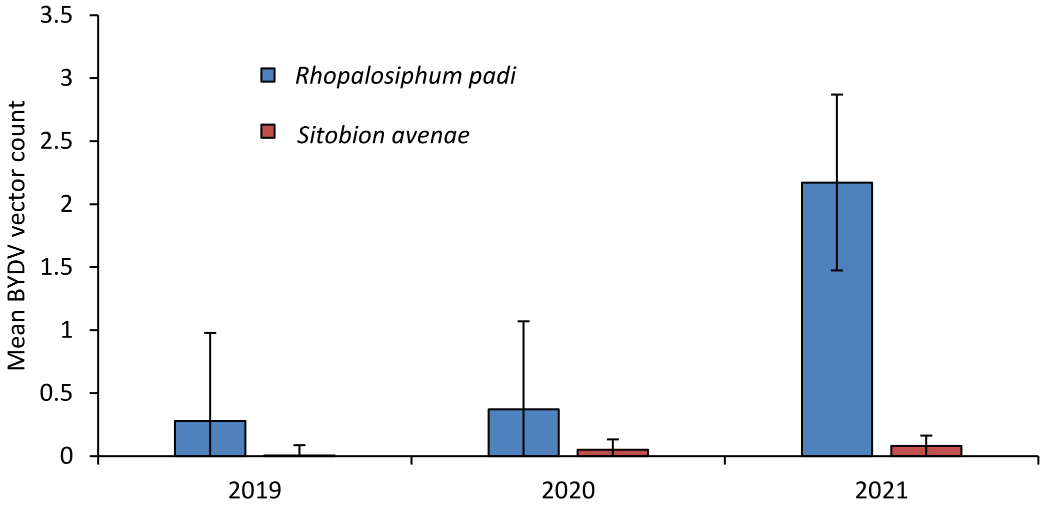

Figure 4. Mean number of BYDV vectors recorded per monitoring site from on-plant counts and sticky and water traps in each of the three years of the project. Bars represent the standard error of the mean.

In autumn 2019, 51 BYDV vectors were found in nine out of 24 monitoring sites, with no BYDV vectors recorded at the 15 remaining sites. 50 of these were *R. padi*, of which 48 (96%) were recorded in monitoring sites around the Broom's Barn suction trap, two aphids were recorded in monitoring sites near to Starcross and no *R. padi* was found in sites near to the Newcastle suction trap (Fig. 5). A single *S. avenae* individual was recorded in a site near the Newcastle suction trap. Assessments took place in November and December, with no aphids being recording in December.

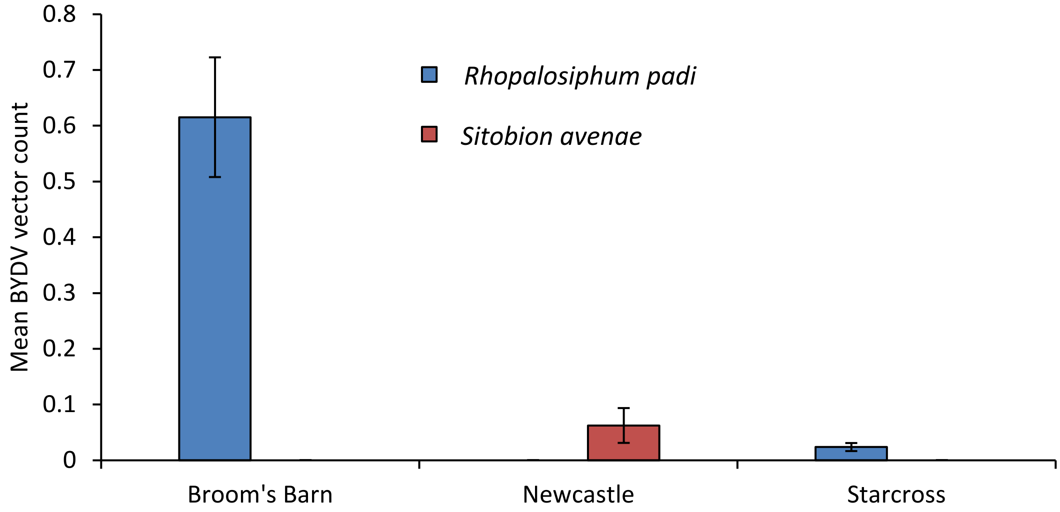

Figure 5. The mean number of BYDV vectors recorded at monitoring sites around suction traps in November 2019. Bars indicate the standard error of the mean.

In 2020, a total of 141 BYDV vectors were recorded 18 out of the 36 monitoring sites; there were no BYDV vectors recorded in the remaining 18 sites. 124 were *R. padi*, of which 46 (37%) were recorded at monitoring sites in the area around the Hereford suction trap, 37 (30%) in sites around Starcross suction trap and 41 (33%) in sites around the York suction trap. 17 *S. avenae* were found, of which two (12%) were recorded from Hereford sites, one (6%) from Starcross, and 14 (82%) from York. Most aphids at York monitoring sites were found in October (65%), whereas most aphids at Starcross monitoring sites were found in November (Fig. 6). Assessments only took place in November for the Hereford monitoring sites.

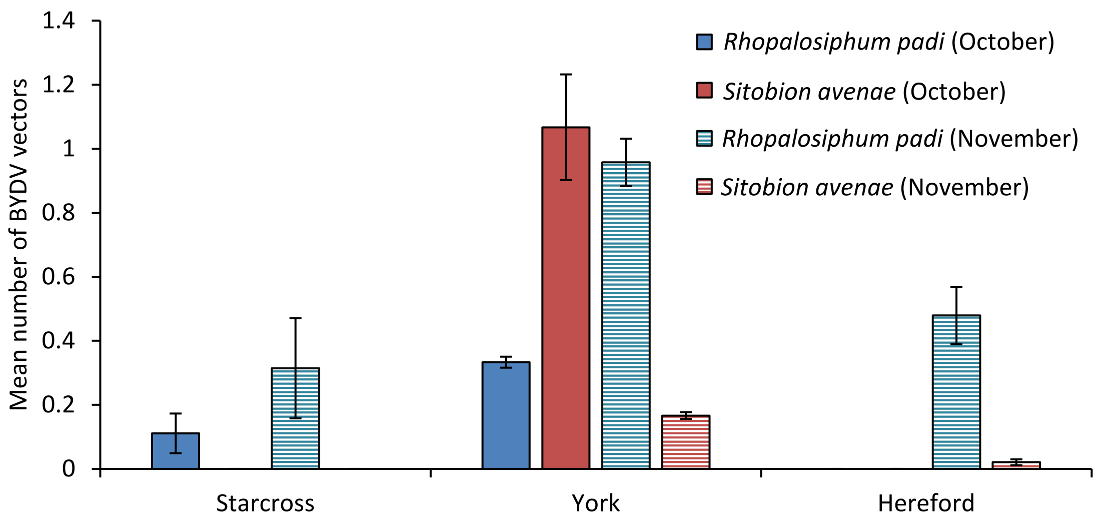

Figure 6. The mean number of BYDV vectors recorded at monitoring sites around each suction trap in autumn 2020. Bars indicate the standard error of the mean.

In 2021, 1190 aphids were recorded in 42 out of 45 monitoring sites, with no aphids being found in the remaining three sites. 1147 (96%) of the aphids were *R. padi* and 43 (4%) were *S. avenae*. 91% of the *R. padi* were recorded at sites around the Broom's Barn and Hereford suction traps (55% and 36% of *R. padi* respectively). 34 (79%) of the *S. avenae* were recorded at Broom's Barn monitoring sites, of which 30 were recorded at a single site. The rest were found in York (12%), Hereford (7%) and Starcross (2%). 94% of *R. padi* were recorded in October and 84% of *S. avenae* were recorded in November (Fig. 7).

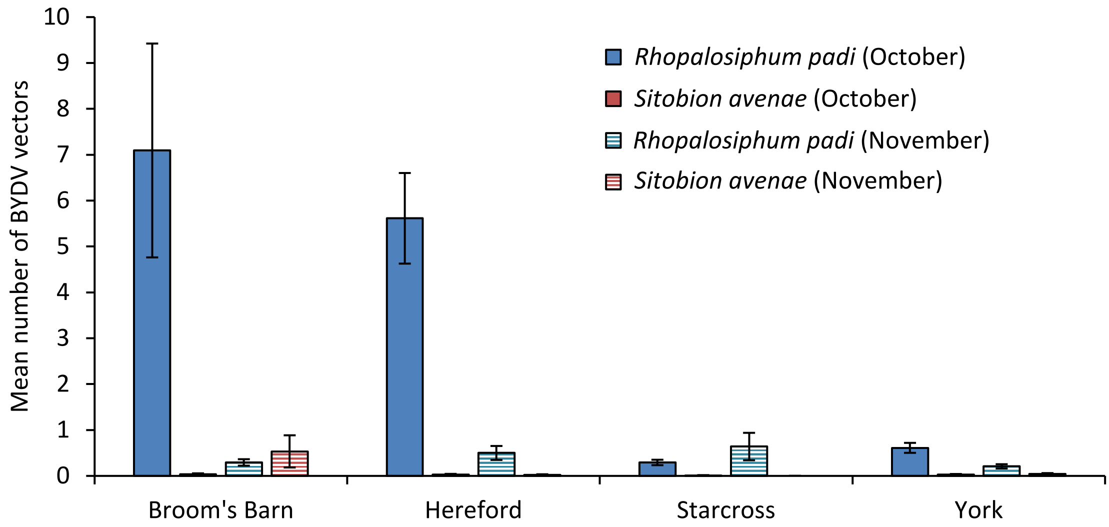

Figure 7. The mean number of BYDV vectors recorded at monitoring sites around each suction trap in autumn 2021. Bars indicate the standard error of the mean.

Across the years, significantly more *R. padi* were recorded in October (mean 2.5), than in November (mean 0.4) (df = 2, F = 8.63, p = <0.001) (Fig. 8). With *S. avenae*, slightly more aphids were recorded in November than October, but the difference was not significant (P <0.05). No aphids of either species were recorded in December, but this assessment timing only occurred in 2019. There was no significant effect of monitoring method (e.g. water traps) on the numbers of aphids caught in different months across the three years of the project (P <0.05).

The differences between aphid catches in different areas was also significant across the years for *R. padi* (df = 3, F = 6.62, P = <0.001) but not for *S. avenae* (P <0.05) (Fig. 9). Significantly more *R. padi* were found in crops around the Broom's Barn (Suffolk, mean 3) and Hereford suction traps (mean 2.2) than the Starcross (Devon, mean 0.3) and York suction traps (mean 0.3). For *S. avenae* the regions with the highest mean counts per site were Suffolk (Broom's Barn) (0.2) and Yorkshire (0.1). Data on the monitoring sites around the Newcastle suction trap was not included in the analyses due to the low number of sites monitored.

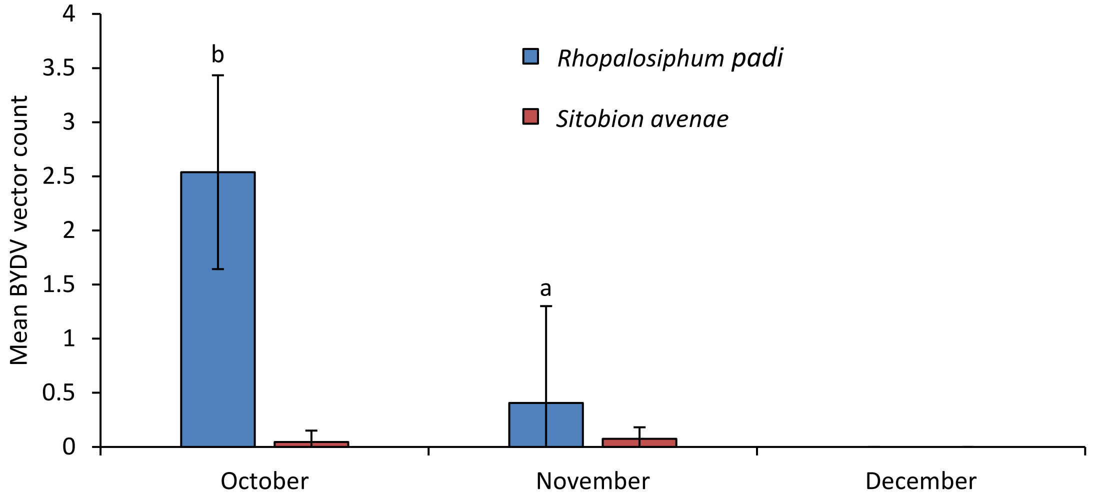

Figure 8. The mean number of BYDV vectors recorded from October to December between 2019-2021. December assessments only took place in autumn 2019. Bars indicate the standard error of the mean. Bars followed by different letters are significantly different (P <0.05).

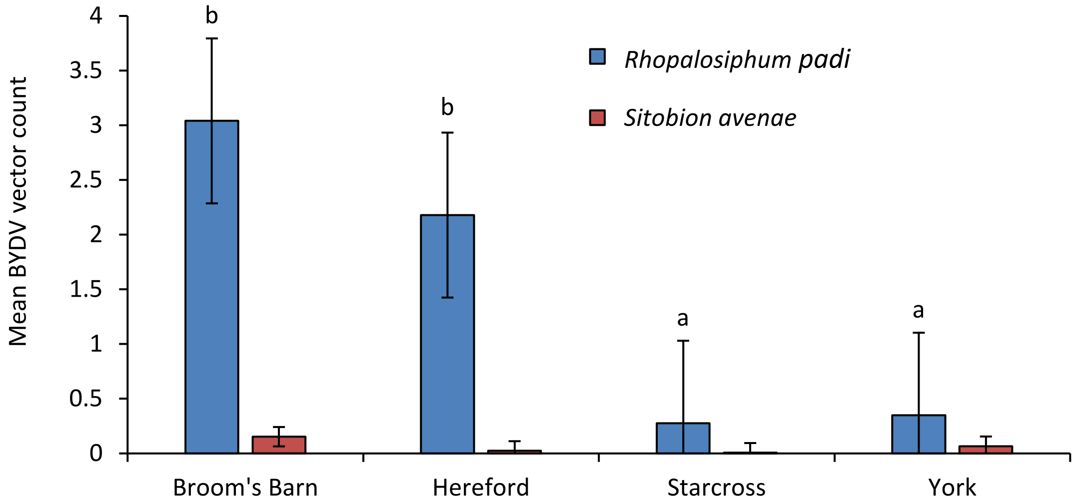

Figure 9. The mean number of BYDV vectors recorded at monitoring sites around each suction trap between 2019-2021. Bars represent the standard error of the mean. Bars followed by different letters are significantly different (P <0.05).

For the in-field monitoring methods, more *R. padi* were found in water traps (mean 1.9) followed by on-plant counts (mean 0.9) and sticky traps (mean 0.9), though these differences were not significant (P <0.05) (Fig. 10). *S. avenae* were found significantly more often using the on-plant count method (mean 0.2) than either water (mean <0.1) or sticky (mean <0.1) traps (df = 2, F = 4.68, P = 0.01). Traps that were 20 m into the field caught more *R. padi* than traps at 70 m, but this was not significant (P <0.05). There were significantly more *S. avenae* caught in traps 20 m into the field than at 70 m (df = 2, F = 4.73, P = 0.009) (Fig. 11).

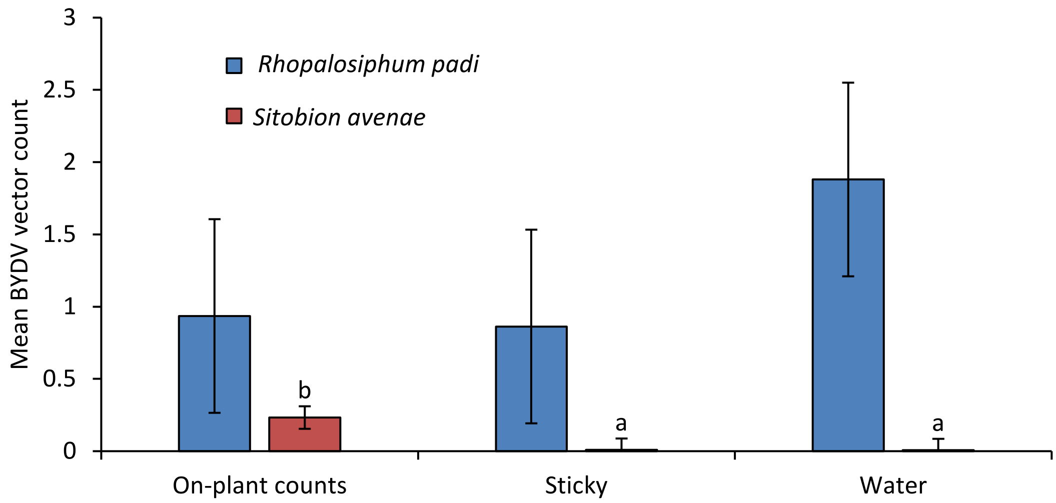

Figure 10. The mean number of BYDV vectors recorded using each of the monitoring methods. Bars indicate the standard error of the mean. Bars followed by different letters are significantly different (P <0.05).

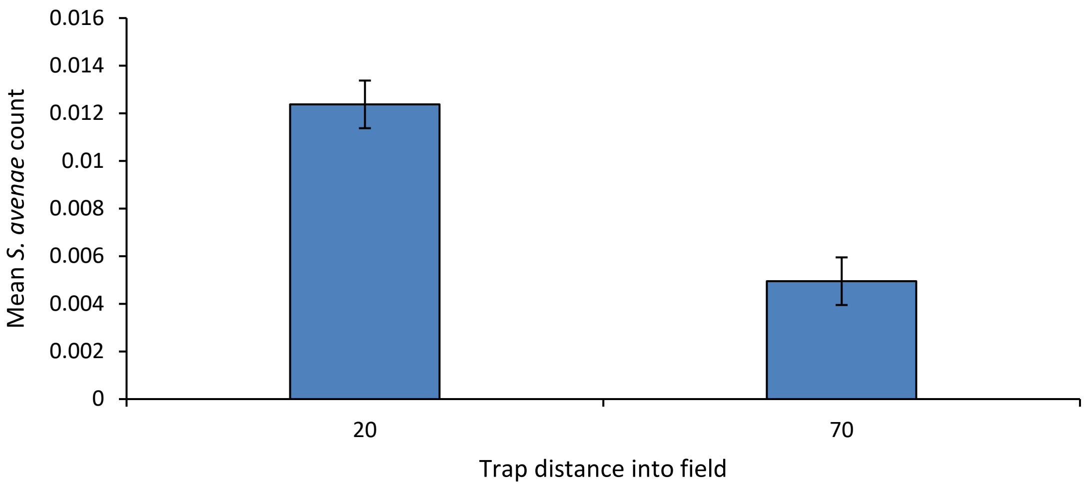

Figure 11. The mean number of *S. avenae* recorded in traps at different distances into the field. Bars indicate the standard error of the mean.

Virus monitoring

In 2019, monitoring for the percent of aphids caught in suction traps carrying BYDV (MAV/PAV) took place between 7 May and 3 December. The percent of viruliferous *R. padi* tended to increase from May until July/August at all sites, after which it fluctuated throughout the autumn (Fig. 12). Peak viruliferous aphids was at Broom's Barn (50%) in August. Monitoring of the % aphids carrying CYDV (RPV) began in September. As for BYDV, the percent of viruliferous aphids with CYDV fluctuated across the autumn, with a peak at Starcross (33%) in November (Fig. 13).

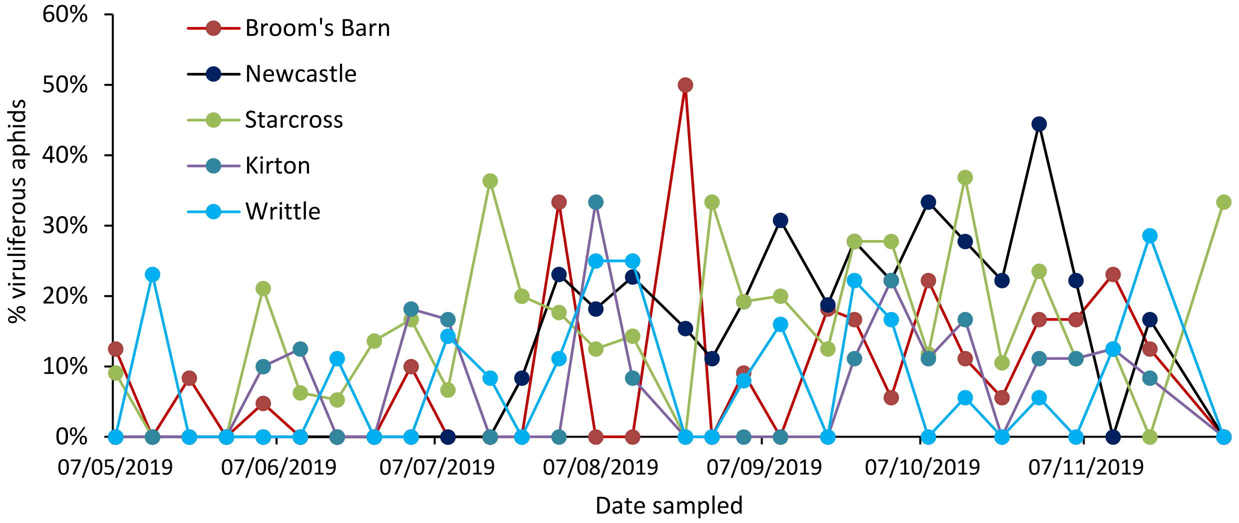

Figure 12. Percentage of *R. padi* from suction traps carrying BYDV in 2019.

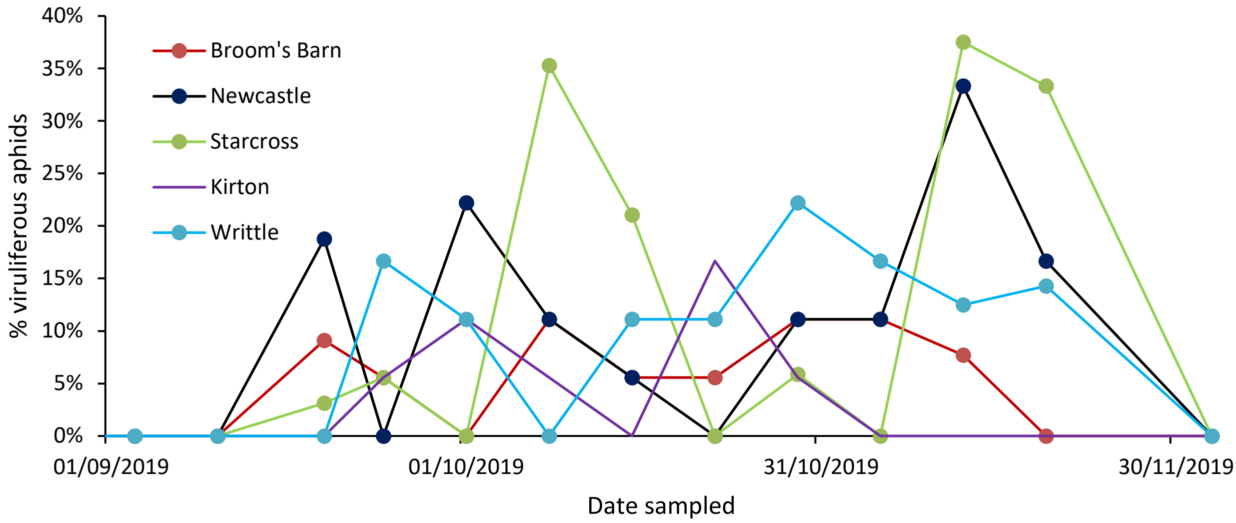

Figure 13. Percentage of *R. padi* from suction traps carrying CYDV in 2019.

In 2020, the testing of aphids from suction traps took place from 1 July to 29 November. No aphids were tested in the Broom's Barn suction trap in the week beginning 6 July and 20 July. The percentage of *R. padi* caught in suction traps carrying BYDV peaked in the summer before fluctuating downwards at all sites except Broom's Barn, where the peak was in September (Fig. 14). Peak viruliferous aphids was at York (67%) in August and Starcross in July and September (both 50%). For CYDV, prominent spikes in % viruliferous *R. padi* were found at York (100%) in July and Hereford (40%) in August, otherwise the values fluctuated between around 0-20% at all sites (Fig. 15). The peaks in viruliferous *R. padi* at York for both BYDV (67%) and CYDV (100%) should be treated with caution as the number of aphids tested were less than 10 in both situations.

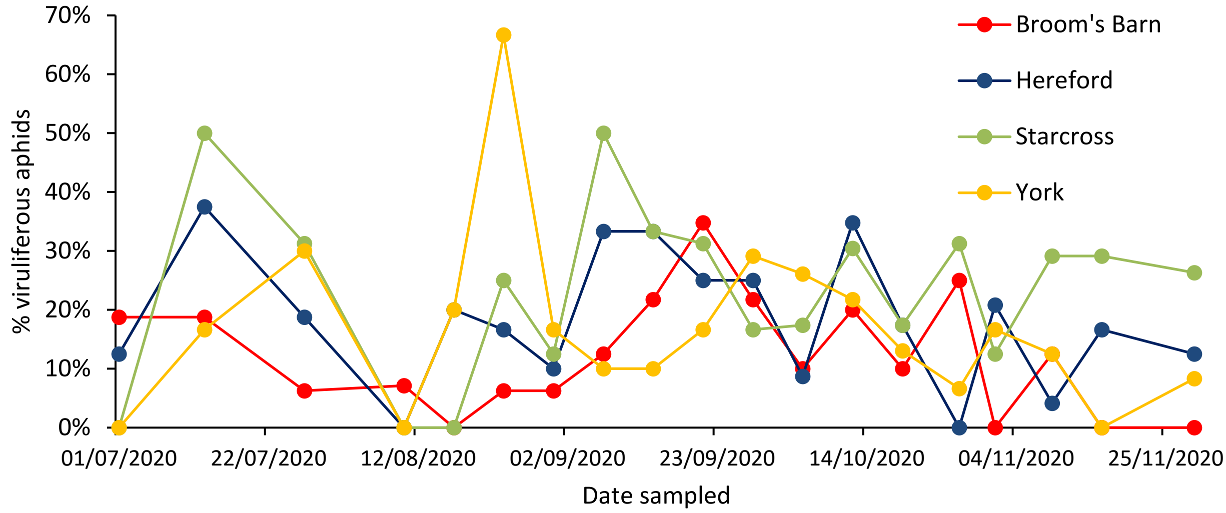

Figure 14. Percentage of *R. padi* from suction traps carrying BYDV in 2020.

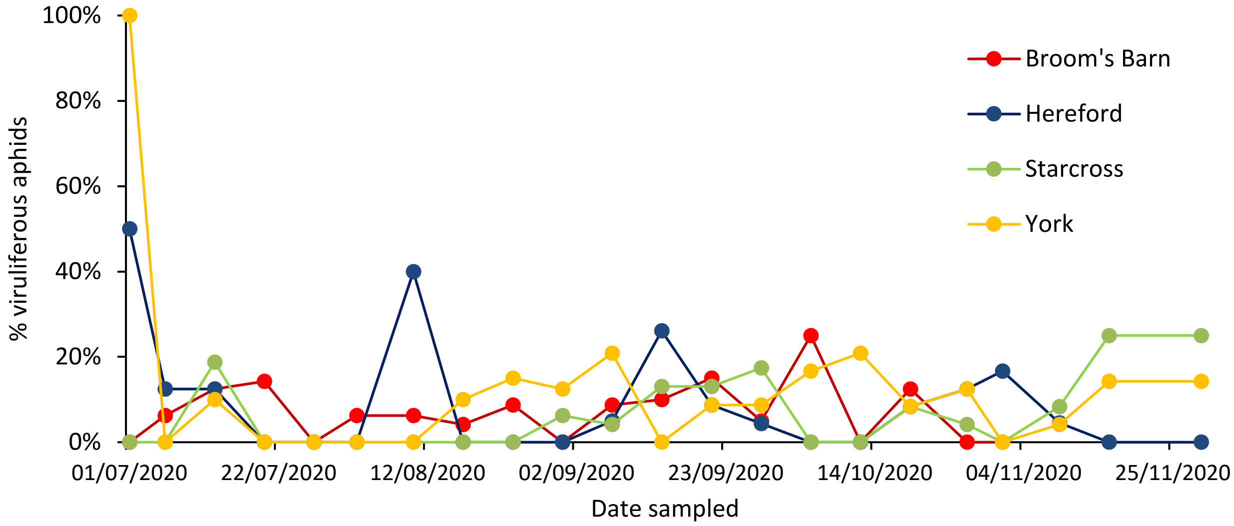

Figure 15. Percentage of *R. padi* from suction traps carrying CYDV in 2020.

In 2021, aphids were tested between 15 July and 28 November. For both BYDV (Fig. 16) and CYDV (Fig. 17), % viruliferous *R. padi* fluctuated across this period at all sites, except Hereford where BYDV peaked noticeably in late November, Broom's Barn where BYDV declined into the autumn, Starcross where CYDV increased into the autumn, and Edinburgh where CYDV remained at 0% from late September. Peak viruliferous aphids was at Hereford (50%) in November for BYDV and at Starcross (22%) in November for CYDV.

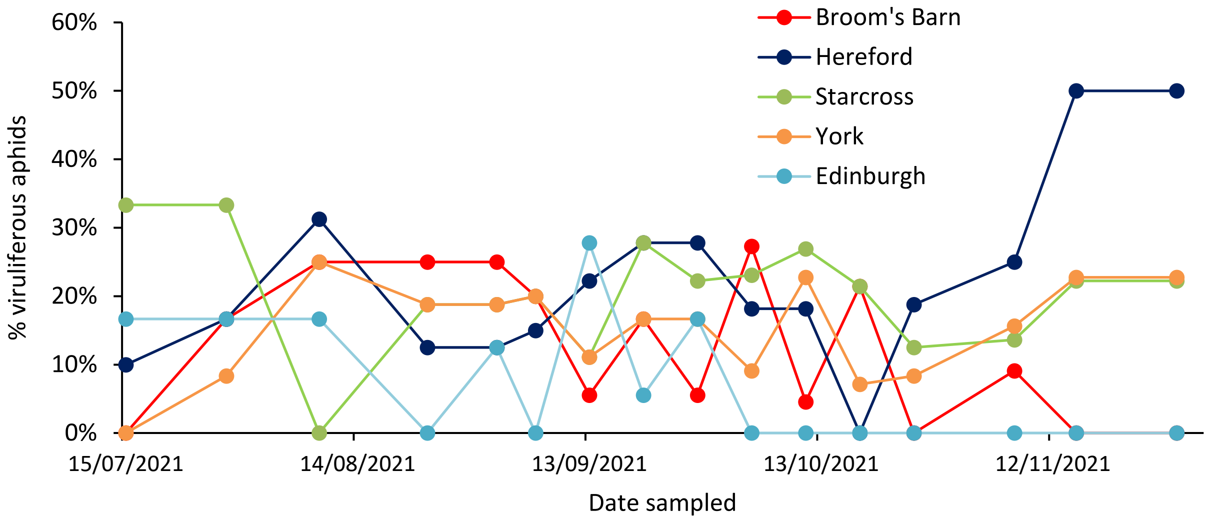

Figure 16. Percentage of *R. padi* from suction traps carrying BYDV in 2021.

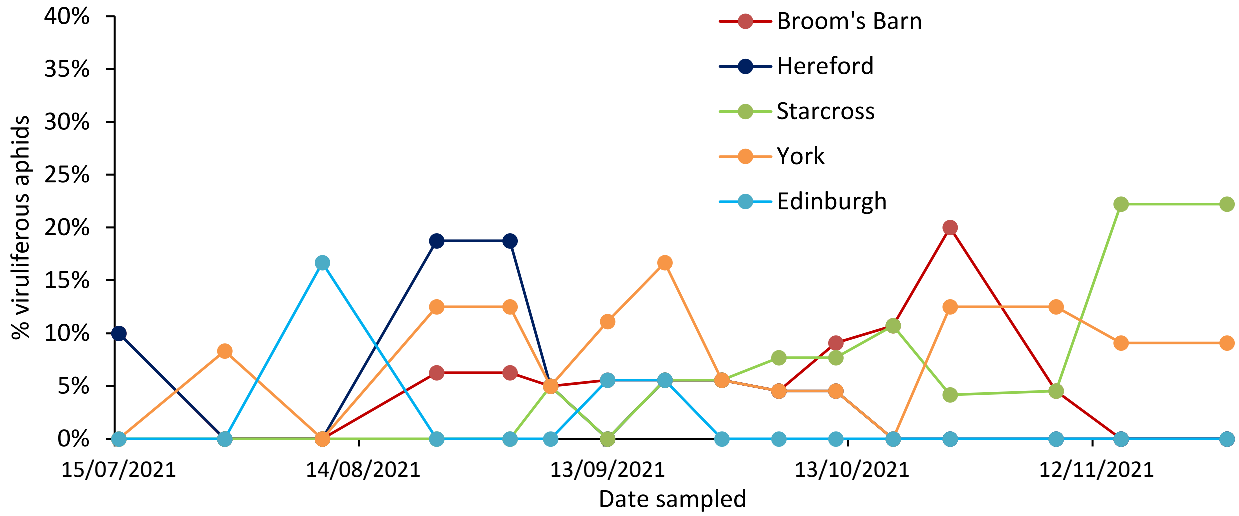

Figure 17. Percentage of *R. padi* from suction traps carrying CYDV in 2021.

The mean percentage of *R. padi* across the year with BYDV in 2019 was highest in the Starcross suction trap at 15% and lowest in Broom's Barn and Kirton at (7%) (Fig. 18). The highest percentage of *R. padi* across the year with CYDV was in Starcross at 5%, and the lowest was in Kirton at 1% (Fig. 19).

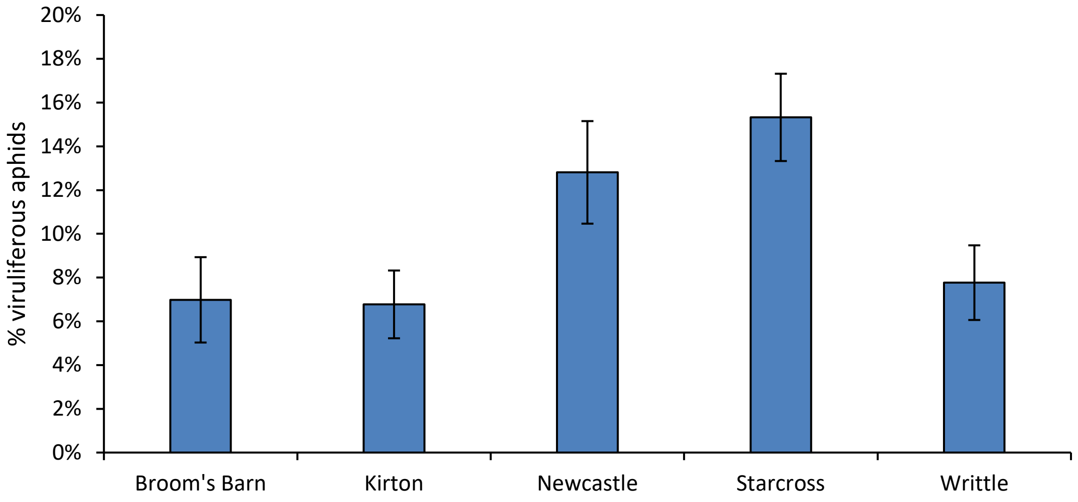

Figure 18. The mean percentage of viruliferous *R. padi* with BYDV in suction traps in 2019. Bars indicate the standard error of the mean.

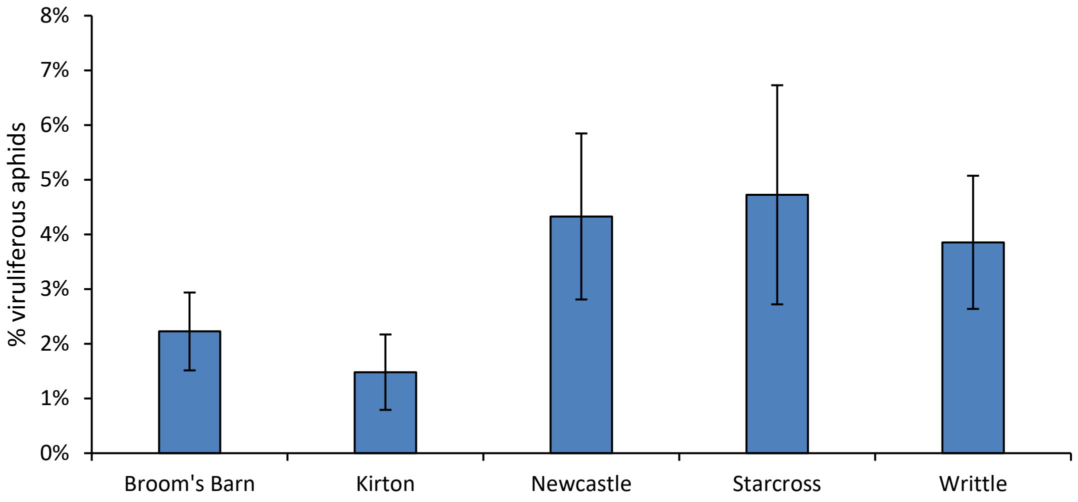

Figure 19. The mean percentage of viruliferous *R. padi* with CYDV in suction traps in 2019. Bars indicate the standard error of the mean.

In 2020, the highest mean percentage of *R. padi* across the year with BYDV was in Starcross at 23%, the lowest annual mean was in Broom's Barn at 12% (Fig. 20). York was the trap with the highest annual mean for *R. padi* with CYDV at 13%, and Broom's Barn and Starcross recorded the lowest at 7% (Fig. 21).

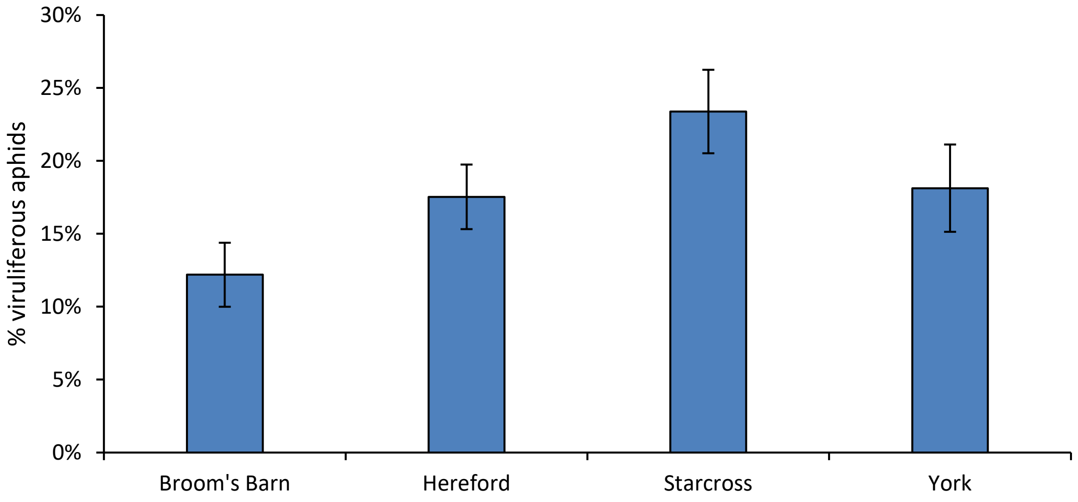

Figure 20. The mean percentage of viruliferous *R. padi* with BYDV in suction traps in 2020. Bars indicate the standard error of the mean.

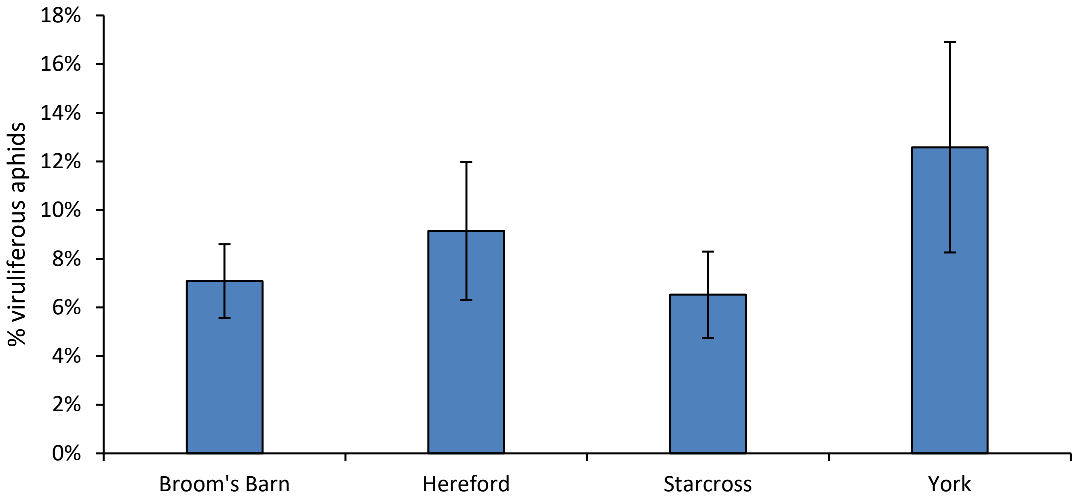

Figure 21. The mean percentage of viruliferous *R. padi* with CYDV in suction traps in 2020. Bars indicate the standard error of the mean.

In 2021, the highest annual mean percentage of *R. padi* with BYDV was recorded from the Hereford suction trap at 22%, and the lowest in Edinburgh at 7% (Fig. 22). With CYDV, the highest annual mean was in York with 8%, and the lowest in Edinburgh at 2% (Fig. 23).

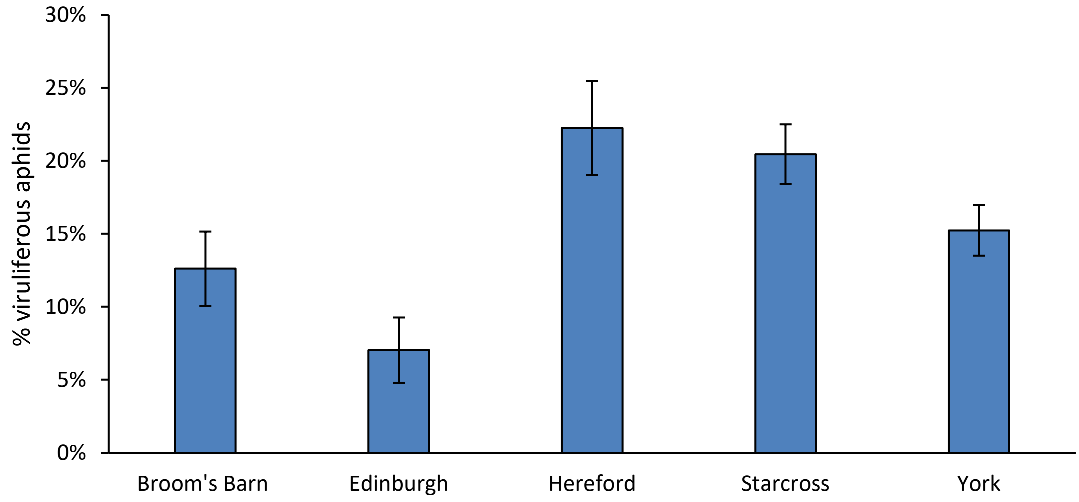

Figure 22. The mean percentage of viruliferous *R. padi* with BYDV in suction traps in 2021. Bars indicate the standard error of the mean.

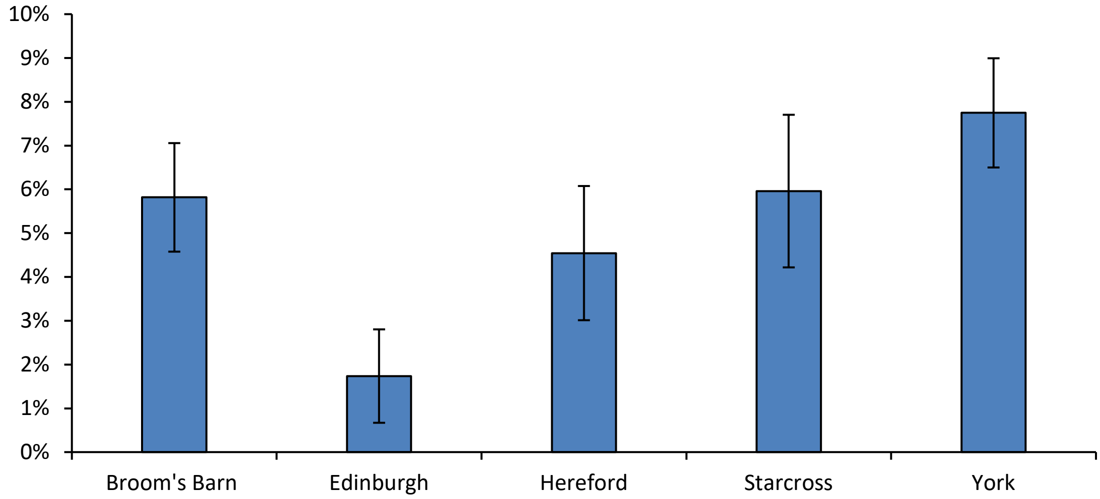

Figure 23. The mean percentage of viruliferous *R. padi* with CYDV in suction traps in 2021. Bars indicate the standard error of the mean.

The mean percent viruliferous *R. padi* (across all traps) was highest in 2020, with 18% and 9% of individuals carrying BYDV (Fig. 24) and CYDV respectively (Fig. 25). The lowest percent viruliferous was in 2019, with 10% and 3% of *R. padi* carrying BYDV and CYDV respectively. These differences were highly significant for both BYDV (df = 2, F = 14.7, P = <0.001) and CYDV (df = 2, F = 9.85, P = <0.001).

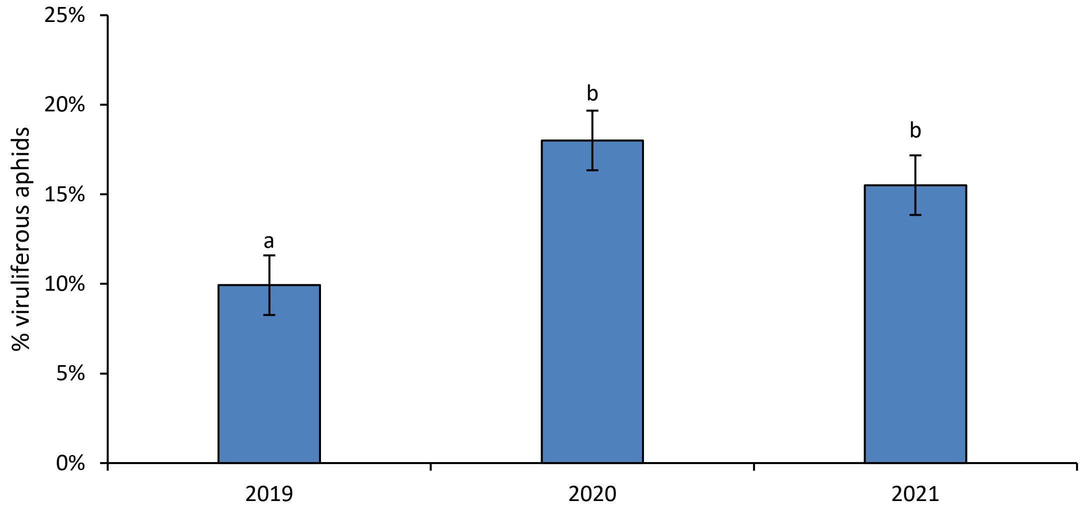

Figure 24. The annual mean percentage of *R. padi* with BYDV as recorded from suction traps. Bars indicate the standard error of the mean. Bars followed by different letters are significantly different (P <0.05).

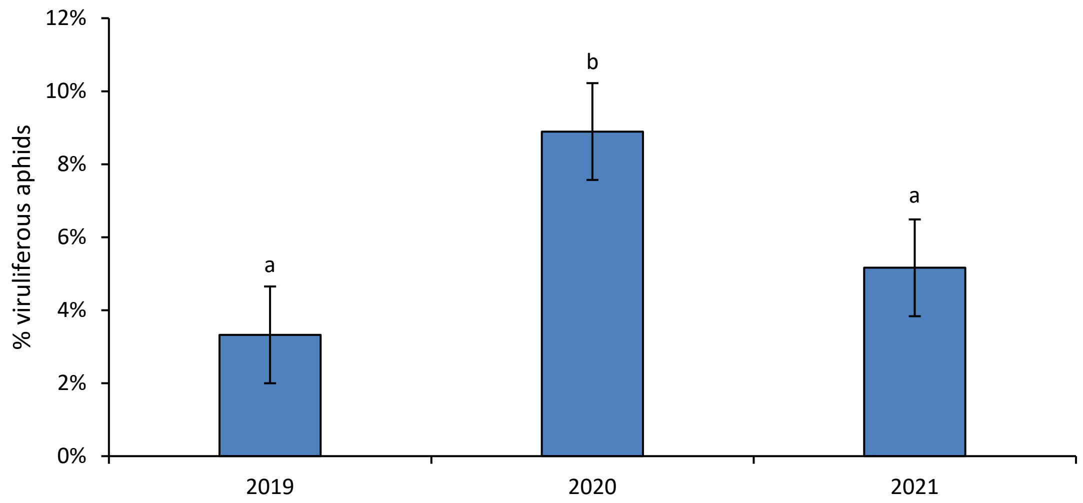

Figure 25. The annual mean percentage of *R. padi* with CYDV as recorded from suction traps. Bars indicate the standard error of the mean. Bars followed by different letters are significantly different (P <0.05).

S. avenae were seldom caught in suction traps so they were not consistently tested for the presence of BYDV/CYDV. For this reason, graphs of the changes in the percentage viruliferous are not presented here. However, of those that were tested, it was found that there was no significant difference between the percentage of *S. avenae* and *R. padi* carrying BYDV (P <0.05) but a significantly higher percentage of *R. padi* carried CYDV than *S. avenae* (df = 1, F = 66.9, P = <0.001) (Fig. 26).

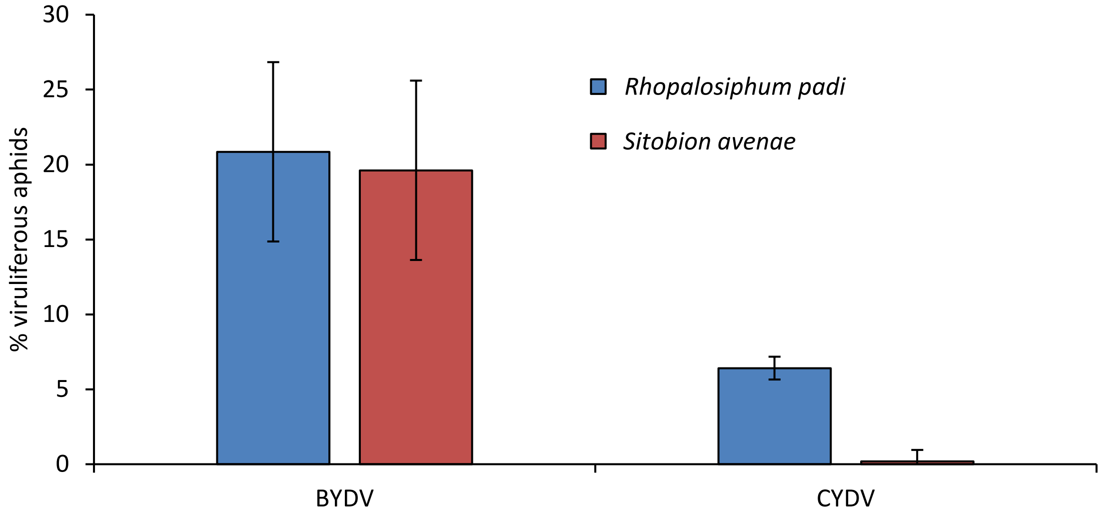

Figure 26. The mean percentage of each aphid species carrying BYDV or CYDV, as recorded from suction trap samples between 2019-2021. Bars represent the standard error of the mean.

Regarding in-field monitoring of percent viruliferous, only two samples of *R. padi* collected from monitoring sites exceeded the minimum requirement of 10 individuals needed to make the virus assay reliable. In 2019, these samples were from sites near Broom's Barn (East of England) and Starcross (South West). Both sites recorded a percentage of viruliferous individuals that were more than double that of the corresponding suction trap over the same period (Fig. 27).

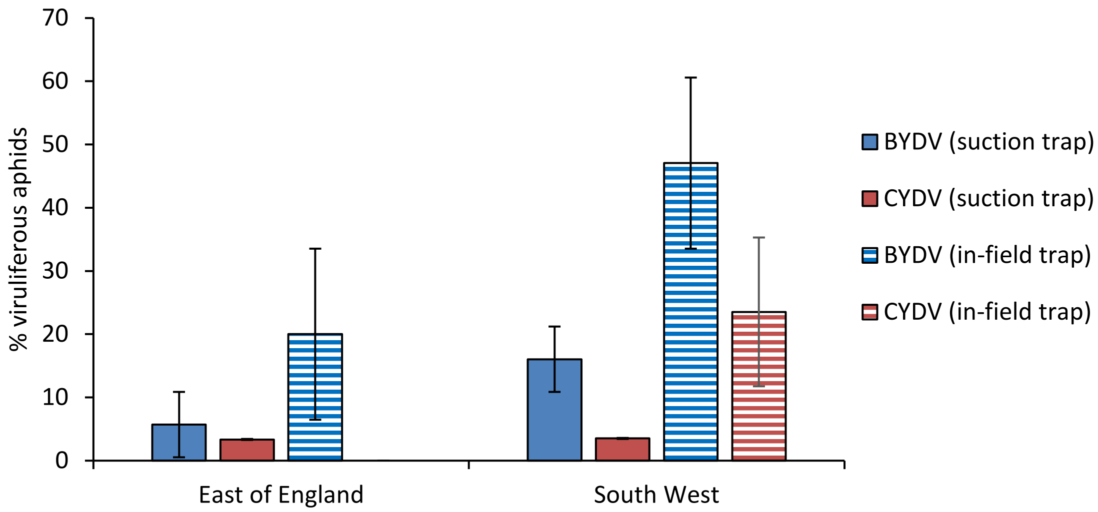

Figure 27. The mean percent of viruliferous *R. padi* caught over the same period in suction traps and in-field traps in autumn 2019. Bars represent the standard deviation.

In 2020, three samples of *R. padi* collected from monitoring sites were large enough to test for BYDV/CYDV. These samples came from each of the suction trap areas. In general, the percentage carrying BYDV or CYDV was similar to that caught over the same time period in the nearby suction trap (Fig. 28).

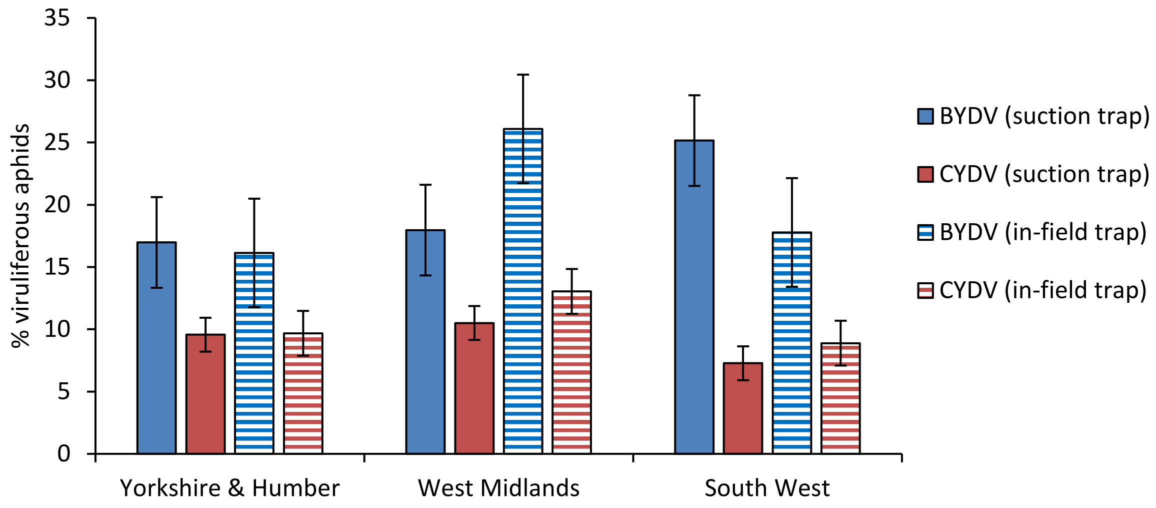

Figure 28. The mean percent of viruliferous *R. padi* caught over the same period in suction traps and in-field trap in autumn 2020. Bars represent the standard deviation.

In 2021, sufficient numbers of *R. padi* were collected from 18 sites for virus testing. The mean percentage carrying BYDV was highest in the South West (20%) and lowest in the East of England (10%). The mean percent carrying CYDV was significantly higher in Yorkshire & Humber (13%) than the other areas (df = 3, F = 6.41, P = 0.006), with the East have the lowest incidence of *R. padi* carrying the serotype (0%) (Fig. 29). The relationship between the percentage viruliferous of aphids caught in crops and the local suction trap was similar in some regions and viruses (e.g. CYDV in the West Midlands and the South West, and BYDV in the South West and Yorkshire) but less so in others (e.g. CYDV in the East and BYDV in the West Midlands) (Fig. 29). In the three years monitoring, insufficient numbers of *S. avenae* were found in crops to justify testing for the presence of the virus.

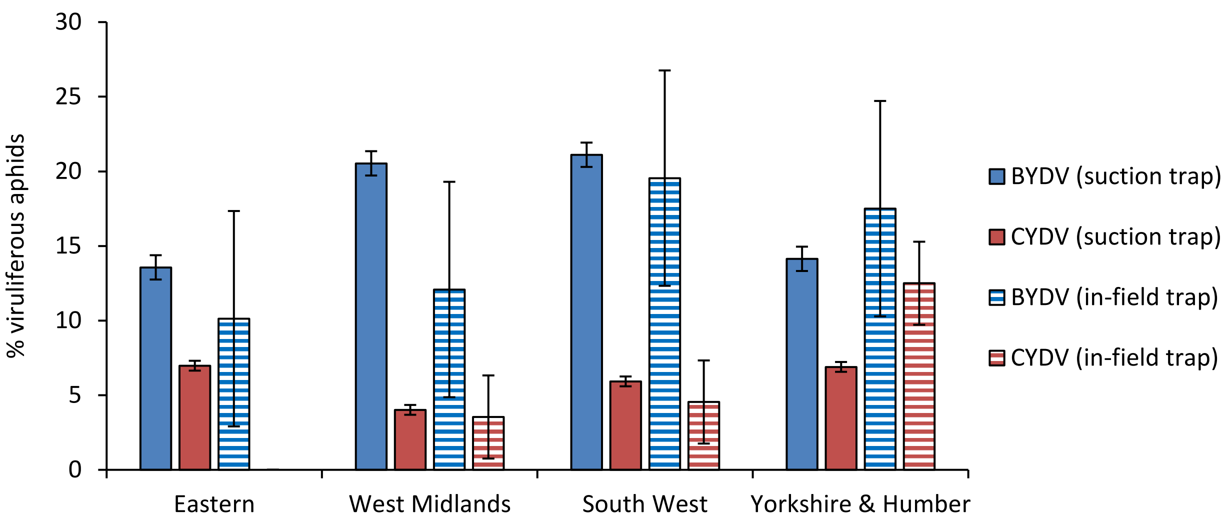

Figure 29. The mean percent of viruliferous *R. padi* caught over the same period in suction traps and in-field traps in autumn 2021. Bars represent the standard error of the mean.

Comparing percent viruliferous *R. padi* caught in in-field traps and suctions traps over the same time period across the three years, the South West (containing the Starcross suction trap) had the highest mean percentage *R. padi* carrying BYDV in suction traps (21%) and in-field traps (28%), and CYDV in in-field traps (8%) (Fig. 30). Mean CYDV from suction traps was marginally higher in Yorkshire (8%) than other suction traps. The East of England (containing the Broom's Barn suction trap) had the lowest mean percentage viruliferous *R. padi* for BYDV in suction traps (10%) and CYDV in suction traps and in-field traps (5% and 0% respectively). Both Yorkshire and the East had the lowest percentage viruliferous *R. padi* with BYDV in-field traps (15% and 15% respectively). However, these differences in BYDV or CYDV between regions were not significant ($P < 0.05$). Note that this comparison only includes suction traps monitored for at least two years and those at which surrounding crops were also monitored.

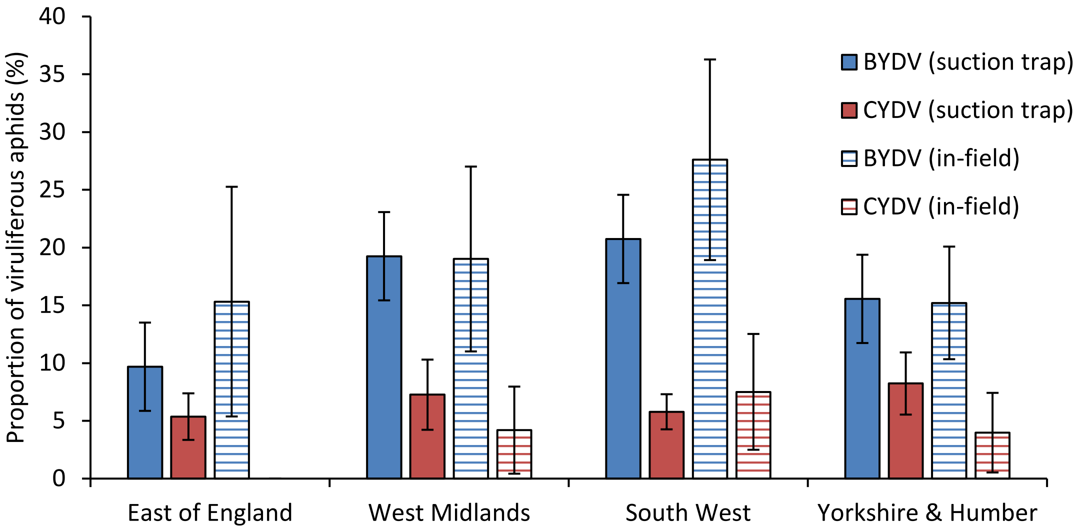

Figure 30. The mean percent of *R. padi* from suction traps and in-field traps positive for each viral serotype by region. Bars represent the standard error of the mean.

Assessing the reliability of suction trap data for surrounding farms

The analysis of the relationship between data from suction traps and surrounding crops for both aphids numbers and percentage viruliferous focussed on *R. padi* because *S. avenae* were so seldom found on plants or caught in traps (be it in-field traps or suction traps) at the monitoring sites. The following analyses uses the annual means for *R. padi* for each suction trap and the corresponding monitoring sites. There was a highly significant but fairly weak relationship between aphids caught in suction traps and aphids recorded from in-field monitoring (total from on-plant counts and water and sticky traps) in the three years of the project (df = 1, adjusted $R^2 = 24.8$, $p = 0.004$) (Fig. 31).

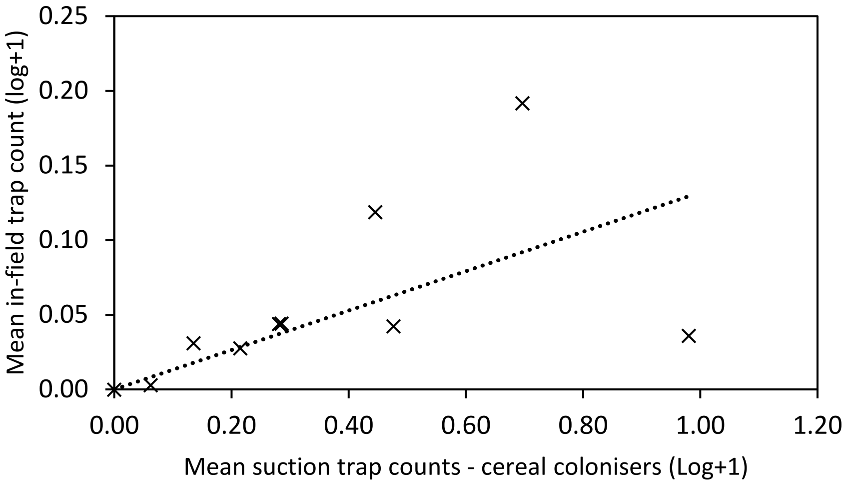

Figure 31. Relationship between *R. padi* numbers caught in suction traps and those recorded in surrounding monitoring sites in the autumn between 2019 and 2021. Adjusted R^2 = 24.8. y = 0.13x.

When assessing the importance of distance from the suction trap, there was a significant correlation between *R. padi* in suction traps and those recorded at monitoring sites (total aphids from on-plant counts and water and sticky traps) that were approx. 10 km from the suction trap (df =1, adjusted R^2 = 48.8, p = <0.001) (Fig. 32). The relationship between suction trap data and monitoring sites approx. 20 km was also significant, but the correlation was weak (df = 1, adjusted R^2 = 6, P = 0.048) (Fig. 33). There was no significant relationship between suction trap data and sites approx. 40 km away (P <0.05).

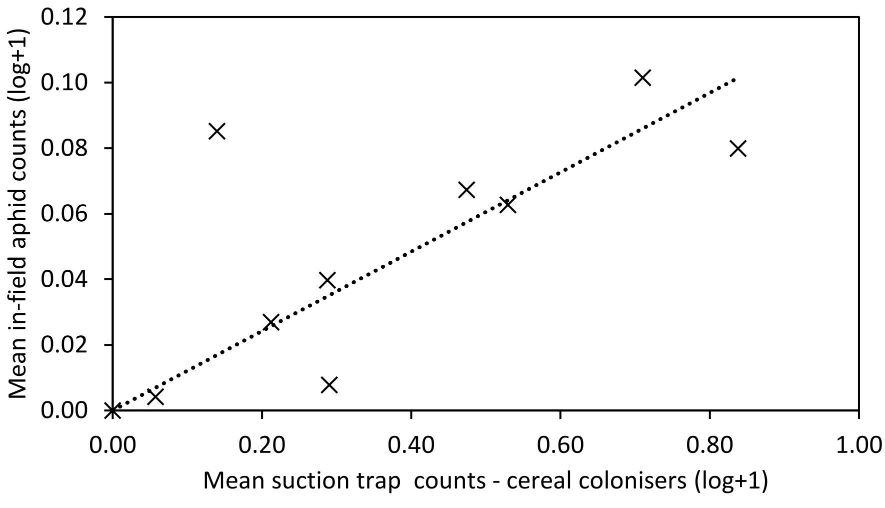

Figure 32. Relationship between *R. padi* numbers in suction traps and in-field counts at monitoring sites in the 10 km category of distance from the nearest suction trap. Adjusted R^2 = 48.8. y = 0.12x.

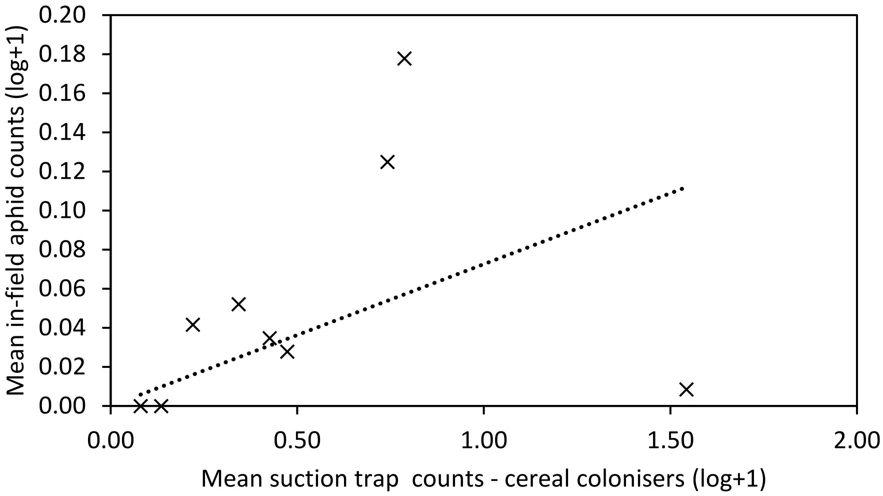

Figure 33. Relationship between *R. padi* numbers in suction traps and in-field counts at monitoring sites in the 20 km category of distance from the nearest suction trap. Adjusted R^2 = 6. y = 0.07x.

In terms of the effect of direction from the suction trap, there was a highly significant and strong correlation between *R. padi* recorded in monitoring sites that were southwest of the nearest suction trap and those counted from that suction trap (df = 1, adjusted R^2 = 65.6, p = 0.002) (Fig. 34). Monitoring sites west of a suction also had a significant correlation with the nearest suction trap (df = 1, adjusted R^2 = 46.8, p = 0.022) (Fig. 35).

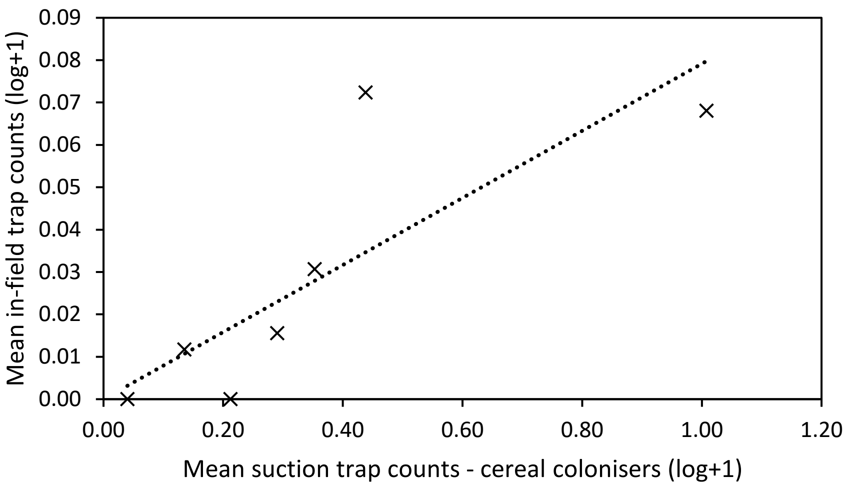

Figure 34. Relationship between *R. padi* numbers caught in suction traps and recorded in monitoring sites southwest of the suction trap. Adjusted R^2 = 65.6. y = 0.08x.

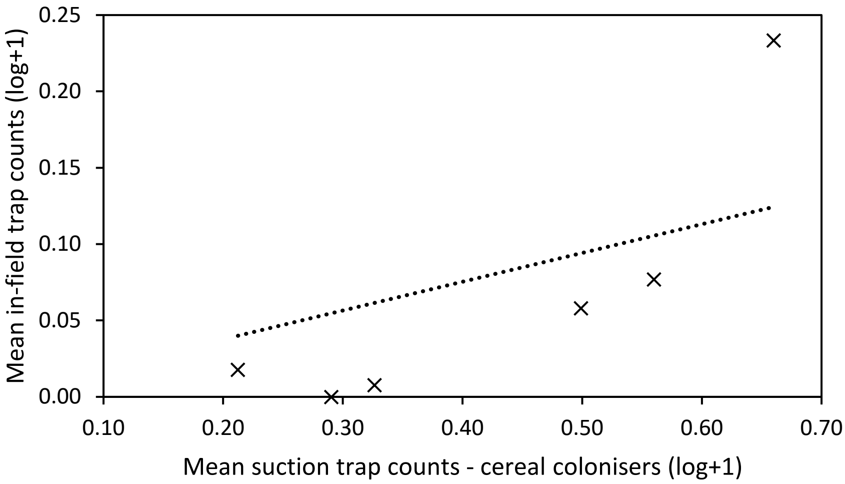

Figure 35. Relationship between *R. padi* numbers caught in suction traps and recorded in the monitoring sites west of the suction trap. Adjusted R^2 = 46.8. y = 0.19x.

When we investigated individual suction traps, a significant correlation between aphid data from that suction trap and that from the surrounding monitoring sites was only found at Hereford (df = 1, adjusted R^2 = 29.4, p = <0.001) (Fig. 36).

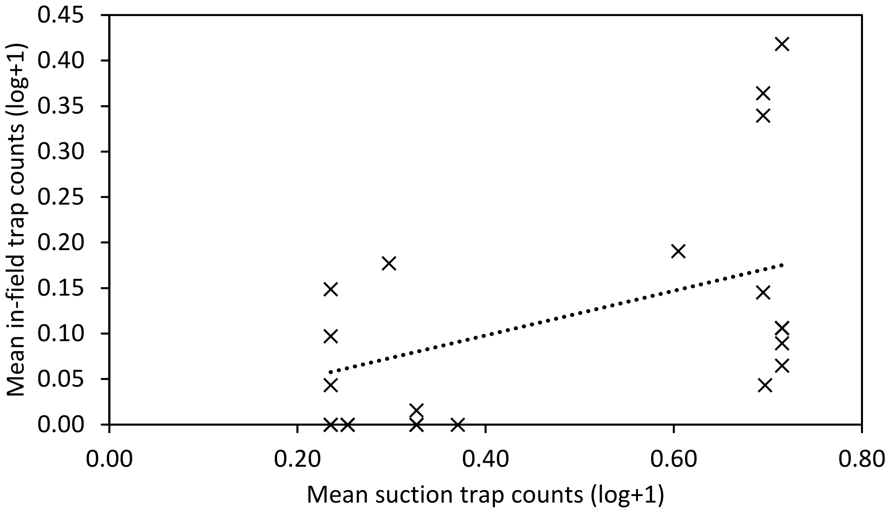

Figure 36. Relationship between *R. padi* numbers in suction traps and in-field counts at monitoring sites near the Hereford suction trap. Adjusted R^2 = 29.4. y = 0.25x.

In terms of trap type, the strongest relationship with suction trap counts was with water trap counts, although the relationship was weak (df = 1, adjusted R^2 = 14.4, p = 0.008) (Fig. 37). The relationship between suction traps and sticky traps was not significant but there was a significant, though weak relationship, with *R. padi* observed on plants (df = 1, adjusted R^2 = 11.1, P = 0.01) (Fig. 38).

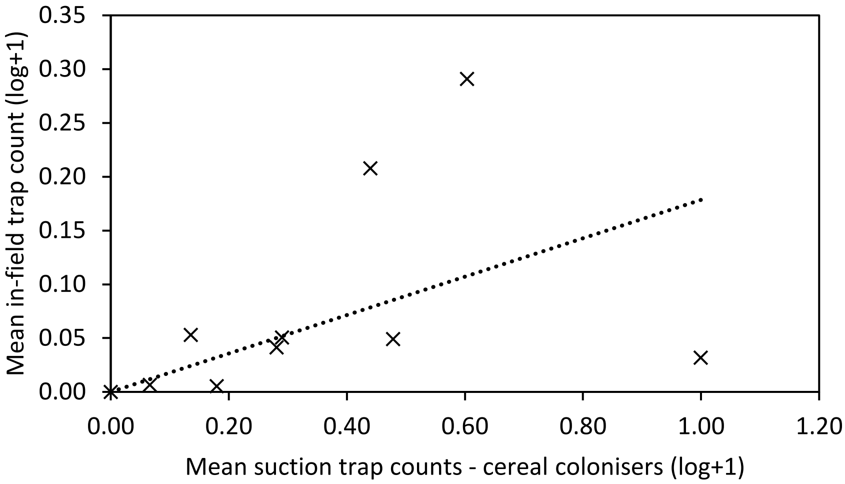

Figure 37. Relationship between *R. padi* numbers caught in suction traps and in water traps at monitoring sites. Adjusted R^2 = 14.4. y = 0.18x.

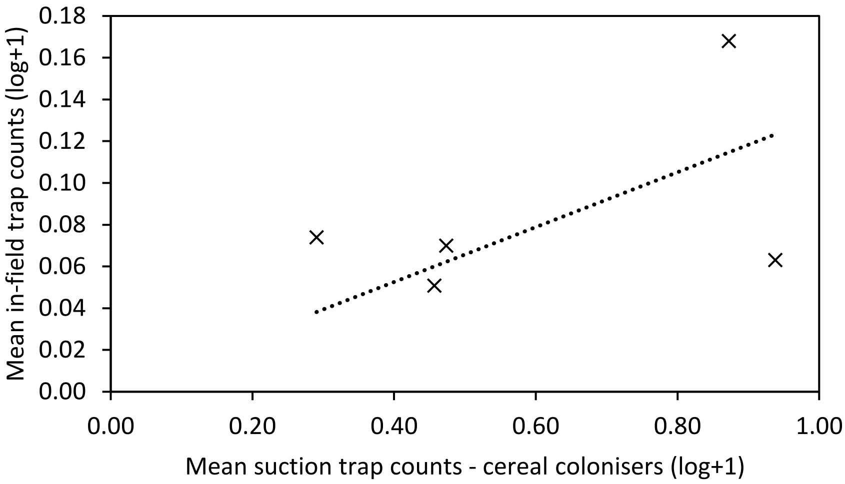

Figure 38. Relationship between *R. padi* numbers caught in suction traps and recorded in on-plant observations at the monitoring sites. Adjusted R^2 = 11.1. y = 0.13x.

The number of *R. padi* found in traps at 20 m into the field displayed a significant but weak relationship with suction trap counts (df =1, adjusted R^2 = 16.9, P = 0.02) (Fig. 39). The number of *R. padi* in traps 70 m into the field also had a significant correlation with the number of aphids found in suction traps but the relationship was weaker than with traps at 20 m (df = 1, adjusted R^2 = 1.8, P = 0.04) (Fig. 40).

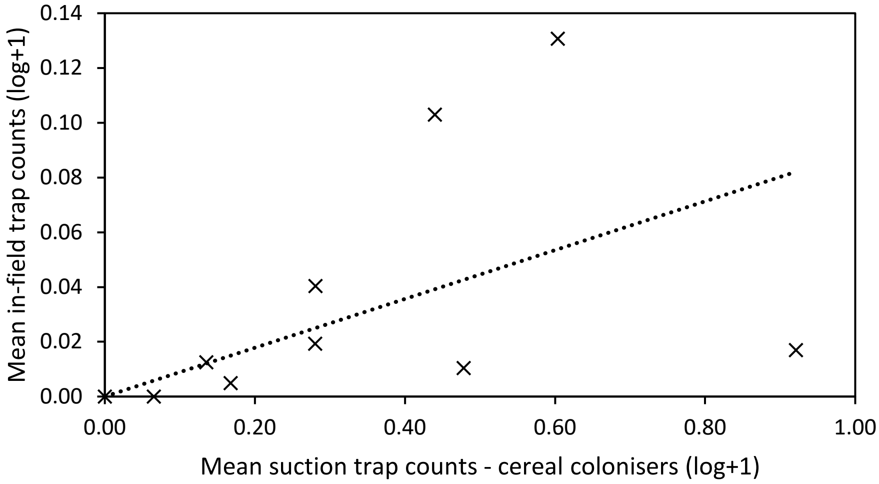

Figure 39. Relationship between *R. padi* caught in traps placed 20 m from the field edge at the monitoring sites and aphids caught in suction traps. Adjusted R^2 = 16.9. y = 0.09x.

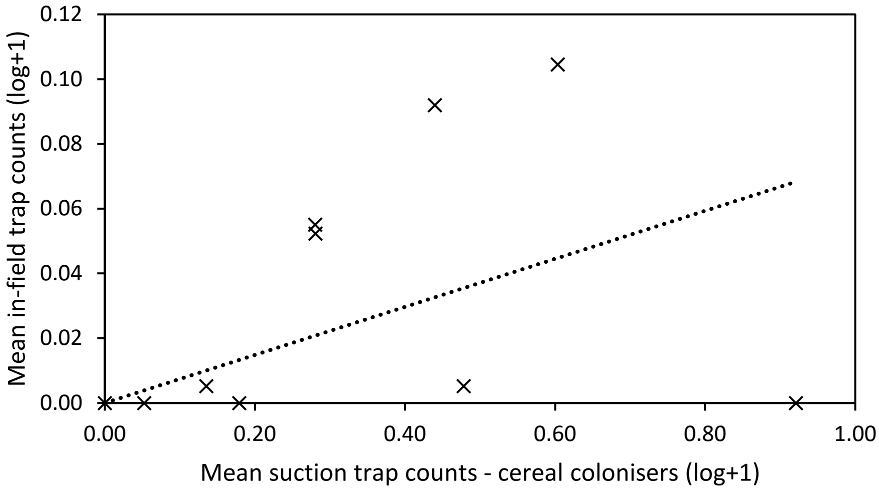

Figure 40. The relationship between *R. padi* caught in traps placed 70 m from field edge at the monitoring sites and the number of aphids caught in suction traps. Adjusted R^2 = 1.8. y = 0.07x.

In terms of the relationship between the percentage of viruliferous *R. padi* caught suction traps and those caught in in-field traps at surrounding farms over the same time period, there was not a significant difference between the overall mean percentage that were positive for BYDV or CYDV in the suction traps (17% and 7% respectively) and the in-field monitoring traps (20% and 8% respectively) ($P < 0.05$) (Fig. 41).

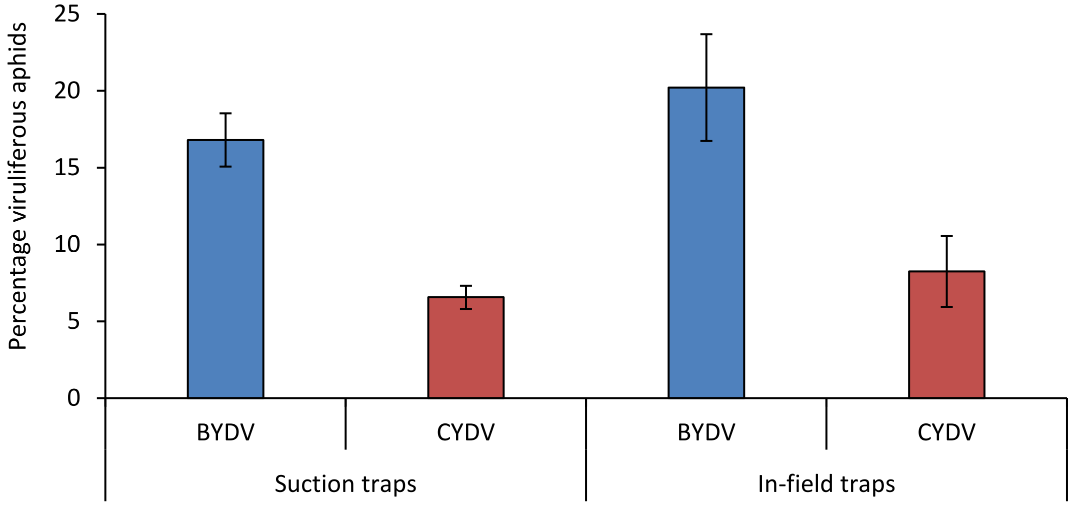

Figure 41. The mean percentage of *R. padi* that were positive for each viral serotype collected from suction traps and in-field traps over the same time period. Bars represent the standard error of the mean.

When comparing the relationship on the percent viruliferous *R. padi* at monitoring sites and local suction traps at the same period in the autumn, there was a significant but weak correlation for CYDV (df = 1, adjusted R^2 = 2.1, P = 0.01) (Fig. 42) but not BYDV (P <0.05). When the percentage of viruliferous *R. padi* for both viral serotypes were combined, the correlation was significant and stronger (df = 1, adjusted R^2 = 24.1, P = <0.001) (Fig. 43).

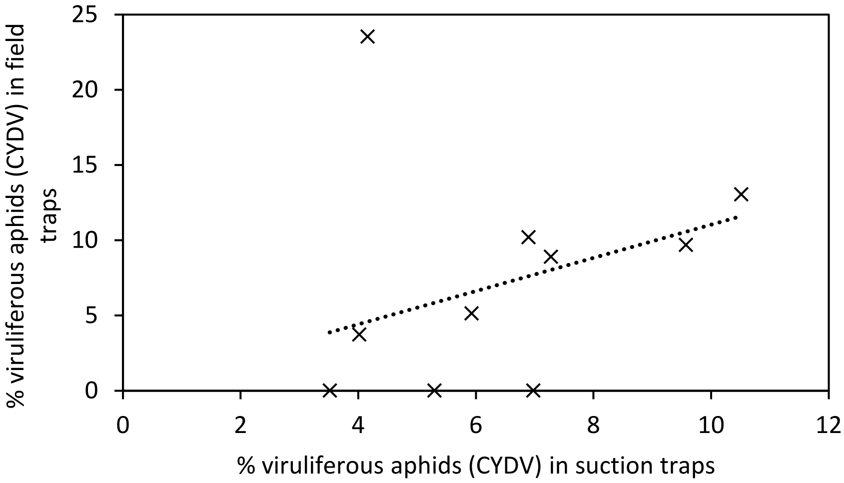

Figure 42. The relationship between the percentage of *R. padi* with CYDV from suction traps and in-field traps over the same period in the autumn. Adjusted R^2 = 2.1. y = 1.1x.

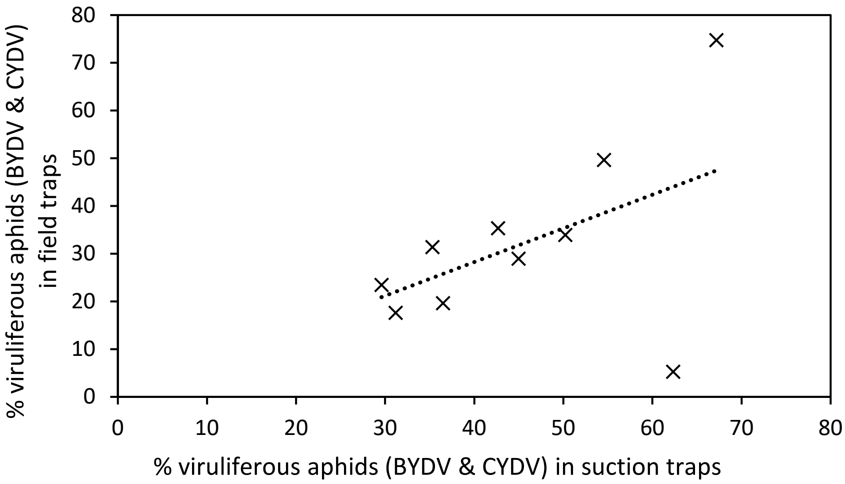

Figure 43. The relationship between the percentage of *R. padi* with either BYDV or CYDV from suction traps and in-field traps over the same period in the autumn. Adjusted R^2 = 24.1. y = 0.71x.

3.3.2. Determining the relationship between aphid numbers on plants and those in suction traps and in-field traps

Aphid numbers in untreated strips

In autumn 2019, just 19 BYDV vectors were recorded in the untreated strips. 14 were *S. avenae*, of which 57% were recorded in the South West (Fig. 44). Three *S. avenae* were recorded in both Yorkshire & Humber and the West Midlands. All *S. avenae* were found on plants rather than in water or sticky traps. Five *R. padi* were recorded, all of which were found in Yorkshire & Humber.

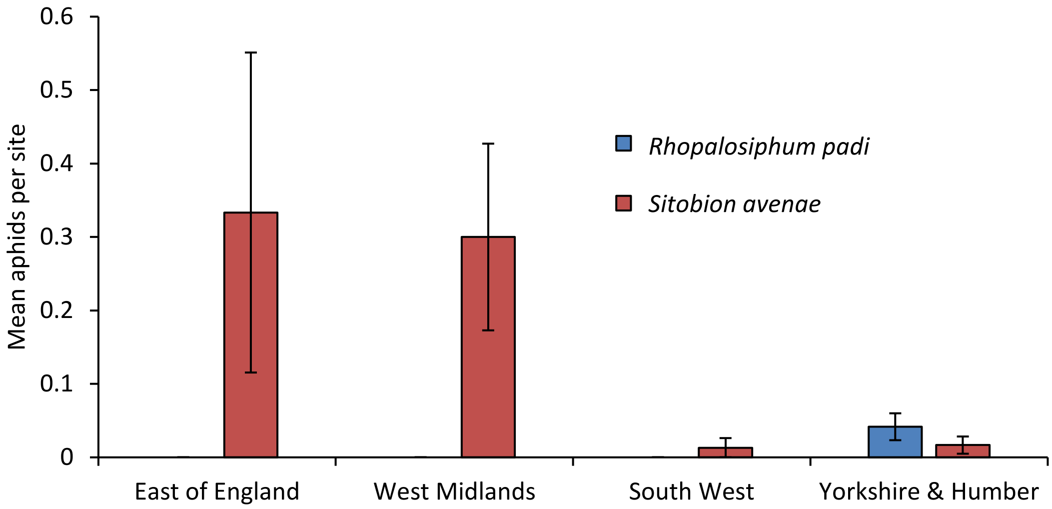

Figure 44. The mean number of aphids recorded from untreated strips in autumn 2019. Bars represent the standard error of the mean.

In 2020, 136 BYDV vectors were recorded in untreated strips in the South West and Yorkshire & Humber. 74% were *S. avenae*, 98% of which were observed on plants in the South West. All *R.*

padi were caught in in-field traps, 86% of which were caught in Yorkshire & Humber and 14% in the South West (Fig. 45)

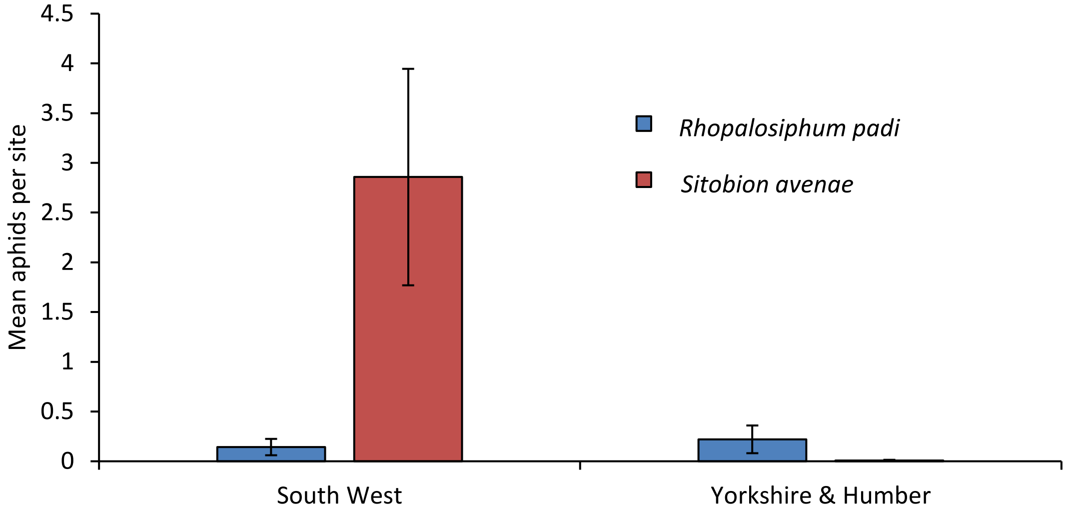

Figure 45. Mean number of aphids recorded from untreated strips in autumn 2020. Bars represent the standard error of the mean.

In 2021, a total of 197 *R. padi* and no *S. avenae* were recorded in untreated strips. 69% (136) of which were found in the South West (Fig. 46). 97% of these were found in traps and the remainder on plants.

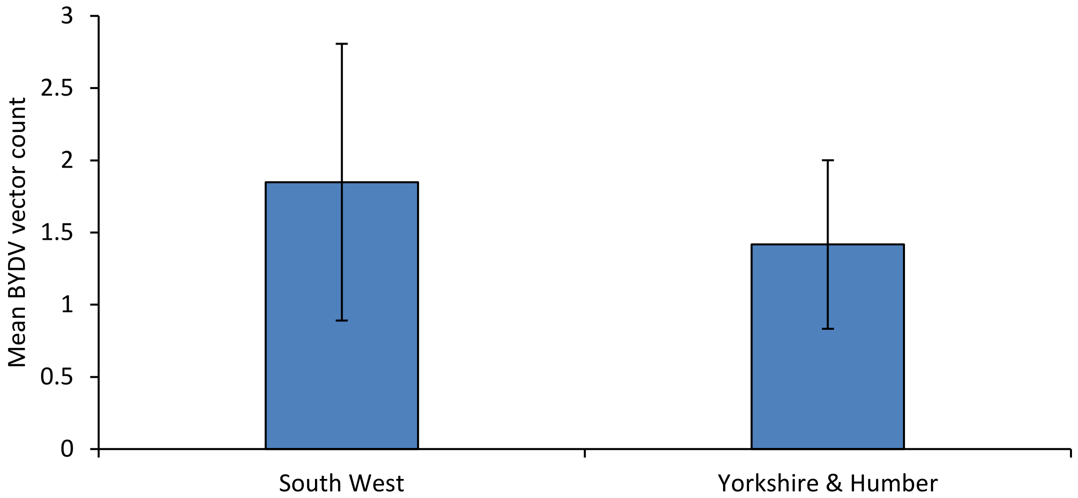

Figure 46. The mean number of *R. padi* recorded in untreated strips in autumn 2021. Note: no *S. avenae* were found. Bars represent the standard error of the mean.

Assessing the relationship between aphids on plants and aphids caught in traps

To understand the accuracy of trapping methods (suction traps, water traps and sticky traps) for determining aphid numbers on plants the relationship between the number of aphids observed on plants and the number of aphids caught in traps was analysed. Data on aphid numbers collected from sites monitored in Section 3.2.1 was included in these analyses where no insecticides were applied prior to an in-field assessment (i.e. sites that were also effectively untreated at the time of monitoring). When on-plant counts of *R. padi* were compared with the mean number of cereal colonisers recorded from the suction traps, there was a highly significant and moderately strong correlation (df = 1, adjusted R^2 = 49.8, P = <0.001) (Fig. 47).

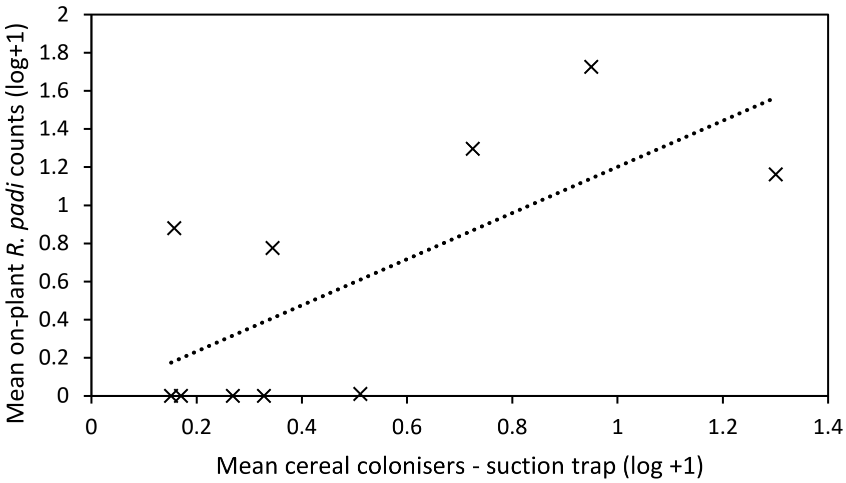

Figure 47. The relationship between *R. padi* observed on plants and recorded from suction traps. Adjusted R^2 = 49.8. y = 1.21x - 0.01.

For *S. avenae*, there was a significant correlation between the number of aphids observed on plants and those caught in suction traps but this relationship was very weak (df = 1, adjusted R^2 = 3.2, P = 0.02 (Fig. 48).

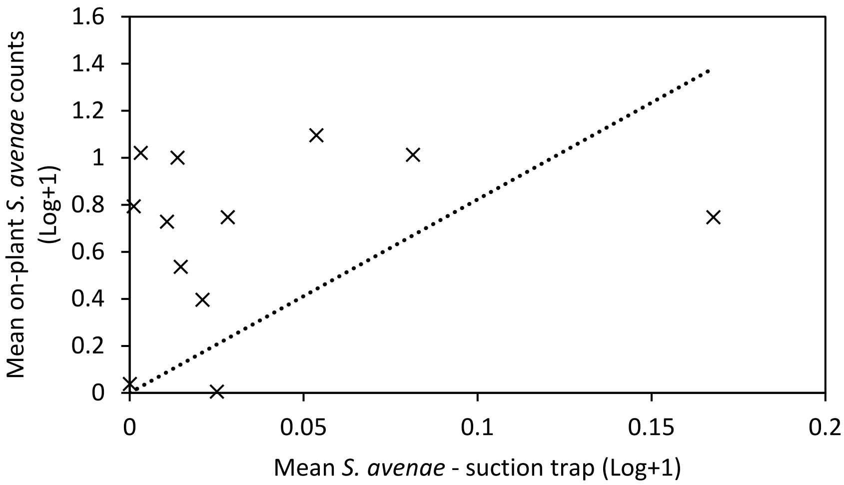

Figure 48. The relationship between *S. avenae* observed on plants and caught in suction traps. Adjusted R^2 = 3.2. y = 8.23x.

Regarding the relationship between in-field traps and on-plant *R. padi* numbers (too few *S. avenae* were caught in in-field traps for robust analyses), a significant but weak relationship was found with sticky traps (df = 1, adjusted R^2 = 15.8, P = 0.009) (Fig. 49). A stronger and highly significant relationship was found with water traps (df = 1, adjusted R^2 = 35.3, P = 0.003) (Fig. 50). When data from both sticky and water traps were combined, the correlation with *R. padi* numbers on plants remained significant but was weaker (df = 1, adjusted R^2 = 2.8, P = 0.034) (Fig. 51).

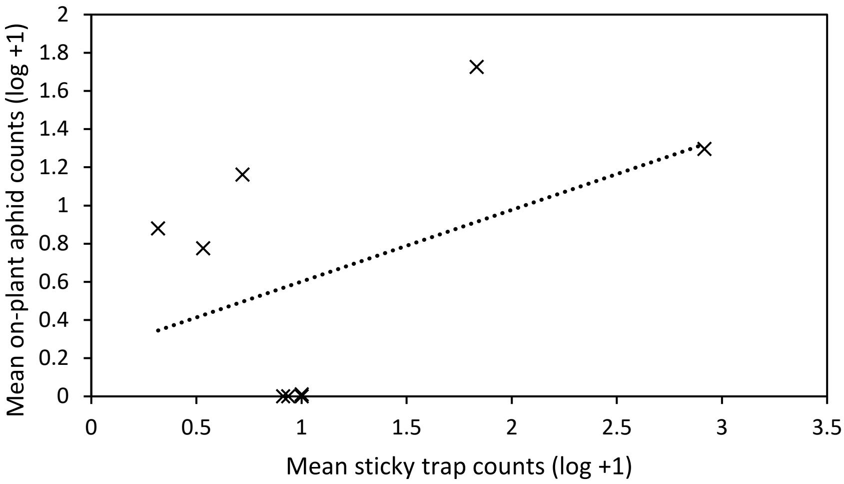

Figure 49. The relationship between *R. padi* observed on-plant counts and caught on sticky traps. Adjusted R^2 = 15.8. y = 0.3755x + 0.2258.

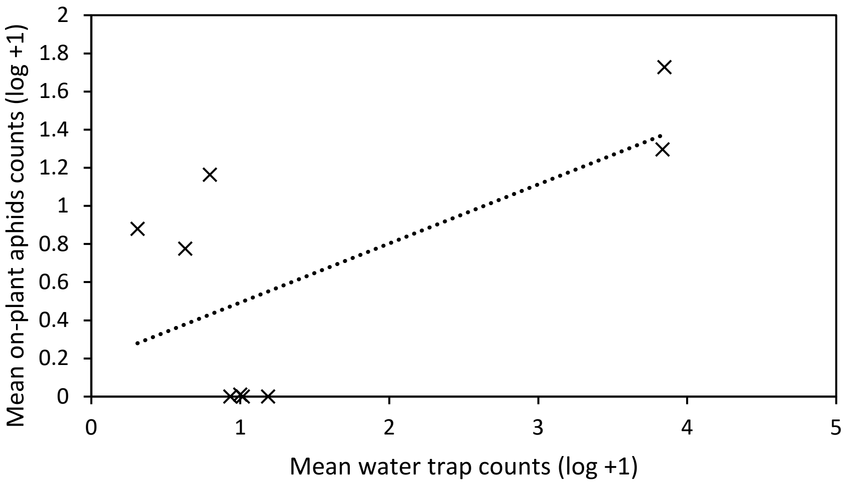

Figure 50. The relationship between *R. padi* observed on-plant counts and caught in water traps. Adjusted R^2 = 35.3. y = 0.3097x + 0.1838.

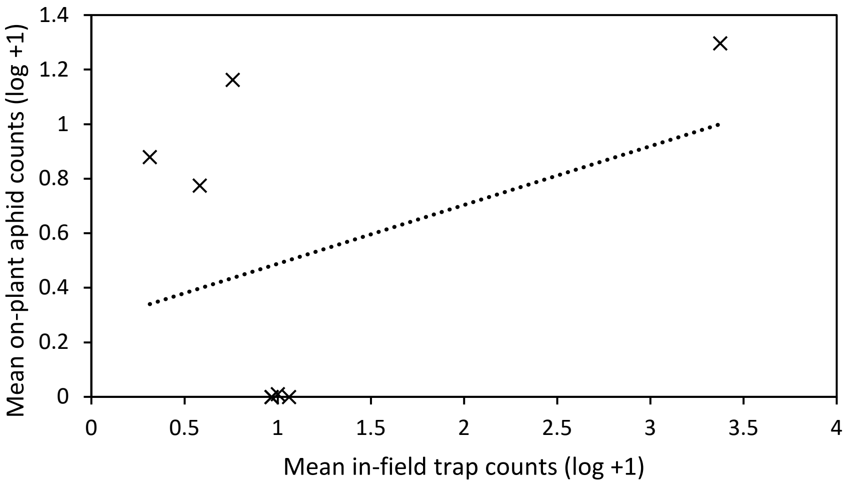

Figure 51. The relationship between *R. padi* observed on-plant counts and caught in in-field traps. Adjusted R^2 = 2.8. y = 0.2156x + 0.2724.

3.3.3. Investigating the potential of image analysis techniques for identifying BYDV vectors

In the three years of the project, ADAS technical staff took, in total, 1217 images of traps. Of these, 60 images of traps containing BYDV vectors were sent to project partners for the years 2019 and 2020. The low number of photos sent in these years reflects the low number of traps containing aphids. In 2021, aphid pressures were higher and the photography methodology was improved resulting in 223 images being sent to project partners; these included 159 photos of traps with BYDV vectors, 42 photos of traps without BYDV vectors and 22 photos of traps with other non-target aphid species. Both BASF Digital Farming and Syngenta investigated the potential for developing image analysis software using these images. Both companies encountered similar challenges. The small size of these aphids was found to be a major issue, as it made the aphids difficult to distinguish. BASF Digital Farming have already developed a similar tool for identifying Coleopteran pests in oilseed rape, but these insects are larger and easier to discriminate, though even then the three *Ceutorhynchus* species of weevils are not identified to species due to their similarities. Variable light conditions in the field when photographs were taken further complicated the process. Image resolution was also an issue. Higher resolution, better quality images would reduce the issue of aphid size as differences may still be identifiable. Ultimately, it was not possible to develop image analysis software for these aphids.

3.3.4. Comparing the cost-effectiveness of different BYDV vector monitoring methods

Analysis of cost-effectiveness

There are costs to establishing and carrying out the various in-field monitoring methods for BYDV vectors and percentage carrying the virus. The cost depends primarily on the amount of time and degree of expertise required to deliver the tasks. Where aphid identification is done on-farm, the use of pest recognition software was the cheapest monitoring method at between £11.25 and £11.75 (depending on monitoring method) for each monitoring occasion (Table 13). It should be noted that this doesn't include costs for the purchase or use of pest recognition software because, as there are few such products currently available, the cost is difficult to estimate. Of the currently available monitoring methods, sticky traps were found to be the cheapest monitoring method at £33 for each monitoring occasion, followed by water traps (£45 per monitoring occasion) and on-plant counts (£50 per monitoring occasion). The price of water traps was not included in the costing because they can be reused. They cost approximately £10 each so whilst this increases the upfront cost to develop a monitoring programme, they can last for many years and are likely to be cheaper on a per use basis than sticky traps. It should be noted that if travel time is factored in then it is likely that on-plant counts would be closer in cost to the use of sticky and water traps, as on-plant counts involve a single visit compared to the two visits needed for water or sticky traps for each monitoring occasion.

Table 13: Cost for each monitoring method per monitoring occasion (i.e. one set of on-plant counts or a single period of trapping).

Monitoring method	Cost per visit monitoring occasion (£)
Pest recognition software: on-plant	11.25
Pest recognition software: water traps	11.25
Pest recognition software: sticky traps	11.75
Sticky traps (on-farm ID)	33
Sticky traps (lab ID)	41.75
Water traps (on-farm ID)	45
On-plant counts	50
Water traps (lab ID)	52.5
Sticky traps (on-farm ID & BYDV testing)	150.5
Sticky traps (lab ID & BYDV testing)	159.25
Water traps (on-farm ID & BYDV testing)	162.5
Water traps (lab ID & BYDV testing)	170
On-plant counts (+ BYDV testing)	267.5

When traps are sent to a laboratory for aphid identification additional charges are incurred. In this situation, the cheapest method per monitoring occasion remained sticky traps at £42 followed by water traps at £52.5 (Table 13). Molecular testing of aphids to determine the percent carrying the viruses increases the cost considerably (Table 13). An extra £100 for the minimum 10-aphid sample is the approximate cost to run the RT-PCR assays for BYDV detection. When the molecular testing is added, sticky traps are the cheapest option, whether the aphid identification occurs on-farm (£150.50 per monitoring occasion) or in a laboratory (£159.25 monitoring occasion). Virus testing using water traps was slightly more expensive (£162.50-170 depending on whether aphid identification occurs on-farm or in a laboratory). Collecting aphids from plants for virus testing is the most expensive option at £267.50 per sample collected, primarily due to the time needed to collect sufficient aphids, which can vary widely but would have taken a long time at the majority of sites we monitored in this project. If ten aphids are collected quickly then the cost would be much closer than for sticky and water traps.

The effectiveness score for the different in-field monitoring methods relates the number of aphids recorded in traps to that when plants are inspected for their presence; the latter being the traditional method of monitoring aphids. Water traps were the most effective means of monitoring *R. padi*, catching almost 3.5 times the number found on 100 plants (Table 14). However, on-plant counts were far more effective at monitoring for *S. avenae*, primarily because this species was rarely caught in water or sticky traps. This indicates that on-plant counts are the only effective means of monitoring *S. avenae* in crops drilled from mid-September (which made up all of the crops monitored in this work), and for this reason the following cost-effectiveness scores for the different monitoring methods are only given for *R. padi*.

Table 14: Relative effectiveness of different aphid monitoring methods.

Monitoring method	*R.padi*	*S.avenae*
On-plant counts	1	1
Water traps	3.47	0.07
Sticky traps	1.62	0.06

The cost effectiveness of each method is given as the price per aphid found. Water traps were the most cost-effective method of monitoring in all scenarios (aphids identified on-farm, in a laboratory, with a pest recognition software, or if aphids were tested for BYDV) (Table 15), while sticky traps tended to be more cost-effective than on-plants counts. The addition of testing aphids for the presence of the viruses increases the cost in each method considerably, with the cost to run the RT-PCR for each aphid (£10) accounting for the majority of the increase.

The time taken for the results to be reported is an important consideration in assessing the practicality of the different monitoring methods and making timely control decisions (Table 16). On-plant counts provide results within an hour or so, whereas sticky or water traps need to be left for at least three days. Sending aphids away for identification will add at least a further two days, while testing for BYDV will add a further two days. This means that results can take a week to receive where traps need to be sent away for aphid identification and virus testing (although the laboratory could conceivably provide the aphid identification results after five days while the BYDV testing is happening).

Table 15: Cost effectiveness of each monitoring method according to the cost per aphid recorded.

Monitoring method	Cost per aphid (£)
Pest recognition software: water traps	0.01
Pest recognition software: sticky traps	0.03
Pest recognition software: plant counts	0.05
Water traps (on-farm ID)	0.06
Water traps (lab ID)	0.07
Sticky traps (on-farm ID)	0.09
Sticky traps (lab ID)	0.12
On-plant counts	0.23
Water traps (on-farm ID & BYDV testing)	10.08
Water traps (lab ID & BYDV testing)	10.09
Sticky traps (on-farm ID & BYDV testing)	10.14
Sticky traps (lab ID & BYDV testing)	10.17
On-plant counts (+ BYDV testing)	10.77

Table 16: Time taken until completion, start to results, for each monitoring method.

Monitoring method	Time until results
Pest recognition software: plant counts	0 days 0.75 hours
On-plant counts	0 days 1 hour
On-plant counts (BYDV testing)	2 days 5.5 hours
Pest recognition software: water traps	3 days 0.75 hours
Pest recognition software: sticky traps	3 days 0.75 hours
Sticky traps (on-farm ID)	3 days 1 hour
Water traps (on-farm ID)	3 days 1.25 hours
Sticky traps (lab ID)	5 days 1.25 hours
Water traps (lab ID)	5 days 2 hours
Sticky traps (on-farm ID & BYDV testing)	5 days 3.25 hours
Water traps (on-farm ID & BYDV testing)	5 days 3.5 hours
Sticky traps (lab ID & BYDV testing)	7 days 3.5 hours
Water traps (lab ID & BYDV testing)	7 days 4.25 hours

Validating the Fabre et al. (2005) model

A stepwise regression of 'Year' and 'Trap' were not significant ($P<0.05$). GLM analysis showed that 'Trap' was significant ($df = 3$, $F = 11.36$, $P = 0.036$) (Fig. 52) but 'Temp' was not significant ($P<0.05$) (Fig. 53), the interaction between the two was also not significant ($P<0.05$). GLM analysis of 'Land use' and 'Trap' was not significant ($P<0.05$) (Fig. 54). Variance in annual accumulated degree days and land use therefore does not correlate with % viruliferous aphids.

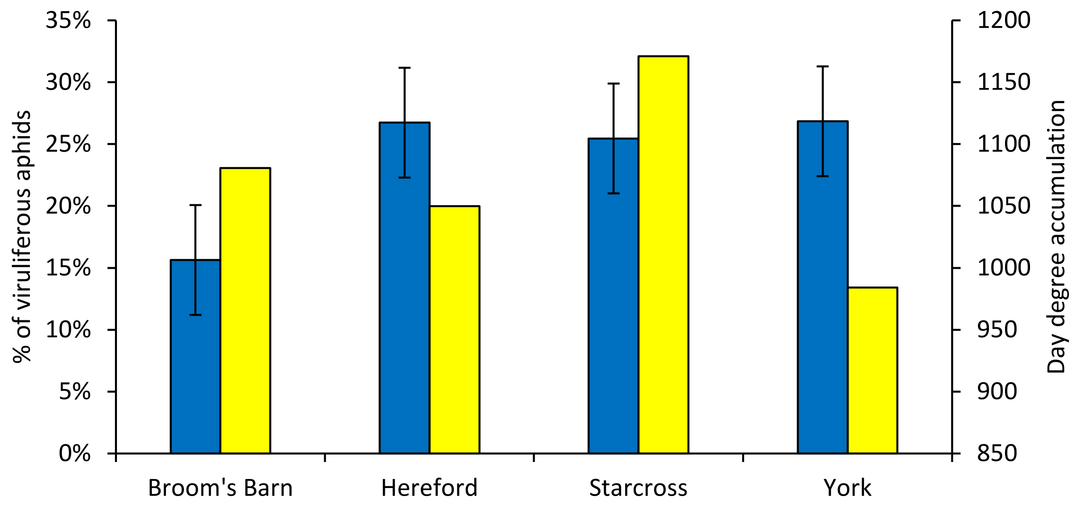

Figure 52. Mean proportion of viruliferous *R. padi* (blue bars) and annual accumulated day degrees (yellow bars) for the four suction traps monitored in this project.

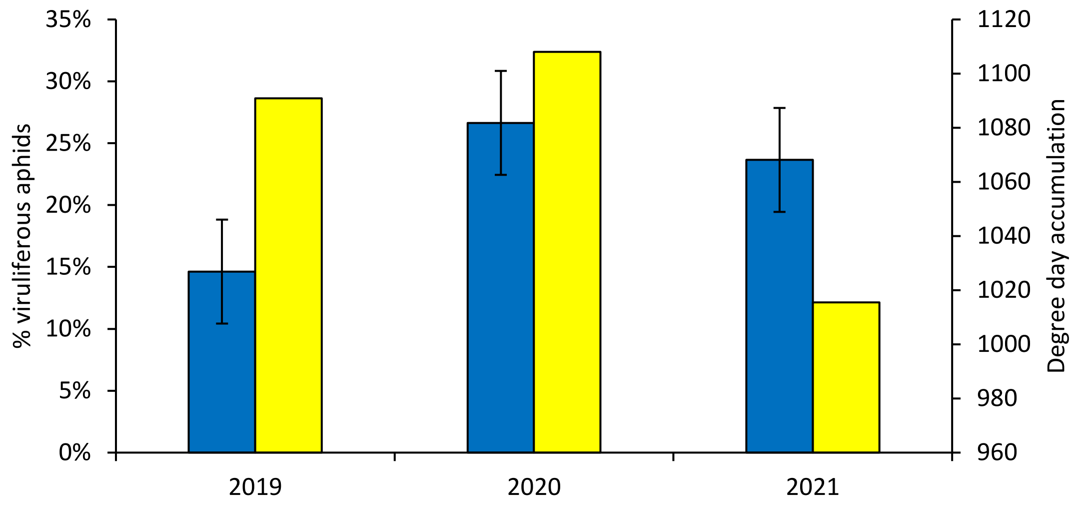

Figure 53. Mean proportion of viruliferous *R. padi* (blue bars) and annual accumulated day degrees (yellow bars) per year of the project.

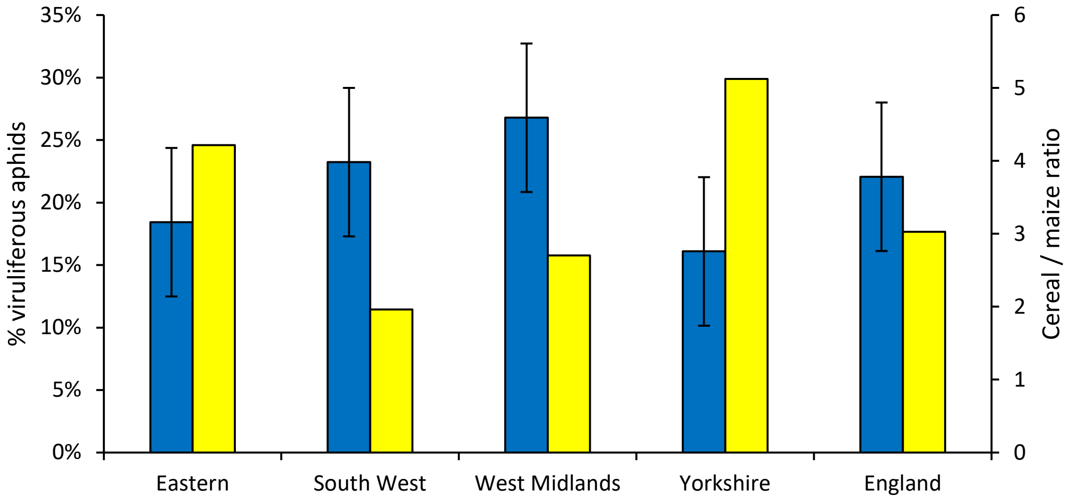

Figure 54. Average proportion of viruliferous *R. padi* in the regions studied in this project (blue bars) and the proportion of small grain cereals to maize for each region (yellow bars). Note that regional level data was not available in 2020 so England is substituted for this.

3.4. Discussion

3.4.1. Aphid monitoring

Monitoring of BYDV aphid pressure in winter crops between 2019 and 2021 showed large interannual differences in aphid numbers, with far more found in 2021 than 2020 (an 8-fold increase) and 2019 (a 20-fold increase). To a degree, these in crop counts reflect the numbers of *R. padi* caught in each year in the autumn (Fig. 55), though the in-crop counts in 2019 may also be low due to the reduced monitoring in October (note *S. avenae* is not included in Fig. 55 because these are rarely caught in suction traps in the autumn, which is discussed further below).

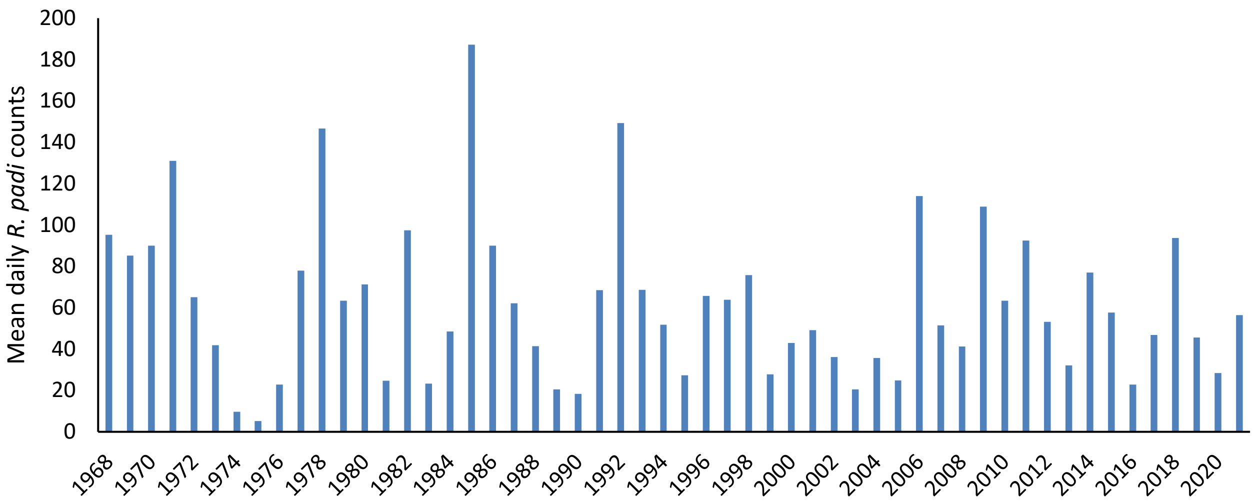

Figure 55. Mean daily numbers of *R. padi* caught in the autumn (Sept-Nov) each year in suction traps in England. Data shown from traps monitored continually from at least 1980 until at least 2019.

R. padi was much more common than *S. avenae* in crops, even in northern regions of England where *S. avenae* has long been considered the more important vector of BYDV (McGrath et al., 1987; McGrath & Bale, 1990). The lower importance previously attributed to *R. padi* in northern England was due to the species being predominantly holocyclic in this area (McGrath & Bale, 1989), meaning that the majority of these aphids overwinter on bird cherry trees rather than cereals. It is possible that changes to the climate and/or changes in the density of bird cherry trees (McGrath & Bale, 1990) have selected for increased numbers of the anholocyclic form, which overwinters on cereals. Mild winters are associated with higher winter survival of anholocyclic forms that in turn leads to higher a proportion of these forms the following autumn (Harrington et al., 2012). *R. padi* was more commonly recorded in crops in the East of England and the West Midlands than the South West and Yorkshire, although this trend was not consistent between years, e.g. *R. padi* was more common in Yorkshire in 2020.

More *R. padi* were found in crops when monitoring occurred in October than in November or December. This is likely due to the increasingly colder and wetter conditions as autumn progresses, which reduce flight activity (Walters & Dixon, 1984; Dengfa et al., 2002), development and reproduction (Dean, 1974; Williams, 1987), and causes aphids to shelter in the soil at the base of plants (Tones & Jenkins, 1985; Wiktelius, 1987). This is thought to be especially true in later drilled crops that offer less protection from the weather (Saynor, 1985). Trial work has shown that aphid population dynamics in winter barley is strongly affected by sow date, with the proportion of the plants infested with aphids increasing rapidly in plots sown in early September, while the proportion infested remained low throughout the autumn in late September sown plots (McGrath & Bale, 1990). Crops emerging before mid-September may also suffer immigration of holocyclic *R. padi* morphs before their transition to sexual forms seeking bird cherry trees (Tatchell et al., 1988), as well as the anholocyclic forms later in the autumn. Although as wide a range of drilling dates were sought for the crops monitored in this project, no crops that were drilled before mid-September were put forward by growers. This does highlight a potential a weakness of the work in that risks to very early drilled crops may not be well represented. The trend in *R. padi* numbers in crops across the autumn is in line with the numbers of *R. padi* caught in suction traps, where numbers build up in the spring and early summer, often followed by a midsummer decline, before peaking in September or October, and followed by a steep decline in November (Fig. 56). The conclusion is that aphids are less likely to be found on plants or in-field traps as autumn progresses, which illustrates the importance of sow date and consulting suction trap data when considering likely aphid pressures and monitoring effort.

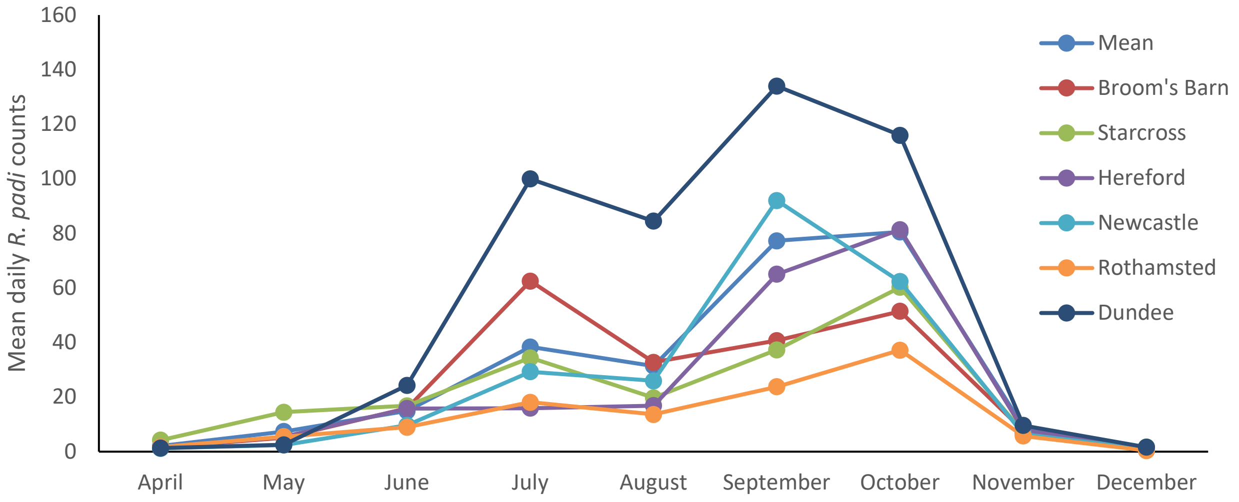

Figure 56. Mean daily numbers of *R. padi* caught each month at select suction traps. Mean shows average across traps monitored continually from at least 1980 until at least 2019. Data shows means across monitoring years.

S. avenae were rarely recorded in crops, with more than three individuals found at just ten of the 130 sites visited; eight of which were in the South West, two in the East of England and one in Yorkshire. As mentioned above, the low incidence relative to *R. padi* in the North was unexpected. An ADAS technical bulletin from the 1980s describes the BYDV risk in Northern regions to be primarily from aphids flying into crops drilled from August to mid-September (MAFF, 1984). An increase in the proportion of later sown cereals in northern areas may therefore explain the low incidence of *S. avenae* in these crops. Certainly, none of the crops monitored in Yorkshire or the North East were drilled before 14 September, although this self-selecting group of farmers may not reflect the wider trends in sow date in these areas. While blackgrass problems have tended to shift sow dates later in more southerly parts of the country, the weed has been less of an issue in northerly areas meaning sow dates have been less affected (P. Berry, pers. comm.). Drilling later reduces risk from *S. avenae* because, while these aphids are caught in suction traps in high numbers during the summer, peaking in July in most areas, their numbers drop off rapidly thereafter so that very few are caught in September and negligible numbers thereafter (Fig. 57). The peak shifts slightly later in more northerly traps (e.g. Dundee), which likely reflects the colder conditions delaying spring activity, summer population build up and migration. Even in September, migration is negligible at all but the northerly traps, where the numbers are low after mid-September (Fig. 58). This suggests that only very early drilled crops that emerge no later than mid-September are at risk from *S. avenae*, although further work in such crops is needed to confirm this.

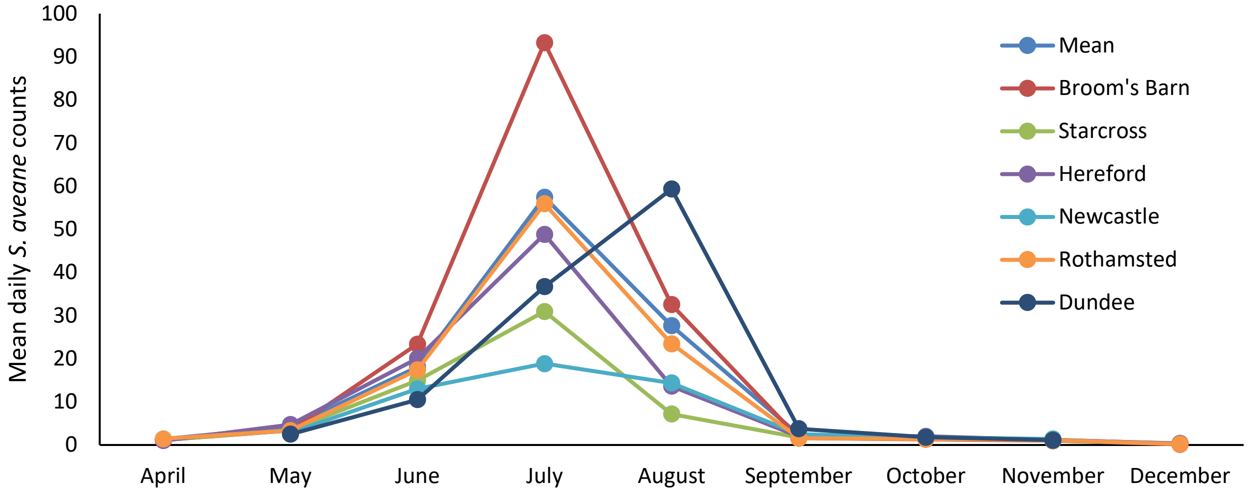

Figure 57. Mean daily numbers of *S. avenae* caught each month at select suction traps. Mean shows average across traps monitored continually from at least 1980 until at least 2019. Data shows means across monitoring years.

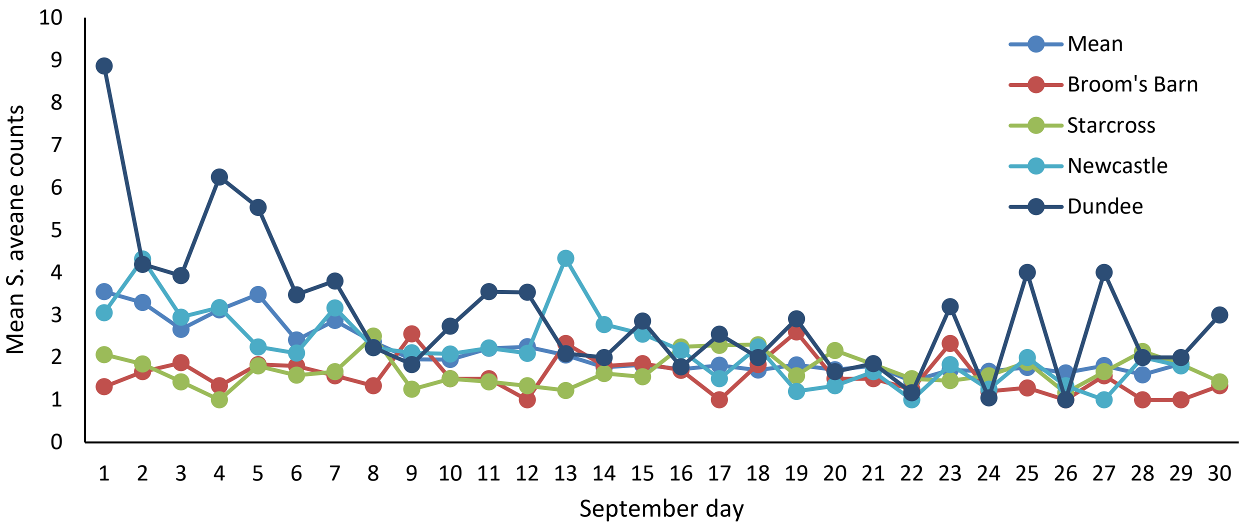

Figure 58. Mean daily numbers of *S. avenae* caught each day in September at select suction traps. Mean shows average across traps monitored continually from at least 1980 until at least 2019. Data shows means across monitoring years.

3.4.2. Virus monitoring

Testing to investigate the size of the aphid population carrying virus found this ranged from 0-67% for BYDV and 0-100% for CYDV, with the peaks tending to occur in the summer. In the autumn, the highest percentage of aphids carrying BYDV or CYDV was 50% and 38% respectively. The annual mean percent viruliferous (BYDV+CYDV) ranged from 13% in 2019 to 27% in 2020. This annual variation is possibly due to the population dynamics of the vectors and other host plants earlier in the year. Previous surveys occurring from 1969-1973 (Plumb, 1976), 1982-84 (Torrance et al., 1986), 1984-1986 (McGrath & Bale, 1989) and 2018 (Holland et al.; 2019b) found the annual mean percent viruliferous ranged from 1-14%. There are several possible explanations for the higher incidence of viruliferous aphids in this work. Except for Holland et al. (2019b), the previous surveys used ELISA tests or infectivity assays, in which aphids were placed on oat seedlings and infections recorded either visually or by ELISA. Both approaches are less sensitive than the RT-PCR assay used here (Rochow, 1979; Torrance et al., 1986; Fabre et al., 2003) and the ELISA tests may not have been able to detect all the BYDV serotypes that the RT-PCR assay can. Holland et al. (2019b) monitored just two sites and used the same RT-PCR assay as in this work but only tested for BYDV-PAV, so their % viruliferous (3%) may be lower due to a smaller monitoring area and not detecting BYDV-MAV and CYDV-RPV. Alternatively, there may simply be large interannual fluctuations in percent viruliferous or a genuine increase in the percent viruliferous aphids due to changes in BYDV reservoirs in non-crop species, climate change or pest control methods. For instance, the widespread use of neonicotinoid seed treatments may have resulted in many crops suffering from late BYDV infections that produced no symptoms or yield impact, but nevertheless increased the prevalence of the virus more generally. The high proportion of aphids carrying the viruses means that serious BYDV problems between 2019-2021 were probably only avoided because of the poor weather conditions for aphid migration and within crop spread.

The widespread incidence and moderately high prevalence of RPV has implications for the use of tolerant or resistant crop varieties, as these might be susceptible to this serotype. RPV is generally thought to be the least important of the three main BYDV/CYDV serotypes found in the UK, and mainly affects oats (Smith, 1967). Reports of its virulence and yield impact in oats, wheat and barley vary from weak (Rochow, 1969) to severe (Smith, 1967). Barker (1990) found similar incidence of aphids carrying the virus as in the current project, however other work has shown that incidence of RPV in crops has generally been low (Henry et al., 1993; Foster et al., 2004; Flint, 2015). It is possible that RPV is more easily transmitted to non-crop grass species than crop species ; *S. avenae* appears to be a poor vector (Guo et al., 1997) and a 1987/8 survey found it most commonly in perennial grass leys (Henry et al.; 1993), however *R. padi* can readily infect wheat with RPV (Foxe & Rochow, 1975; Guo et al., 1997). The current work did not investigate the presence and distribution of BYDV/CYDV in crops so whether the relatively high levels of RPV seen in aphids corresponds to crop infection is not known. If crop infections with RPV were found to be high or increasing, then it may have important implications for varietal tolerance in barley and resistance in wheat. Tolerant barley varieties currently available in the UK rely on the *Ryd2* gene, which confers protection against MAV and PAV serotypes but offers less protection to RPV (Scholz et al., 2009; Jarošová et al., 2016). Wheat varieties resistant to BYDV (e.g. RGT Wolverine and RGT Grouse) are based on the *Bdv2* gene (Brown, 2021), which confers high resistance to PAV and the non-UK serotypes, GPV and GAV (Zhang et al., 2009). This means that the increasing incidence of RPV may compromise the protection afforded by tolerant barley and resistance wheat varieties that rely on these genes.

Some regional variation in the percent of viruliferous aphids was evident in this work, with the South West, West Midlands, Yorkshire and the North East tending to have a higher percentage than the East of England. This likely reflects the larger areas and higher proportional land use of perennial grassland in these areas (Defra, 2022; ONS, 2022). A range of grass species (including perennial ryegrass, timothy, and especially Poa spp.) are known hosts of BYDV (Oswald & Houston, 1953; Bruehl & Toko, 1957; Catherall, 1963; Doodson, 1967; Plumb 1977; Fargette & Lister, 1982; Masterman et al., 1994) and so provide a major source of virus for aphids to carry into winter crops. Therefore, regions with a high incidence of long-term grassland are generally at higher risk from BYDV (Foster et al., 2004). There was no clear pattern to the % viruliferous across seasons, with this generally fluctuating around a mean for each suction trap. Overall, around a fifth of *S. avenae* and *R. padi* were found to carry BYDV, and 6% of *R. padi* carried CYDV. Very few *S. avenae* were found with CYDV. These results are in line with previous work showing that both species transmit BYDV well (certainly the PAV serotype) (Rochow, 1969a; Plumb, 1974; Barker, 1990), while CYDV is transmitted by *R. padi* but rarely by *S. avenae* (Rochow, 1969a).

3.4.3. Monitoring methods

Suction trap data on aphid numbers and the percent of these carrying BYDV/CYDV was found to be informative for surrounding farms, but the analyses identified several important relationships. The number of *R. padi* caught in suction traps could be directly correlated with their numbers in surrounding fields. This relationship was strong for fields approx. 10 km away from the suction trap but weaker for fields approx. 20 km away. However, there was no clear relationship with fields around 40 km away, which contrasts with other work that found that suction trap data was reliable for fields 39-50 km away (Harrington et al., 1999; Harrington et al., 2007). The reasons for this difference may be due to the where the work was carried out, the timing of the work and seasonal differences in aphid abundance. Harrington et al. (1999) monitored aphids in three fields 0.25, 0.75 and 39 km away from the Rothamsted Tower suction trap in Hertfordshire weekly between late September and early November in 1996 and 1998. It is possible that the topography and climate around the Rothamsted Tower allow for the aphid pressures in the vicinity to be more uniform across a wider area than the suction traps investigated in this study (in Suffolk, Devon, Yorkshire, Herefordshire and Northumberland), and so make the data from that suction trap representative of aphid migration across a wider area. A more likely reason for the differences between the findings is that Harrington et al. (1999) began monitoring earlier and in doing so found the majority of their aphids (73%) before mid-October, and so is relevant mainly for early sown crops. Our work focussed on October and November monitoring because these results would be applicable to most winter cereal sow dates, and especially those in the popular sowing window of late September/ early October. As mentioned above, our work featured few early drilled sites, whereas the crops monitored by Harrington et al. (1999) must have been drilled by mid-September at the latest and likely earlier. The number of *R. padi* caught in suction traps was also higher in 1996 and 1998 than 2019-2021 (Fig. 55). These factors combined meant that that far fewer aphids tended to be found in our work, making detecting strong correlations with suction trap data more difficult.

Suction trap data on *R. padi* numbers also had a stronger correlation with fields to the southwest or west than other directions, which is likely due to these being the prevailing wind directions in autumn (Lapworth & MacGregor, 2008). There was little to indicate differences between suction traps in terms of their relationship with *R. padi* numbers in surrounding fields. The general trends were similar between the suction traps but none, except the Hereford suction trap, had a significant correlation, though this is likely a reflection of the smaller dataset when analysing the relationship at the individual suction trap level. The number of *R. padi* on plants at sites where an insecticide had not been applied had the strongest relationship with that from suction traps, likely because insecticides reduce aphid numbers in crops and so change their relationship with suction trap counts. A correlation between *S. avenae* numbers on plants prior to insecticide application was also found but was weak. *S. avenae* were rarely caught in in-field traps or at sites that had been sprayed making analysis of their relationship with suction trap numbers impossible. As discussed in Section 3.4.1, the low *S. avenae* numbers is a function of the date the monitored crops were drilled and the timing of monitoring. Analyses of the percent viruliferous aphids showed that suction trap data were similar to that from surrounding fields. Finding sufficient aphids for virus testing (i.e. at least ten) in crops was not common so there was insufficient data to test the whether the correlation of % viruliferous between suction traps and crops was affected by the specific suction trap and the distance and direction from the suction trap.

Three different in-field monitoring methods were investigated to determine their effectiveness for monitoring cereal aphid presence and numbers in winter crops: on plant assessments, water traps and sticky traps. They are all relatively simple and cheap to carry out and have the potential to be more effective with a small amount of additional training. Plant counts are the established method of understanding aphid risk in fields. Water traps and sticky traps should be familiar to many growers and advisors as they are already used to monitor a range of pests, including orange wheat blossom midge in wheat, cabbage stem flea beetle in oilseed rape, pea midge in peas and peach-potato aphid in sugar beet (AHDB, 2014). In this work, water traps and sticky traps caught 3.5 and 1.6 times as many *R. padi* as were found on 100 visually inspected plants respectively. In contrast, these traps caught a fraction of the *S. avenae* found on 100 plant inspections. Harrington et al. (1999) also found that traps catching winged aphids were ineffective for monitoring *S. avenae*.

In addition to catching more *R. padi*, water traps often caught these aphids when they were not caught on sticky traps or found when inspecting plants. This ability to detect the presence aphids when numbers are too low to be detected using the other methods is important. When these aphids initially arrive in the crop, they land on a very small number of plants so that the chance of finding them through visual plant assessments is low. Nevertheless, detecting them at these low levels is relevant for assessing BYDV risk. For example, the T-sum DSS requires the date of aphid arrival to trigger the model but, as accurately gauging this is difficult, it simply assumes cereal aphids are present as soon as the crop emerges (AHDB, 2023b). As many crops will not contain aphids this quickly, this clearly means that insecticides are likely to be recommended early or unnecessarily. It should be noted that the T-sum DSS does suggest that growers inspect their crop for the presence of aphids before spraying but it is likely that many growers do not do this, and even if they did, they would not know whether any aphids present are the second wingless generation (the target) or another generation. Water traps are therefore likely to provide a more accurate estimate of the timing of the first aphids arriving in the crop and so lead to better timing of insecticide applications using the T-sum tool.

The number of *R. padi* caught in water traps were better correlated with on-plant counts than were those from sticky traps. This is useful because some DSS require an estimate of the initial aphid population size to start the model, e.g. the ACroBAT DSS developed in this project (see Section 4). The initial aphid population size can be estimated from suction trap data for fields close enough to a suction tower but for fields further away water traps would provide a better estimate. Water trap counts were also correlated with suction trap counts, whereas sticky traps were not. Traps were also better correlated with suction trap data when placed 20 m from the field margin than when placed 70 m from the margin. More aphids were also caught 20 m from the field margin, which supports work by Holland et al (2019a) that found more aphids in traps placed within 10 m of the field edge than 70 m into the crop.

The work in this project to investigate whether image analysis techniques could be developed to identify cereal aphids caught in water or sticky traps was ultimately unsuccessful. Despite several adjustments to the way in which the photographs were taken (e.g. emptying water traps onto a white tray and then taking photographs), it was concluded that a new methodology would be required to develop image analysis for these species due to their small size. This might involve taking images through a microscope to increase magnification. This would help pick out diagnostic features and improve the likelihood that the machine learning methodology could be “trained” to identify the aphid species, although even this would likely need thousands of images to develop the algorithm. Such an approach would need significantly more resource than was available in this project. Matters were not helped by the low aphid pressures in the first two years of the project, which meant that very few images of traps containing aphids were available until the final year of the work, limiting the time to develop algorithms. Image analysis to assist in identifying these species remains a desirable goal. However, approaches that require very high-resolution images would limit their usefulness for growers or advisors with only a camera phone at their disposal. Similarly, the need to decant water trap contents into trays, take images under controlled light conditions or magnify them would also reduce the practicality of such a tool. Recent advances elsewhere have shown the potential to identify aphids in water traps (Gao, 2023) and for using camera phones to identify a range of wheat pests on plants (Liu et al., 2019), including aphids (Du et al., 2022; Li et al., 2023; Shunbao et al., 2023), although the ability to identify aphid species remains elusive.

Our cost-benefit analysis of the various in-field monitoring methods found that pest recognition software, were it to be available, was the cheapest and most cost-effective method of monitoring. For the currently available monitoring methods, sticky traps were the cheapest but, when the ability to catch aphids were factored into the calculation, water traps were the most cost-effective, even where the aphids were sent to a laboratory for identification. Water traps were at least 33% more cost effective than sticky traps and 70% more cost effective than visually assessing plants for aphids. The ability to identify the aphids on-farm was always more cost-effective than having to send aphids to a laboratory for identification. Assessing the percentage of aphids carrying the virus on a field-by-field basis would cost at least £150.50 per occasion, which is likely to be prohibitively expensive. The time for monitoring data to be available is important, with plant counts generating relatively immediate results while sticky or water traps ought to be left for at least three days. Sending aphids away for identification and/or BYDV testing delays matters by 2-4 days.

Validation of the French model correlating land use and temperature with the percent of viruliferous aphids (Fabre et al., 2005) found that these correlations were not present in England. However, there was a relationship between the trap location and the percent of viruliferous aphids. That the Fabre et al. (2005) model was not replicated for England may be due to the differences in the area of small grain cereals grown in England proportional to that for maize; in France this ratio ranged from 1:1 to 10:1 while in England it was between 4:1 and 24:1. The geographical differences in maize cultivation is also marked, being more much common in the south-west than eastern and north-eastern areas of England. The relatively smaller land area given over to maize production in England, and geographic variations in cultivation, may make this crop a less important determinant of viral incidence in the aphid vectors. Instead, the area of other plant species may be more important. For example, as discussed in Section 3.4.2, trends were found between the percent viruliferous aphids and the proportion of land given over to perennial grassland. Therefore, further work using species that make up such grassland in place of maize may be worthwhile for investigating relationships with percent viruliferous aphids. An additional source of difference between our work and the Fabre et al. (2005) model was that the latter used ELISA to determine % viruliferous, whereas the former used RT-PCR. As discussed in Section 3.1.1, RT-PCR is more sensitive than ELISA changing the relationship with the variables analysed.

In conclusion, this work demonstrates the importance of suction trap data for assessing risk from BYDV but also that a range of variables affect the reliability of this data for surrounding farms. Suction trap data on *R. padi* numbers is especially reliable to growers within 10 km of a trap and to the southwest or west of a trap. The reliability of the data decreases at distances further than 10 km, though due to the lack of early drilled crops in this work, it is possible that suction trap data is more reliable at greater distances in crops emerging before October. It should be noted however that recent work has cast doubt on the use of suction traps to predict in-field aphid pressure at any distance (Bell et al., 2022). Their in-depth analysis of *Myzus persicae* distribution in the spring and summer found that the aphids showed little spatial synchrony (i.e. fields close to one another are likely to have as different aphid infestations as fields far away), meaning that suction trap data would have little predictive power. While further work is needed to test whether this applies to cereal aphids in the autumn, this might suggest that all fields should be monitored for cereal aphids regardless of proximity to a suction trap. Nevertheless, the work here and by others (Harrington et al., 1999; Harrington et al., 2007) demonstrates that suction trap data provides a useful indication of cereal aphid pressure. The use of more complex statistical methods (e.g. Hierarchical Bayesian Modelling) may further improve the potential of using suction trap data for predicting crop colonisation by cereal aphids (Fabre et al., 2010).

The impact of the reduction in the zone of reliability around each suction trap in relation to aphid data can be seen in Figure 59. If suction trap data on *R. padi* are a reliable indication of aphid numbers in crops 39 km away (Harrington et al., 1999) then the suction traps cover a considerable area of the UK. However, if, as this work suggests, suction trap data are reliable only up to 10 km or 20 km from a suction trap, then the great majority of the UK is not covered by suction traps.

As suction trap counts are more indicative of aphid numbers on plants where no insecticides are applied, suction trap data can be most relied upon up until the first insecticide spray. It should be noted however that the calculation used in this work to determine the proportion of *R. padi* caught in the suction traps that are the cereal colonising form was based on data from the Rothamsted suction trap (Harrington et al., 2012), and there is a possibility that this relationship differs for other areas of the UK. Further work is needed to test this assumption. Suction trap data on the percent viruliferous aphids appears to be reliable for surrounding crops up to at least 40 km away, though a smaller dataset than for aphid numbers was available to test this.

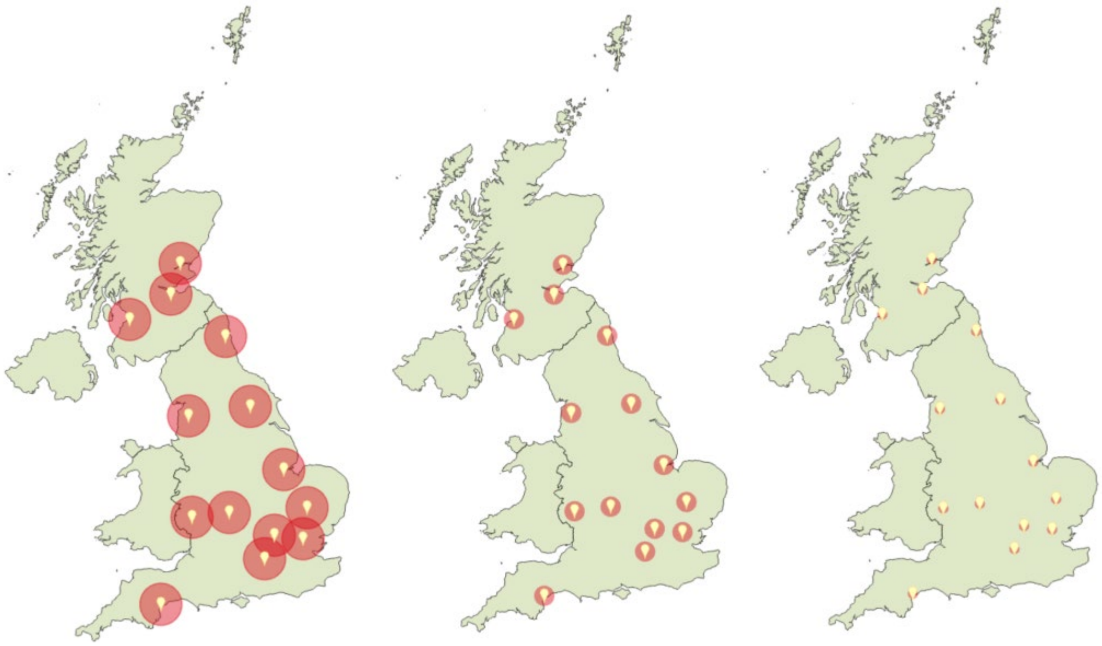

Figure 59. Maps showing the location of the suction traps (yellow pins) in the UK and the zones (red areas) in which data on *R. padi* numbers are deemed to be reliable; 39 km, 20 km and 10 km zones are shown left, centre and right respectively.

For growers further than 10 km from a suction trap, and certainly those further than 20 km, in-field monitoring should be implemented to reliably gauge the presence and numbers of BYDV vectors in their crops. As most winter cereals are at risk from *R. padi* due to their migration throughout the autumn (Fig. 56), we recommend water trapping for monitoring this species due to its effectiveness at detecting these aphids throughout the autumn and cost-effectiveness to implement. Water traps are likely to provide a more accurate estimate of the timing of the first aphids arriving in the crop and so lead to better evaluation of early risk and timing of insecticide applications from the T-sum tool. They are also suitable for use in estimating aphid populations on plants for starting the ACroBAT DSS (see Section 4). We recommend plant inspections are used to monitor *S. avenae* as they were the only effective means of finding them. As far as possible, plant inspections should occur on a warm, sunny day, and not after a frost or rain (Foster et al., 2004). The base of plants should be included in these inspections as aphids can shelter there. A magnifying glass with 10-45x magnification and built-in light will also help (Holland et al., 2019b). However, as mentioned above, crops drilled from mid-September onwards are likely to be at low risk from *S. avenae* due to their minimal flight activity from this time, and so these crops could be effectively monitored using just water traps. It is possible that more *S. avenae* would be caught in sticky or water traps put out before mid-September in those that crops that have emerged but, as no such crops featured in this work, further would be needed to confirm this.

Water traps simply need to be filled with water, detergent and a sterilising agent, all of which are widely available and low cost, and require little training to use. A single trap should be sufficient for each field, but more traps are likely to provide a better indication of infestation. Holland et al. (2019b) found large differences in cereal aphid numbers between fields on the same farm and we found similar differences in trials in Section 4. This suggests that a water trap is needed in each winter cereal field. Traps placed adjacent to a wood or a treeline (Holland et al., 2019a) and within 20 m of the field edge are more likely to catch aphids. Traps ought to be put out at crop emergence and monitoring continued at least once a week until aphid migration has ended. A recent survey found that 90% of farmers were willing to monitor four fields on a weekly basis for aphids (Holland et al., 2019b), suggesting that such a monitoring scheme may be widely adopted. Suction trap data can be used to determine when aphid migration is beginning and ending, and so inform the start and end of in-field monitoring. Analysis of suction trap and in-field cereal aphid numbers caught in the autumn in Germany identified several meteorological variables associated with crop colonisation, such as wind speed, temperature and global radiation (Klueken et al., 2009). A similar approach could be applied in the UK and used to help predict crop colonisation in fields that are distant from suction traps, so better informing monitoring effort.

Understanding the percentage of the population that carry BYDV/CYDV is essential for determining the risk of infection. Currently, aphids collected from three or four suction traps are tested for BYDV/CYDV on a weekly basis each autumn. An alternative would be for growers to send BYDV vectors from in-field traps to a laboratory for testing. This would provide an accurate view of the BYDV pressure in the local area but, unless testing becomes cheaper, it is likely to be too expensive. Finding sufficient aphids to test for BYDV/CYDV in a crop may also be difficult. Therefore, due to the reliability of percent viruliferous aphid data from suction traps and the high cost of generating this data on a field basis, we recommend that this data continues to be generated using aphids caught in suction traps, and that this is widened to include aphids from other suction traps to provide a better understanding of BYDV risk over a greater area. For the more than 80% of the UK cereal growing area not within 40 km of a suction trap (Holland et al., 2019b), a water trap network could be set up to monitor the proportion of the aphid population carrying the virus.

Identifying BYDV vectors is crucial to determining risk and making rational treatment decisions. Identifying aphids on-farm is quicker than sending samples to a laboratory for identification (e.g. ADAS Pest Evaluation Services) and more cost effective. Holland et al. (2019b) found that grower and advisor aphid identification skills need improving but that only minimal training improved successful identification considerably. Making such training available is needed. There are multiple events across the UK at which farmers and decision makers could access training, e.g. AHDB monitor farm meetings and regional agronomy conferences, ADAS Farming Associations, Cereals.

Virtual/online training could further increase participation. The provision of effective training material is also important, for instance farmers highlighted a need for high quality photographs of the different cereal aphid species and videos to assist with identifying key diagnostic features (Holland et al., 2019b). It has been suggested that better quality training could be provided to agronomists through BASIS and CPD programmes (Holland et al., 2019b). If pest recognition software were developed, tested and made available then this has the potential to reduce the need for widespread training.

Based on these findings, the following BYDV monitoring scheme is proposed:

- The most effective means of determining the presence of BYDV vectors is by monitoring *R. padi* with yellow water traps and *S. avenae* with on-plant assessments on a field-by-field basis.
- Growers can use suction trap data on numbers of BYDV vectors to reliably gauge infestation in crops within 10-20 km of the suction trap and up to the first insecticide spray.
- All growers can use suction trap data to gauge changes in migration activity of BYDV vectors (e.g. the beginning and end of migration) on a regional basis.
- After the first insecticide spray and for fields further than 10 km from a suction trap, and certainly those further than 20 km, in-field monitoring using water traps should occur to gauge the presence and numbers of *R. padi*. At least one water trap should be placed in each field, within 20 m of the field edge and, if present, adjacent to a wood or a treeline. This should be left for at least three days. Crops should be monitored weekly from emergence until the end of aphid migration.
- Visual assessment of plants is needed for *S. avenae*, although only early sown crops are likely at risk from this species. Plant inspections should occur on a warm, sunny day, and not after a frost or rain, and should include the base of plants. Using a 10-45x magnifying glass is advised.
- As the costs of sending of aphids for identification is high, training for growers and advisors should be provided to improve their aphid identification skills.

Suction trap data on the percentage of aphids carrying BYDV/CYDV is reliable for fields up to 40 km away from a suction trap. Due to the costs of generating this data on a field-by-field basis, we recommend that this data is generated by testing aphids caught in suction traps in all regions throughout the autumn.

3.5. Conclusions

- *R. padi* was more commonly found than *S. avenae* in crops in all regions monitored.
- The percentage of aphids carrying BYDV/CYDV was notably higher in than previous surveys.
- The high frequency of aphids carrying RPV has potential implications for varietal tolerance and resistance.

- Suction trap data on cereal aphid numbers was most reliable for fields 10 km away and to the southwest or west. Reliability of aphid data reduced after 20 km.
- Suction trap data on the percentage of aphids carrying BYDV/CYDV is reliable for fields 40 km away.
- For fields further than 10 km from a suction trap, and certainly those further than 20 km, in-field monitoring using water traps should occur to gauge the presence and numbers of *R. padi*.
- At least one water trap should be placed in each field within 20 m of the field edge. This should be left for at least three days. Crops should be monitored weekly from emergence until the end of aphid migration.
- Visual assessment of plants is needed for *S. avenae*, although only early sown crops are likely at risk from this species.
- A French model for predicting the percentage of aphids carrying BYDV was found not to be accurate for England.
- A BYDV monitoring scheme is proposed.

4. Developing DSS for guiding the use of insecticides and non-chemical control of BYDV

4.1. Introduction

Decision support systems (DSS) are interactive tools that help users identify problems, make effective decisions and provide solutions (Leybourne et al, 2023). There are different types of DSS, from simple treatment thresholds and decision trees to more complex regression models, physiological (degree day) models and simulation models (Norton et al., 1993). The more complex DSS designed for growers and advisors are usually dynamic, software-based tools that guide the user through decision stages and options in a clear manner, ultimately presenting the outcomes of different choices (Rose et al., 2016). Many DSS have developed to assist with the complexities of managing BYDV, including those simulating aphid migration (Lankin-Vega et al., 2008; Klueken et al., 2009; Thackray et al., 2009), aphid population dynamics (Wiest et al., 2021), yield loss (Fabre et al., 2003), using Bayesian models to predict crop infection and the need for sprays (Fabre et al., 2006) and those guiding all BYDV management decisions (Walls III et al., 2016). DSS specific to the UK include those forecasting aphid flight (A'Brook, 1983), aphid population dynamics (Morgan, 2000), disease epidemiology (Kendall et al., 1992), both aphid and disease dynamics (Morgan & Morse, 1996) and the risk from primary infection (Plumb, 1976).

Few DSS for BYDV management have ultimately been adapted for use by growers/advisors, and even fewer have been widely adopted. In the UK, the Infectivity Index was developed to simulate the risk of primary infection (Plumb, 1976). This used aphid numbers and the proportion of these carrying the virus to calculate risk, with the predictions disseminated to the industry through organisations such as ADAS. However, it was found to be less reliable in some regions (McGrath & Bale, 1989; Holmes et al., 1995). The Decision Support System for Arable Crops (DESSAC) suite of DSS was developed in the 1990s to provide guidance on risk and spray decisions (see Section 4.2.3 for more information) but this also fell out of favour. There are a variety of reasons for the lack of uptake of DSS, including the manner in which they are made available to growers (Jørgensen et al, 2007), the time needed to input data, processing power required to run the models (Magarey et al, 2002), accuracy, trust, relevance and cost (Rose et al., 2016). Modern technology, such as smart phones, mean that DSS can now be more used more flexibly (e.g. in the field), while the availability of geo-located data can increase DSS accuracy (Walls III et al., 2016). Developing DSS with end users in mind and by consulting them in the process can also help uptake (Walls III et al., 2016).

In 2019, AHDB made the T-sum DSS available to assist growers in making spray decisions. This is a degree day model that predicts the appearance of the second wingless generation of the aphids in the crop, which is the generation thought to be associated with the start of secondary spread (see

Section 2.3 for full details). However, there are reservations about this DSS; it assumes aphids are present from crop emergence and that all aphids are carrying the virus, though we now know that usually only a small fraction do (see Obj. 1). Additionally, the origin of the T-sum value is unknown (C. Rowley, pers. comm.) and though both Williams & Wratten (1987) and Knight (1987) have been suggested, neither quite fit the T-sum value in the DSS. For the same reason, it is unknown whether the T-sum value relates to *R. padi*, *S. avenae* or both. There's also no evidence that it has been validated. Finally, it may be too conservative; for instance, for much of England it can recommend that four or more sprays be considered for a crop emerging in late September. This is likely to be more than most growers would envisage applying without using the DSS.

The implications for overuse of insecticides generally are clear, with consequences in terms of environmental, economic and societal impacts. There also important implications that are more specific to BYDV; pyrethroids are currently the only insecticides available in winter cereals and their broad-spectrum nature means they will kill a range of non-target invertebrate species, including important natural enemies of BYDV vectors (Wiles & Jepson, 1992; Jansen et al, 2011), in turn reducing the BYDV control these provide. Lastly, the increased use of pyrethroids increases the risk of insecticide resistance developing to them (IRAG , 2021b). This risk is exacerbated by having no option to rotate pyrethroids with other modes of action in controlling BYDV vectors (IRAG , 2021b). *S. avenae* already has moderate levels of resistance to pyrethroids in the UK (IRAG, 2021a) and while no resistance has so far been detected in UK populations of *R. padi*, resistance has been detected elsewhere (Wang et al., 2020) (see Section 2.3 for further details). Were stronger or new forms of pyrethroid resistance to appear in these species in the UK then BYDV control would be severely compromised. There is now an additional reason to reduce insecticide use, with the UK government's 2023 announcement that avoiding insecticide use entirely will result in a £45/ha payment as part of their Sustainable Farming Incentive programme (Crown, 2023).

Objective 2 of this project focuses on developing DSS for the management of BYDV. Previously developed DSS will be assessed, updated and improved, and performance tested in field surveys and trials. The DSS will assist growers with decisions on the need for and timing of insecticide sprays and cultural control. Available data, such as the RIS data on migrating aphid numbers, will be utilised, along with newly available data on the proportion of aphids carrying the virus. Ultimately, the DSS should improve control of BYDV while rationalising insecticide use.

4.2. Materials and methods

4.2.1. Model development

This project proposed to develop standalone DSS from previously developed BYDV models and validate them. This would include updating the models and including data previously not readily available e.g. the percentage of viruliferous aphids. Salinari & Holland (2019) reviewed 11 models that had been developed in the UK and abroad and recommended two for further research and consideration of their potential to be updated and used as part of DSS. Their criteria were based on the 1) amount and complexity of inputs needed for the models, 2) relevance of outputs (e.g. providing information on the onset and severity of BYDV infection), 3) readiness for development into a DSS (e.g. is further work needed? Is it ready for testing? Is it applicable to UK conditions?). The two models they identified for further investigation were Kendall et al. (1992) and the models embedded in DESSAC.

4.2.2. Kendall et al. (1992)

This mechanistic model was developed from experimental work at the now defunct Long Ashton Research Station near Bristol. It captures the dynamic pattern of vector activity and infection of plants and vectors (both *R. padi* and *S. avenae*) within a crop. The model is based on two processes.

1) The frequency of virus transmission to uninfected plants by infected aphids.
2) The frequency of virus acquisition by uninfected aphids from infected plants.

A distinction is made between virus spread into crops by alate migrant vectors (primary transmission) and more localised spread within crops, mainly by apterous (wingless) vectors (secondary transmission). The model includes a latent period of 4-5 days following plant or aphid infection during which the plant/aphid cannot pass on the virus. The model requires sow date, daily temperatures, plant population, numbers of alates and apterae, and the proportion of alates carrying the virus (% viruliferous) as input variables. The model outputs the proportion of plants infected. Model predictions were found to be accurate, both in terms of disease progression and final disease levels. Highly significant correlations between observed and predicted disease values were achieved in both wheat (r = 0.94) and barley (r = 0.98), and no systematic deviation between predictions and field observations was found.

Kendall et al. (1992) recognised two major weaknesses with the model: the difficulty with determining the percentage of viruliferous aphids and the aphid populations. The former can now be determined simply and relatively affordably using the RT-PCR assay developed at Rothamsted Research. The latter is relatively intractable, requiring extensive and repeated field observations of alate and apterous field populations. The authors also recognised that the model requires a component linking damage (the proportion of plants infected) with yield loss to develop a DSS that provides control guidance based on economic thresholds. Due to these two issues we realised that the model would need significant alterations and additions before it could be used as a standalone DSS.

4.2.3. DESSAC

DESSAC was a suite of DSS developed for farmers in the 1990s, funded by various organisations. It comprised three sub-models: 1) an aphid population model, which simulated aphid population dynamics in a crop, 2) a BYDV epidemiology model, which simulated crop infection, and 3) a risk model, which predicted yield impact and calculated the cost-benefit of an insecticide application. The structure of DESSAC is described in several papers (e.g. Morgan & Morse, 1996; Harrington et al., 1999; Defra, 2002) and was essentially an internet-based DSS that calculated BYDV risk levels separately for 15 regions (centred around suction traps). These risk levels were then used to produce field-specific risk levels based on local risk factors.

Aphid population sub-model

The aphid population sub-model is described in Morgan (2000). It was developed for UK crops and simulates the life cycle and population dynamics of both alate and apterous *R. padi* in winter barley crops. The model uses equations to describe immigration into the crop of alates, development, survival of adults and nymphs, reproduction, and morph determination (alate or apterae) every day during the simulation period (Fig. 60)

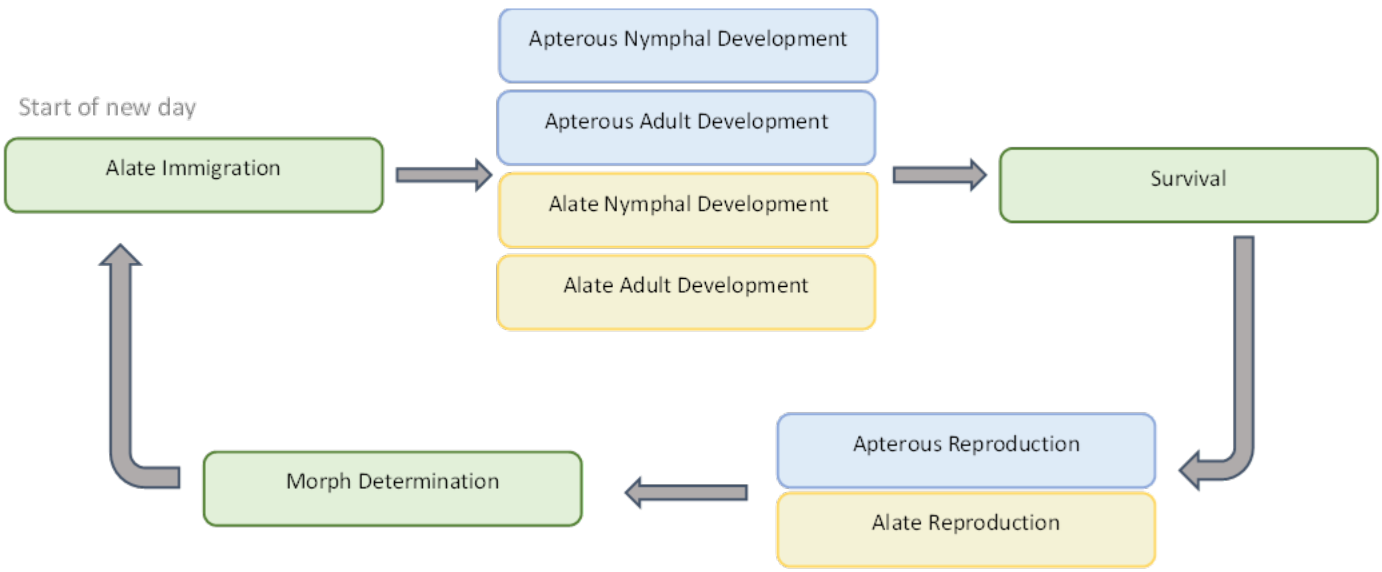

Figure 60. Dynamic events calculated in the aphid population sub-model (Morgan, 2000).

All the equations are fully parameterised, with the only inputs required being plants per m^2, numbers of aphids caught in the closest suction trap and the daily maximum, minimum and mean temperatures. The model is based on several assumptions:

1) The model is initiated with and driven by immigrant alates, which are assumed to be reproductively mature as soon as they have landed. The model calculates that for every

aphid caught in the suction trap, 237 will colonise 1 ha of crop. This is based on an average flight duration and height-density gradient.

2) Reproduction is calculated based on temperature and adult morph using a logistic function of fecundity against temperature. It was assumed that apterae are 1.3 times more fecund than alates, and that immigrant alates immediately produce offspring, whereas apterae experience a pre-reproductive period.
3) Morph determination was based on aphid density.
4) Aphid development is temperature dependent. Alate nymph development is 1.5 times longer than that for apterous nymphs.
5) Linear regression is used to determine development time and life span based on temperature.
6) Fourth instar alatiform nymphs would fly on becoming adults and therefore be a net loss to the population.

The model outputs the number of alate and apterous aphids per m^2. Validation work found the model to accurately predict *R. padi* population dynamics, peak aphid density and the date of peak aphid density (Morgan, 2000).

BYDV epidemiology model

In contrast to the aphid population sub-model (see above) and the risk sub-model (see below), the precise description of the BYDV epidemiology sub-model was elusive. Outputs from the various projects that were funded in relation to DESSAC were published in multiple MAFF/Defra reports, scientific papers and conference proceedings, and while a general structure of the epidemiology sub-model was available (Morgan & Morse, 1996, Harrington et al., 1999) efforts to find a detailed description were initially unsuccessful. Several MAFF/Defra reports suggested that the model was described in the final report of the MAFF/DEFRA project CE0410. However, Defra were unable to locate this report when we contacted them. After some effort we were able to contact Dr Derek Morgan, the author of the aphid population model, and he informed us that the epidemiology model was fully described in his doctoral thesis (Morgan, 1990), a copy of which was available at the University of Southampton library. Unfortunately, our enquiry with the University of Southampton (UoS) library in March 2020 coincided precisely with beginning of the first UK lockdown during the Covid-19 pandemic, which meant that the library closed with no clear indication of when it would reopen. Despite still not being open, the UoS library kindly shared a copy of Morgan (1990) with us in January 2021.

The BYDV epidemiology model described in Morgan (1990) simulates the rate of spread of BYDV from alate and apterous aphids to plants. This was calculated through multiplying:

1) The number of inoculations each day, predicted from aphid density and the probability that an aphid sampled randomly will be viruliferous.
2) A transmission coefficient defined as the number of newly infected plants per vector per day, defined as 0.0166.
3) The proportion of aphids that were knocked off a plant by rainfall.
4) A shelter coefficient, dependent on crop growth stage, acting to protect aphids from the effects of the rainfall.

There were several concerns however, surrounding the thesis and its applicability to the project. Morgan (1990) describes how there was varying success when validating the model against field observations. Reasons given for this include the presence of the virus before crop emergence in the field experiments, lack of inclusion of predators and the impact of "leaf bridges" which would link plants allowing for greater infection rates. When validating the model for use within this project there were also several inconsistencies regarding the values of parameters provided in the text and the accompanying model code.

Risk sub-model

The risk sub-model is described in MAFF (2001). This model uses the virus incidence in the crop (the proportion of the crop infected) to calculate the expected yield loss and provide guidance on whether treatment is economically worthwhile. It uses a Yield-Virus Relationship (YVR) to determine the expected yield loss. This is a multiplication factor defining the relationship between the yield loss and the BYDV incidence in the crops. A different YVR was provided for barley (0.62) and wheat (0.165), indicating that barley is more severely affected by BYDV than wheat. This differential YVR is based on field trials investigating the yield response, using six studies in barley and two in wheat.

The model then calculates the break-even virus incidence (V), which is the proportion of the crop infected at which the predicted yield loss is calculated to result in a greater reduction in crop value than the cost of a treatment (i.e. applying an insecticide is economically worthwhile to prevent that yield loss). The calculation is shown in Equation 1 (where treatment cost = £/ha, yield = t/ha, grain price = £/t).

$$Break\ Even\ Virus\ Incidence\ (V) = \frac{Treament\ Cost}{(Yield * Grain\ Price\ * YVR)} \qquad \text{(Equation 1)}$$

Based on the predicted risk (the proportion of the crop infected, or PR) at any specified time point, the model assigns the crop to one of five risk categories, from "very low" to "very high" (Table 17). For example, in the "low" risk category the predicted virus incidence (PR) is calculated to be between 50% and 95% of the break-even virus incidence (V), meaning that the predicted crop loss may be close to, but is not currently predicted to exceed, the cost of an insecticide treatment (i.e. applying an insecticide it likely to not yet be economically worthwhile), though it is worth continuing to run the model as the break-even virus incidence may soon be reached.

Table 17: Risk Categories, their associated break-even virus incidence and their interpretation. PR = the proportion of the crop infected with BYDV, V = the break-even virus incidence.

Risk Category	Range	Interpretation
Very Low	PR < 0.5V	The BYDV incidence in the crop is well below the economic action threshold.
Low	0.5V < PR < 0.95V	The BYDV incidence in the crop is below the economic action threshold.
Medium	0.95V < PR < 1.5V	The BYDV incidence in the crop is slightly above or below the economic action threshold.
High	1.5V < PR < 2.5V	The BYDV incidence in the crop is over the economic action threshold.
Very High	PR > 2.5V	The BYDV incidence in the crop is well over the economic action threshold.

As DESSAC was designed to generate regional risk maps for wheat and barley in a range of sowing categories, the predicted risk was then adjusted to account for field-specific risk factors, allowing growers to estimate risk in their fields. The model scaled the risk to be applicable to a specific field by multiplying the predicted risk (PR) by a tailoring factor (Table 18). Two factors were considered in determining the tailoring factor:

- Whether the field was within 10 km of the sea.
- Whether the land use immediately surrounding the field was exclusively arable.

The tailoring factor was calculated based on statistical analysis of an extensive survey, comprising 623 winter cereals across three years (Harrington et al., 1999; Foster et al, 2004). This "tailored" PR was then used to determine the risk category for a specific field, as per Table 17.

Table 18: Farm specific tailoring factors.

Factor Combination	Tailoring Factor
Away from the sea and in an area completely dominated by arable land	0.6
Near the sea in an area completely dominated by arable land	1.4
Away from the sea and in an area not completely dominated by arable land	1.4
Near the sea in an area not completely dominated by arable land	3.4

4.2.4. Developing the ADAS Crop BYDV Assessment Tool (ACroBAT)

As mentioned above, the original intention of this project was to update and develop both models recommended in Salinari & Holland (2019), i.e. Kendall et al. (1992) and the DESSAC suite of models, into separate DSS in the first year of the project. Both would then be validated, their performance compared and adjustments made in years two and three. However, issues with both models presented us with a problem. Kendall et al. (1992) required onerous assessments of in-field aphid numbers as an input and lacked a component relating virus incidence to yield loss, meaning that any standalone DSS would need major alterations before being of practical use to growers/advisors. For DESSAC, while the aphid population sub-model (Morgan, 2000) and the risk sub-model (MAFF, 2001) were sound and available when needed, the virus epidemiology sub-model (Morgan 1990) was not available until mid-way through the second year of the project. This meant that any updated DSS based on the DESSAC suite of models would not be ready for validation until the final year of the project. There were also concerns with the performance of Morgan (1990) and the discrepancies between some of the parameter values and the model code.

This left us in a quandary; we had the DESSAC aphid population model and the risk model but not the BYDV infection model that would link them. On the other hand, Kendall et al. (1992) was a virus epidemiology model that needed in-field aphid numbers as an input and lacked an estimation of yield loss. We explored the possibility of updating other models (e.g. Fabre et al., 2006; Thackray et al., 2009; Walls III et al, 2016) but chose not to due to concerns over their utility, relevance to the UK climate and the need for large UK-specific datasets for parameterisation. Our solution was instead to combine Kendall et al. (1992) and the available DESSAC models into a single DSS; the ADAS Crop BYDV Assessment Tool (ACroBAT). The model structure is shown in Figure 61. ACroBAT was designed to provide two types of DSS; 1) a spray decision support tool that provides growers with in-season guidance on the level of risk and whether an insecticide spray is economically worthwhile, and 2) a cultural decision support tool that allows growers to explore different cultural control measures that may reduce BYDV risk.

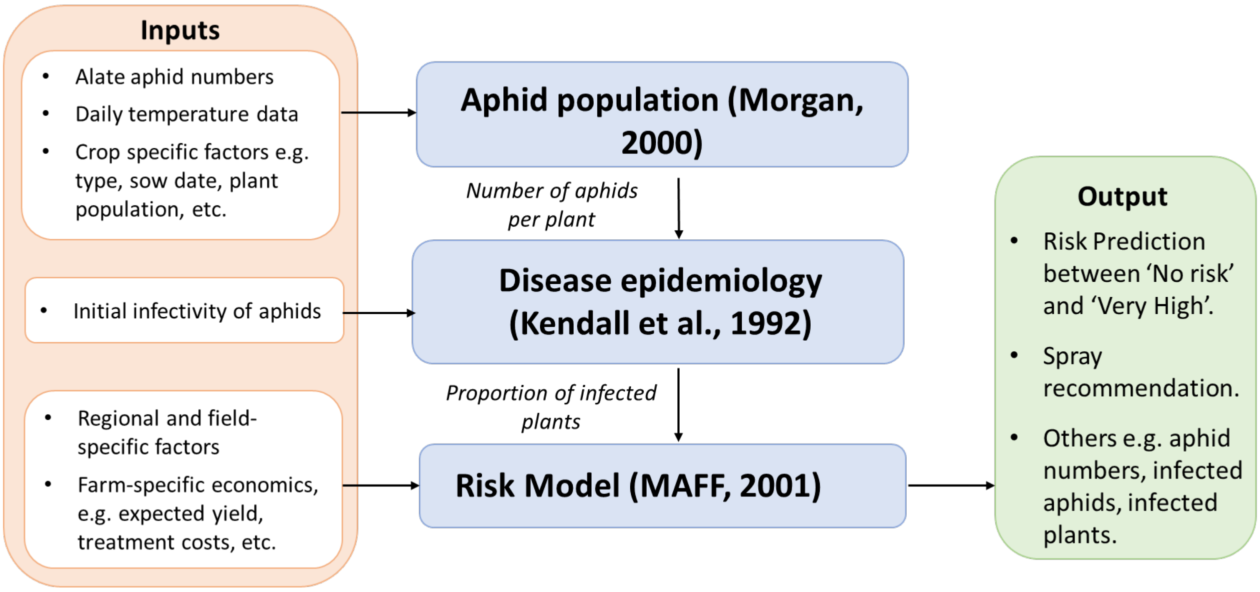

Figure 61. Model structure, inputs and outputs of the ADAS Crop BYDV Assessment Tool (ACroBAT) DSS.

Spray DSS

The ACroBAT spray DSS begins at crop emergence, which is defined as 150 degree days from the sowing date (AHDB, 2021; AHDB, 2023a). It then uses the Morgan (2000) model to simulate aphid population dynamics. This is initiated with immigrating aphids, if present in the suction traps, and stepped forward day by day to predict the number of apterous and alate aphids per plant per day. Along with the initial percentage of viruliferous immigrating aphids, the data on aphids per plant are then used as a direct input into the Kendall et al. (1992) BYDV epidemiology model to calculate virus transmission. This generates the proportion of infected plants as an output, which is then used by the MAFF (2001) risk model to calculate yield loss and the break-even virus incidence, ultimately generating a risk prediction between "no risk" and "very high risk" (see Table 17 in Section 4.2.3). This risk prediction is used to infer a spray recommendation, in this case that a spray should be considered when risk reaches the "medium risk" threshold, i.e. the point at which BYDV incidence in the crop is close to the economic action threshold. Additional outputs are the numbers of aphids per plant, the proportion of aphids carrying the virus and the proportion of the crop infected. The model is designed to be run until the crop reaches GS31, when new plant infections have minimal impact on yield (Smith, 1967, Doodson & Saunders, 1970).

We made several additions/modifications to the DSS. The Morgan (2000) aphid population model uses data from suction traps to calculate the number of immigrating aphids, however it assumes that all *R. padi* caught in the suction traps in the autumn are migrating to cereal crops (i.e they are all the anholocyclic form), whereas in reality the majority of *R. padi* are migrating to bird-cherry trees (the holocyclic form). Harrington et al. (2012) explored the relationship between winter temperatures (from 1st December to end of February) and the proportion of the anholocyclic form the following autumn using 48 years of data from the Rothamsted suction trap, finding that the anholocyclic form tended to increase with mean winter temperatures (Fig. 62).

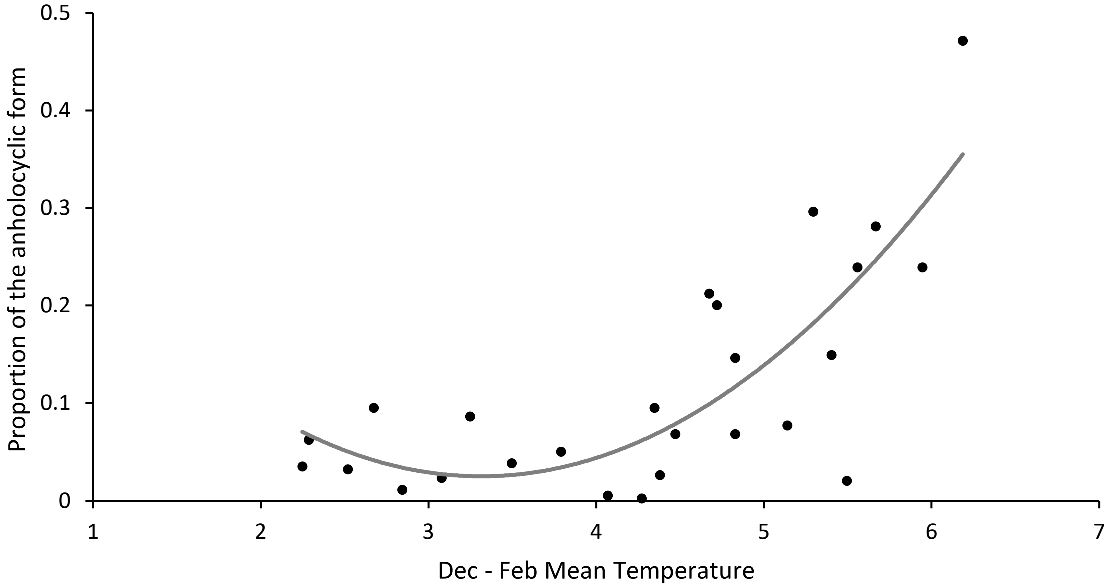

Figure 62. Recreation of the relationship between winter temperatures and proportion of cereal colonisers the following autumn found in Harrington et al. (2012).

Harrington et al. (2012) fitted a polynomial to the relationship between winter temperature and the proportion of the anholocyclic form. However, we felt that a simpler approach could describe the relationship equally well. It can be seen in Figure 63 that at or below 4.5°C the proportion of the anholocyclic form clusters around a fixed value of approx. 0.05 but above 4.5°C to 6.2°C the proportion of the anholocyclic form increases in a linear relationship. It is unknown what happens if the temperature exceeds 6.2°C but as Harrington et al. (2012) reports a maximum proportion of the anholocyclic form of 0.47, it was agreed that that if our calculation of the proportion of the anholocyclic form produced a value greater than 0.5, then it would be reduced to 0.5. Four data points on the proportion of the anholocyclic form has been available from the RIS since the start of this project; these have been added to Figure 63 and show that this data is generally in-line with the model and the data spread it was based on, which gives confidence on the modelled relationship. This modification to the model was made during the second year of the project, and so was in time for the validation trials in 2021/22 of the project but not for those in 2020/21. This means that the DSS will have overestimated immigrating aphid numbers (and so risk) in the trials in 2020/21 (see Section 4.3.4).

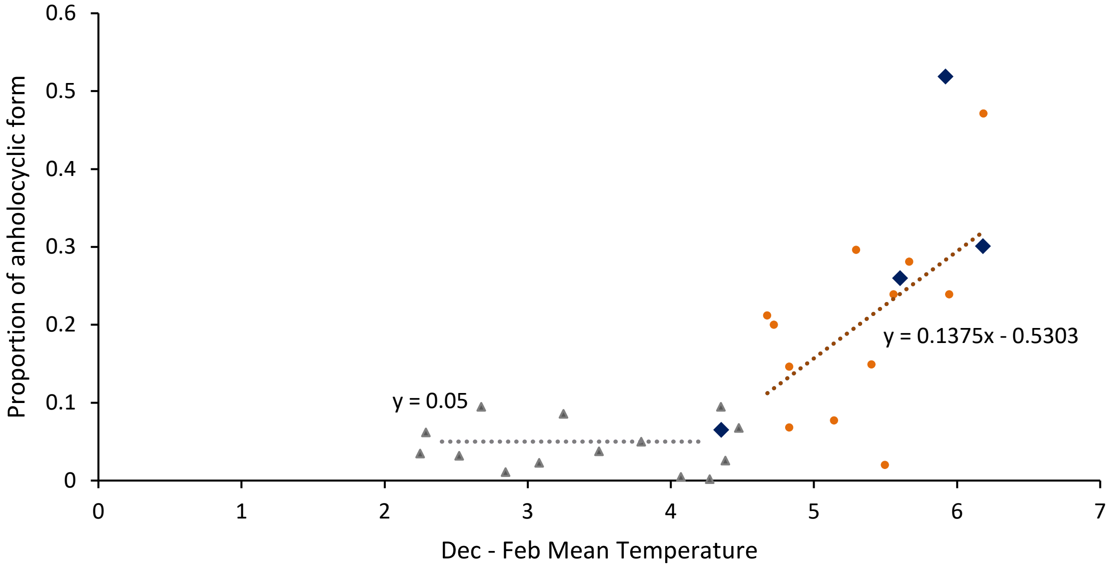

Figure 63. Recreation of the relationship between winter temperatures and proportion of the anholocyclic form the following autumn found in Harrington et al. (2012). Grey points and line indicate data and relationship ≤4.5°C, orange points and line indicate data and relationship >4.5°C-6.2°C, blue diamonds indicate data available from 2019-2022.

A further modification relates to the prediction of a spray programme. As the MAFF (2001) risk model predicts the point at which an economic treatment threshold is reached (based on the proportion of the crop infected with BYDV) and because once a plant is infected it cannot lose the infection, this model is essentially a single spray model. Any subsequent sprays to control further infection are essentially damage limitation. However, there will be situations when a single insecticide will not be sufficient to control BYDV (e.g. when a crop is exposed to prolonged aphid migration and/or secondary spread, for example early sown crops or in mild winters). To overcome this limitation and allow the model to predict further sprays, we designed the model to switch to an adjusted version of the T-sum model after the first spray.

The adjusted version of T-sum takes the general principles established by the AHDB version, in that it predicts the second wingless generation of aphids in the crop (see Section 2.3), but instead uses a set of equations based on the work of Dean (1974) to calculate the daily development based on mean daily temperature. The hourly data on instar development time for *R. padi* in Table II of Dean (1974) were first converted to days by dividing by 24 and then converted to a daily rate of development by calculating the inverse of the number of days. A regression analysis was then used to fit a sigmoidal development curve to the data. Where there was clear evidence of a downturn above a set temperature, a split line approach was taken using the sigmoidal curve to describe the relationship between temperature and development rate to a maximum asymptote and then a linear decline to zero at 30°C above a maximum threshold temperature equivalent to the asymptotic threshold temperature for the sigmoidal response. The sigmoidal curve had the following form:

$$y = \frac{c}{1 + e^{-b\,(x-m)}}$$

The linear equation having the form:

$$y = kx + d$$

The values of the parameters *b,c,d,k* & *m* along with the threshold temperatures for each nymphal instar are shown in Table 19. In this way, ACroBAT aims to limit secondary spread of the aphids and virus, and in so doing any further yield loss, from the second insecticide application.

Table 19: Parameter values for *R. padi* immature development used in the adjusted T-sum sub-model.

	Temperature thresholds			Parameter values				
Instar	Minimum	Downturn	Maximum	b	m	c	k	d
I	8.1	22.2	30.0	0.142	22.2	1.39	-0.166	4.99
II	4.7	20.0	30.0	0.131	20.0	1.42	-0.187	5.61
III	4.2	17.0	30.0	0.156	17.0	1.20	-0.186	5.58
IV	2.8	15.8	30.0	0.153	15.8	0.98	-0.156	4.69
Pre-oviposition	3.6	11.2	30.0	0.357	11.2	3.18	-0.632	18.96

A final addition was to include varietal tolerance to BYDV in winter barley. Project partners KWS and Limagrain produce several barley varieties containing the *Ryd2* gene conferring tolerance to BYDV. At the start of the project only KWS Amistar and LG Rafaela were commercially available, although others (e.g. KWS Feeris) appeared during the course of the project. Both breeders provided trial data for use in parameterising the effect of this tolerance on BYDV epidemiology (they also provided seed for use in the 'DSS x variety' validation trials described in Section 4.2.5). However, while their trial data clearly demonstrated the benefit of this gene in reducing both BYDV symptoms and yield losses, it was not sufficient to provide reliable parameter estimates for the model. Therefore, it was decided between the project partners to take a relatively conservative approach to including barley varietal tolerance in the DSS, in terms of both general risk reduction and a spray programme. For this reason, we adjusted the model so that the use of a tolerant barley variety meant that any spray recommendation could be delayed for two weeks.

The input parameters for ACroBAT are listed below. Although each sub-model requires different inputs, all are input by the user at the same time.

1) Numbers of alate anholocyclic *R. padi* caught in suction traps. The number of alate *R. padi* are provided a week in arrears by the RIS. This is used in the adjusted Harrington et al. (2012) equation described in Figure 63 to determine the number of alate anholocyclic *R.*

padi. However, the RIS data could be substituted for in-field data (e.g. from water traps) if desired, for example if the nearest suction trap is too far away for the data to be reliable. If so, the relationships identified in Section 3.3.2 could be useful.

2) Daily Temperature data (minimum, maximum and mean temperatures) are required for each day and for a suitable number of days into the future, to allow for predictive forecast. For the validation trials conducted in this work (see Section 4.2.5) AHDB provided weather data from the nearest weather station for seven days into the future. While the model can simulate greater durations into the future, this will be limited by the reliability of longer-range weather forecasts.
3) The mean temperature the previous winter (December to February). For the validation work conducted in Section 4.2.5 this was generated by the ADAS IRRIGUIDE tool (Silgram et al., 2007).
4) Crop type (wheat or barley), sow date, plant population at establishment (plants per m^2), treatment costs (£/ha), predicted yield (t/ha), grain price (£/t), whether the field is within 10 km of the sea, and whether the land use immediately surrounding the crop is exclusively arable. Most of this information should be readily available to the grower/advisor. Determining plant population at establishment may be more onerous but industry estimates can be used, e.g. 70% establishment in September-sown wheat (AHDB, 2021; AHDB, 2023a.
5) The percentage of viruliferous aphids. This data was provided by Rothamsted Research a week in arrears using the RT-PCR method described in Section 3.2.1. For the validation trials conducted in Section 4.2.5 this data came from testing of aphids caught in the local suction trap.
6) Barley varietal tolerance. If the crop type was barley, the user can select whether the variety was one susceptible or tolerant to BYDV.

The ACroBAT spray DSS can be used by grower/advisors throughout the autumn and winter to determine BYDV risk and guide spray decisions. It can be used as regularly as desired to assist with decision-making (e.g. daily, weekly, fortnightly). It is currently a desk-based tool but could be adapted into a web-based format relatively simply.

Cultural control DSS

The cultural control version of ACroBAT is designed to be users used in advance of sowing to explore possible BYDV scenarios and select cultural control methods to limit risk. It uses the same models from the literatures and the same inputs as those in the Spray DSS (see above), however a series of adaptations were made to allow for risk to be predicted before the sow date.

1) The model uses five-year historical weather data to forecast the minimum and maximum daily temperature input data for the autumn and winter ahead. For the validation work in Section 4.2.5, data was sourced from HadUK at 5 km resolution between the years 2014 and 2020. Five yearly average temperatures were then calculated based on the sowing season for every grid cell for 2014-2018, 2015-2019 and 2016-2020, allowing the model to be run for 2019/20, 2020/21 and 2021/22 respectively. These were stored in an excel file which could be loaded as an input to the model.
2) The model uses five-year historical suction trap data from the RIS to forecast the alate *R. padi* input data for the autumn and winter ahead. For the validation work in Section 4.2.5, data was sourced from RIS for each of its locations across the same timespan (2014-2020), which were turned into the same 3 x 5-yearly averages as with the weather data. This data was also stored in an excel file to be loaded in as an input to the model.
3) The model uses historical data on the percent viruliferous aphids to forecast the initial percentage of viruliferous immigrating aphids. For the validation work in Section 4.2.5, this data was based on the three years of data generated by Rothamsted Research as part of Section 3.2.1. If this work to generate data on the percent viruliferous aphids caught in suction traps were to continue, then this could be based on a five-year average in the future.
4) The interface was adapted to allow the user to input the easting and northing of the farm or field of interest.
5) The model simulation was designed to stop at GS39 to allow for comparisons with field surveys of BYDV for purposes of validation (see Section 4.2.5). GS39 was calculated using degree day calculations. For wheat, the stage was reached when the model had accumulated 1700 degree days above 0°C (AHDB, 2021). For barley, this was 2040 accumulated degree days above 0°C (AHDB, 2023a). The model end date can be modified in the model to fit the purpose of the user.

The simulation

The model uses the easting and northing provided by the user to both locate the correct weather data for the 5k m cell in which it fell and to locate the nearest suction trap using Pythagoras Theorem. A diagram of the process is shown in Figure 64.

The cultural control DSS was initiated and ran daily to produce the following:

- Proportion of crop infected on 1st December.
- Proportion of crop infected at GS31.
- Proportion of crop infected at GS39.
- Date of first spray predicted.
- Total number of sprays by the 1st December.

- Total number of sprays by GS31.

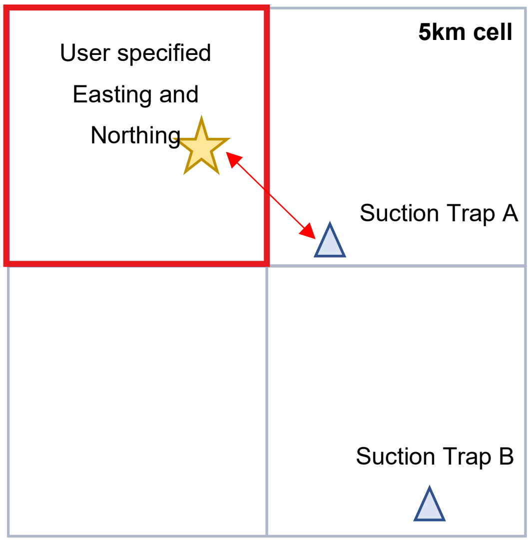

Figure 64. Diagram of the process of locating the correct weather and aphid data from user inputted easting and northing.

By adjusting input parameters such as the sow data, field choice and varietal tolerance (barley only), the user can use the cultural control DSS to compare the impact on the likely level of BYDV infection and spray control programme required. This allows them to check the benefits, or otherwise, of different risk reduction methods (e.g. delaying sow data) several months ahead of sowing, and so plan crop agronomy in good time. Although five-year average data for weather and aphid migration are unlikely to give them a precise prediction of the virus incidence in the autumn ahead, the model would still provide a good indication of the relative benefits of different approaches (e.g. comparing early to late sowing). There are a range of other methods for reducing BYDV risk (e.g. using minimum tillage approaches), which could in the future be included in the cultural control DSS, but at present reliable data on their benefit is not available to warrant this.

User consultation

Growers, advisors and industry representatives were consulted during the development of the DSS at two workshops. These workshops outlined the proposed DSS and asked for feedback on the need, design, inputs and outputs. This feedback was used to guide the structure and design of ACroBAT.

4.2.5. Model validation

ACroBAT cultural control model

The ACroBAT cultural control DSS described in 3.4.2. was validated using unsprayed strips in crops and untreated tramlines from trials. Growers were asked to leave a 30 m long by spray boom wide area of winter wheat or barley crop untreated with an insecticide until May. This occurred at 12, 6 and 6 sites in 2019, 2020 and 2021 respectively. In 2019, the sites were split evenly between the West Midlands, East of England, South West and Yorkshire. In 2020 and 2021, the sites were split evenly between the South West and Yorkshire. The tramline trials, from which the untreated tramline data came, are described below. In the untreated strips and tramlines visual assessments of BYDV symptoms occurred between GS39-59. This allowed the prevalence of BYDV symptoms in the absence of an aphicide to be determined and compared with predictions from the ACroBAT cultural control DSS. The DSS was run based on the location and likely agronomic factors for the field. Observed and predicted values were compared using linear regression to identify whether the observed values differed significantly from the predicted values.

ACroBAT spray DSS tramline trials

The ACroBAT spray DSS was validated using two different tramline trial designs. The first design, "DSS tramline trials", compared BYDV control in three treatments: 1) sprays as recommended by ACroBAT, 2) sprays as recommended by the AHDB T-sum tool and 3) an untreated control. Each treatment was replicated across two tramlines. An example layout of one these trials is shown in Figure 65. In total, seven of these trials occurred, four in 2020/21 and three in 2021/22. These were split between the South West, East of England and Yorkshire.

Figure 65. Example trial plan for a DSS tramline trial. 'AHDB DSS' had aphicide applications based on timings predicted by the AHDB T-sum tool; 'ADAS DSS' had aphicide applications based on timings predicted by the ACroBAT spray DSS; 'Untreated' received no aphicides.

The second design incorporated varietal tolerance with insecticide sprays ("DSS x variety tramline trials"). This design had four treatments: 1) a tolerant barley variety with sprays as recommended by ACroBAT, 2) an untreated tolerant barley variety, 3) a susceptible barley variety with sprays as recommended by ACroBAT and 4) an untreated susceptible barley variety. The original intention was to replicate each of these treatments across two tramlines; however, as it was decided to locate these trials were in the South West to increase the likelihood of BYDV infection, it proved impossible to find host farmers with the capability to generate yield maps and with fields large enough to accommodate eight tramlines. This meant we had to split each trial over two nearby fields, with each treatment occurring in a single tramline in each field. Each field was analysed separately as between-field variation was likely to skew results, effectively producing separate trials with no replication. An example layout of one these trials is shown in Figure 66. In total, eight of trials occurred (four in each of 2020/21 and 2021/22). All were in the South West. Seed was provided by KWS and Limagrain.

Figure 66. Example trial plan for a DSS x variety tramline trial. 'Fun' refers to the susceptible barley variety KWS Funky, and 'Ami' refers to the BYDV tolerant variety KWS Amistar. 'No DSS' received no aphicides and 'DSS' had aphicide applications based on timings predicted by the ACroBAT spray DSS.

NVDI variation was checked for all trials to ensure there were no field variables that may affect yield and confound treatment effects. Each tramline was at least 200m. The ACroBAT DSS and, where relevant, the AHDB T-sum DSS were run by ADAS each week from the day of crop emergence to the 1st March or GS31, whichever was earlier. The T-sum model was run from the AHDB BYDV website (https://ahdb.org.uk/bydv). ACroBAT used weather data provided by AHDB giving the previous temperatures and the forecast for the following ten days. Data on the number of alate *R. padi* and the percentage of viruliferous aphids caught in the local suction trap was provided by RIS a week in arrears.

Host farmers were informed of any spray prediction within two days of a DSS recommendation and treatments were applied by the host farmer. It was expected that host growers would apply an aphicide within five days of the spray recommendation being given, however weather conditions did not always allow for this. Actual spray dates were recorded. Hosts used Hallmark Zeon (lambda-cyhalothrin) provided by Syngenta, spraying at the full application rate (50 ml/ha). Despite both the ACroBAT and T-sum DSS recommending that crop inspections happen once a spray recommendation occurs, these trials assumed that sprays should happen automatically once eitherDSS recommended a spray. This was because crop inspections for aphids had already proved difficult and often found few aphids (see Section 3) raising concerns that there would not be any differences between the trial treatments. This also reflects the likely approach many growers/advisors take in this situation. Even if we had inspected the crops for the presence of aphids after a spray prediction, it is unclear what the threshold would be to confirm that a spray was needed. This means that risk may have been overestimated in the 2020/21 trials.

The effectiveness of ACroBAT and T-sum in managing BYDV was determined through autumn assessments of BYDV vectors, spring visual assessments of BYDV symptoms and harvested yield. Aphid numbers were counted and categorised into '*R. padi*' and '*S. avenae*' on 100 plants in each tramline, grouped by ten plants at ten points equidistant along the full length of the tramline. This assessment was carried out twice in the autumn. BYDV symptoms were assessed between GS39-49 in winter wheat and GS59-65 in winter barley. The number of foci and % of area with symptoms in a 2 m long strip, half the width of the tramline, were assessed at ten equidistant points long the full length of the tramline. Yield map data was taken from host farmers after harvest. All tramline trial hosts were chosen for yield mapping on their combine harvesters.

ACroBAT spray DSS inoculation plot trial

Due to the unreliable nature of natural aphid infestation and the low infection observed in tramline trials in 2020/21, a trial in which plots were artificially inoculated with viruliferous *R. padi* was conducted in 2021/22. This was so that infection could be guaranteed and so improve the likelihood of generating treatment differences. This trial compared different methods for aphicide timings with BYDV tolerant (LG Rafaela) and susceptible (KWS Funky) varieties. There were four aphicide treatments: 1) sprays as recommended by the AHDB T-sum tool, 2) sprays as recommended by ACroBAT, 3) a calendar programme with three sprays applied at four-week intervals, and 4) an untreated control. These treatments were replicated in each variety, giving eight treatments in total, each of which were replicated six times.

Plots were 12 m x 4 m, arranged as two 12 x 2 m half plots with a 20 cm gap between them. The layout was chosen to minimise the spread of inoculated aphids between plots and allow the spread of foci within a plot. *R. padi* carrying BYDV-PAV were provided by Alan Dewar and confirmed to be viruliferous in a RT-PCR test performed by Rothamsted Research. All plots were drilled on 16 September 2021, reaching full emergence on 28 September. 600 aphids were inoculated on 5 October into each plot at six points, 100 aphids for each point. These aphids comprised approx. <1% alates, 17% apterae, 54% early instar nymphs and 29% late instar nymphs. Inoculation points were marked with a plot marker and covered with a small shelter post-inoculation to protect against high winds and rain. Each shelter was removed after four days when the aphids had begun to move over to the in-field plants from the inoculated tillers. DSS predictions and input data were as in the tramline trials (see above). Hallmark Zeon (lambda-cyhalothrin) was applied at 50 ml/ha using an OPS sprayer.

DSS effectiveness was determined through assessments of aphid populations, BYDV symptoms, green area index and yield. Aphid numbers were counted and categorised into *R. padi, S. avenae* and 'other aphids' in each plot on six occasions: 3-5 days before the and after the first calendar spray (18/10/2021), 3-5 days before and after the second calendar spray (05/11/2021), 3-5 days before and after the third calendar spray (04/12/2021). Aphids were counted on five plants within half a metre from each inoculation point. BYDV symptoms were assessed twice: mid-December (GS 24-26) and May (GS61). Symptoms were quantified through the percentage of each plot with visible BYDV symptoms and a count of the number of foci. Green area index (GAI) was calculated from drone imagery taken in January, April and June. Images were analysed using ImageJ to quantify the amount of green area within each plot. The areas of plot that were not classified as green were classified as BYDV symptoms. Although rudimentary, this method allowed for visual assessments of symptoms to be validated. Plots were harvested using a Sampo-Rosenlew 2010 plot combine harvester with a two-metre header. This calculated yield of each half plot in kilograms per plot. This was converted to kilograms per half plot, then hectare to calculate the yield at tonnes per hectare. Grain analysis for specific weight and grain moisture was carried out with a Dicky John 2500 UGMA.

Data analysis

Data from aphid infestation, BYDV symptom and GAI assessments from all trials were analysed through ANOVA. Significant results were followed by a post-hoc Duncan's Multiple Range test to identify significant differences between treatments. Analysis of yield map data from tramline trials was performed using Agronomics software to identify the mean yield for a single treatment and the relative increase or decrease from that mean for the other treatments. Treatments differences were analysed with ANOVA was carried out to identify the significance of the differences, with a Duncan's Multiple Range test used to identify the significance of the interactions of the treatments. Analysis of yield and grain data (specific weight and moisture) results from the inoculated plot trial were analysed with ANOVA.

4.3. Results

4.3.1. Exploring BYDV scenarios with ACroBAT scenarios

To demonstrate how ACroBAT works and the way in which different factors affect BYDV pressure and management, we ran simulations using dummy data and controlling all variables but one. These scenarios are representative of likely real-world situations and provide an overview of changes to the risk and timing of the first insecticide recommendation in response to changes in the selected variable. Graphs are presented showing the predicted change in crop infection over time and when the first spray is recommended under each scenario. Subsequent sprays are not predicted in these scenarios and crop infection is simulated to continue as if the first spray has not been applied to demonstrate differences in infection rate.

The baseline inputs for these scenarios are as follows: a field located in Starcross, Devon, a susceptible winter wheat variety sown on 16 September, 100% emergence on 28 September and an expected plant population of 260 plants per m^2. Temperature data were generated for the site using the ADAS IRRIGUIDE tool (Silgram et al., 2007) and the previous mean winter temperature was 5°C. Ten *R. padi* were caught in the Starcross suction trap per day and the percentage of viruliferous aphids was 10%. The expected yield was 9 t/ha, grain price was £200/t and treatment costs were £13.94/ha, based on the agrochemical cost for lambda-cyhalothrin (£3.40/ha) and the farmer costs for the spray operation, i.e. fuel and machinery costs, and labour, (£10.54) (Redman, 2019). The site was within 10km of the sea and not surrounding exclusively by arable land. Any changes to these inputs for specific scenarios are described below.

Aphid pressure

Numbers of migrating aphids can vary considerably with region and year. This scenario investigated the effect of different numbers of aphids caught in the local suction trap. Only aphid numbers were changed in this scenario, with four levels of aphid pressure examined: 1) a baseline aphid population of 100 *R. padi* caught in the Starcross suction trap each day (a slightly higher pressure than normal for Starcross, see Fig. 56 in Section 3.4.1), 2) a 50% reduction, 3) a 75% reduction and 4) a 95% reduction in aphid numbers. BYDV infection increased most rapidly at the baseline aphid level, with 100% plant infection predicted by mid-November and a spray recommendation on 20 October (Fig. 67). BYDV infection (approx. 80% by mid-November) and timing of spray (27 October) was similar with the 50% and 75% reductions in aphid numbers. With a 95% reduction in aphid numbers, the spray was recommended on 10 November and crop infection was 26% by mid-November.

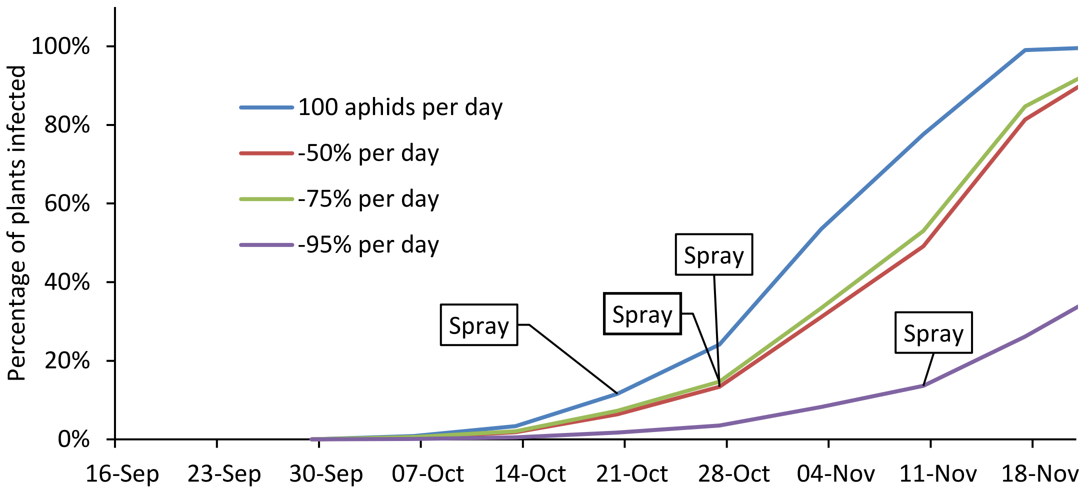

Figure 67. The effect of differing aphid pressure on the prediction of insecticide application by ACroBAT and the spread of infection if untreated.

Aphid infectivity (% viruliferous)

The percentage of the aphid population that is viruliferous is an important, and rarely considered, metric in determining risk of infection. A low aphid population with high initial infectivity can pose a greater threat than a large aphid pressure with low infectivity. Only the % viruliferous was changed in this scenario, with four levels of infectivity examined: 1) 50%, 2) 25%, 3) 10% and 4) 1% infectivity. In the work carried out in Objective 1, 50% infectivity was rarely recorded, 10-25% infectivity was more common and 1% infectivity uncommon. With 50% infectivity a spray was recommended on 3 November and crop infection reached 68% by late November (Fig. 68), while at 25% and 10% infectivity the spray recommendation was delayed a week respectively and crop infection by late November was 47% and 25% respectively. At 1% infectivity no spray had been recommended by late November and crop infection was just 4%.

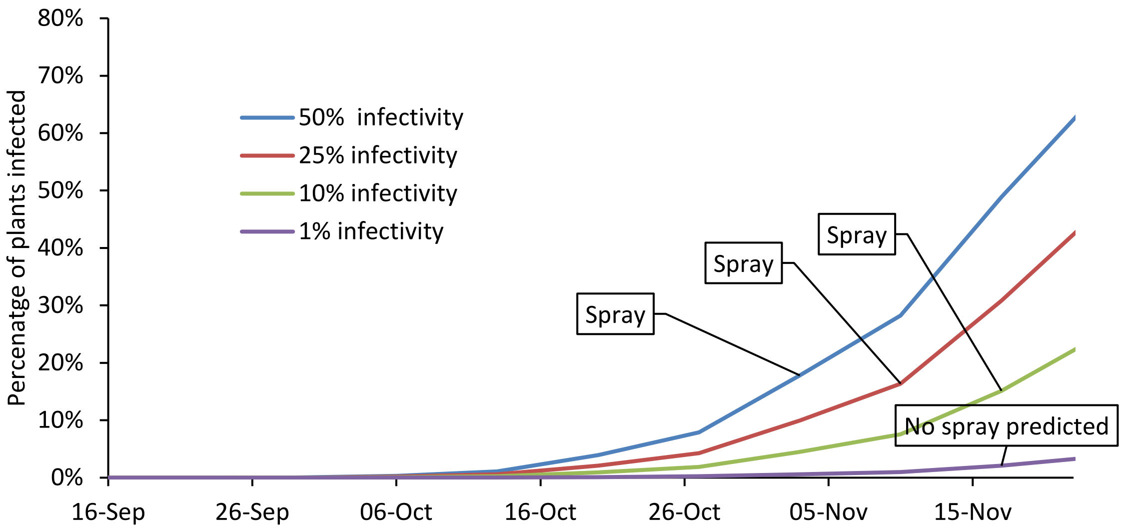

Figure 68. The effect of differing aphid infectivity on the prediction of insecticide applications by ACroBAT and the spread of infection when untreated.

Aphid pressure and infectivity

Combining the two previous scenarios, this scenario demonstrates the effect of the interaction of aphid pressure and initial infectivity. It is the combination of both factors that determine the overall risk from BYDV infection. Four interactions of these two variables are considered here: 1) 100 aphids per week of which 10% are viruliferous, 2) 10 aphids per week of which 10% are viruliferous, 3) 100 aphids per week of which 40% are viruliferous, and 4) 10 aphids per week of which 40% are viruliferous. Level 3 (100 aphids/ week @ 40% infectivity) had by far this most the most rapid infection rate (99% crop infection by the end of November) and earliest spray date (20 October) (Fig. 69). Levels 1 (100 aphids @ 10% infectivity) and 4 (10 aphids @ 40% infectivity) were initially similar, with the same spray date (3 November), but the rate of infection at level 1 began to diverge, ultimately resulting in a crop infection 19% higher than level 4 by the end of November. The slowest infection rate (just 4% by the end of November) was seen in level 2 (10 aphids @ 10% infectivity), with no spray was predicted during the time period.

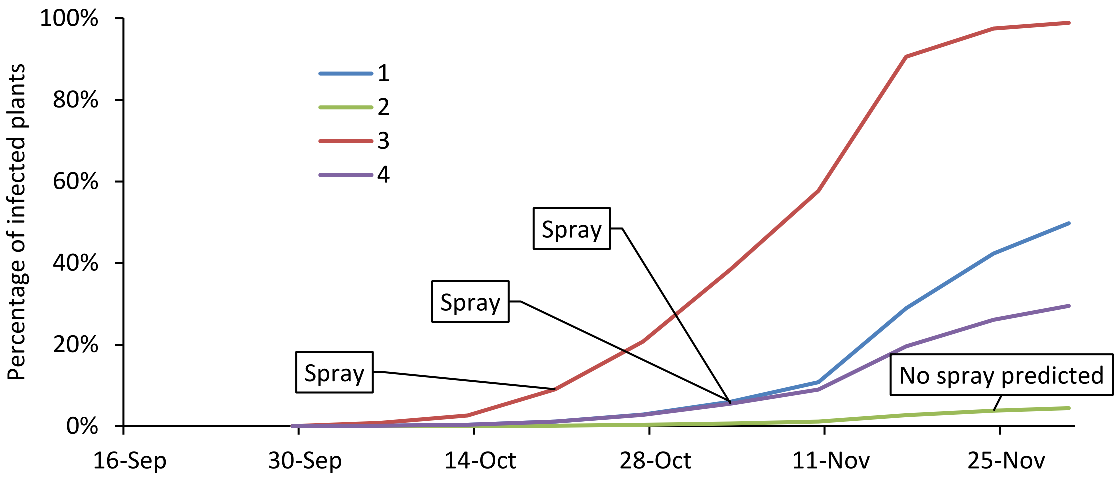

Figure 69. The effect of aphid pressure and initial infectivity on the percentage of plants infected as estimated by ACroBAT and the timing of spray prediction by the model. Scenario lines are as follows: 1) 100 aphids per week, 10% initial infectivity. 2) 10 aphids per week, 10% initial infectivity. 3) 100 aphids per week, 40% initial infectivity. 4) 10 aphids per week, 40% initial infectivity.

Autumn temperature

Temperature is a key determinant of a range of aphid life-history parameters (see Section 2.2), which in turn have an important effect on primary infection and secondary spread of BYDV. Climate change is predicted to have important impacts on cropping in the UK, including through warmer temperatures (Harkness et al., 2020). This scenario investigates the effect changes in autumn temperature, examining three levels: 1) A baseline, being the actual mean temperature data from autumn 2021 at the Starcross suction trap, 2) a 10% increase to the baseline and 3) a 10% decrease to the baseline. The differences are stark. The baseline temperature triggered a spray recommendation on 10

November, ultimately resulting a 59% crop infection by the end of November (Fig. 70). An increase in temperature of 10% resulted in a decision to spray being made almost two weeks earlier (27 October), and complete crop infection by the 3rd week of November. A reduction in temperature of 10% triggered a spray decision on 17 November and just 15% crop infection by late November.

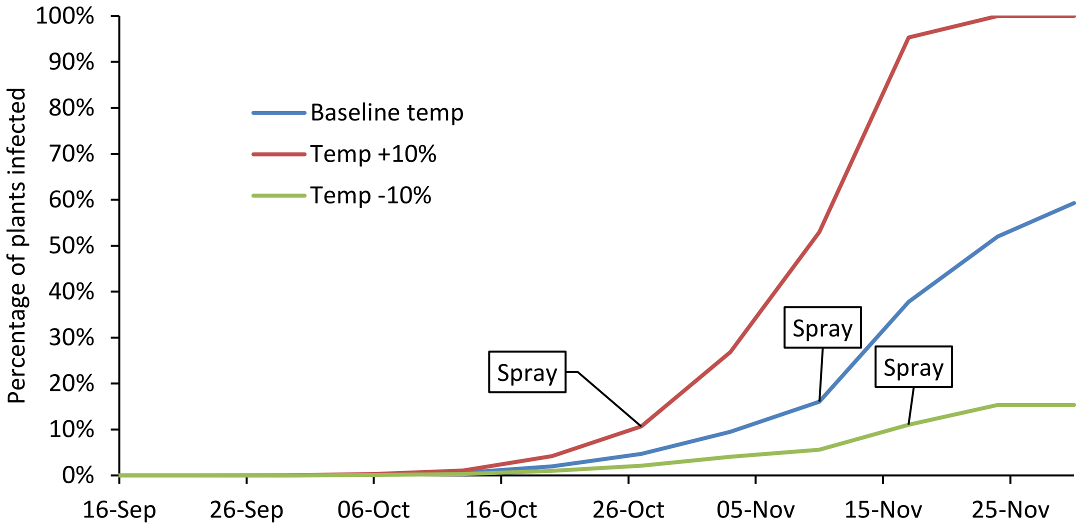

Figure 70. The effect of autumn temperature on the prediction of insecticide applications by ACroBAT and the spread of infection when untreated.

Crop type

The two major cereal crops that are used in ACroBAT, winter wheat and barley, are affected differentially (included in the DSS as differences in their Yield-Virus Relationships, see Section 4.2.3). The increased yield loss expected in barley has an important effect on the timing of spray recommendation, which is demonstrated in this scenario examining each crop. Changes to the baseline parameters were that 50 *R. padi* were caught in the Starcross suction trap per day (to ensure a spray recommendation was predicted for both crops) and the expected plant population was set to 305 plants per m² for barley. While the disease progression lines were similar for both crops (any differences are likely due to the different plant populations), the spray dates and associated crop infection level were not; a spray being recommended a week earlier in barley (13 October) than wheat (20 October) at crop infections of 3% and 12% respectively (Fig. 71).

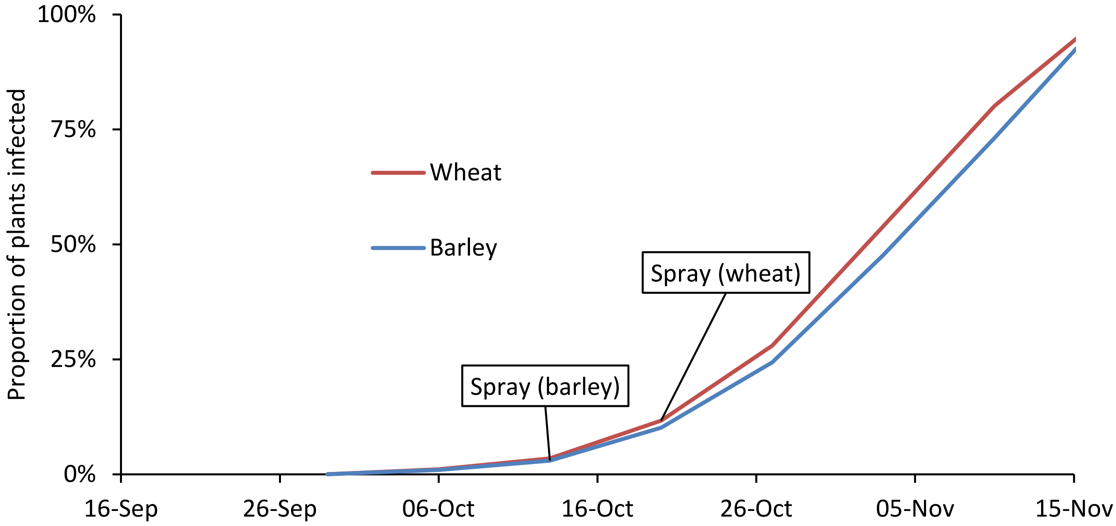

Figure 71. The effect of different crop types on the prediction of risk by the ACroBAT model and the spread of infection when untreated.

Drill date

Drill date is known to have an impact on BYDV risk (see Section 2.4), with growers in high-risk areas advised to consider delaying drilling (AHDB, 2023c). Three drill dates are considered in this scenario. In line with AHDB recommendations for sowing winter wheat at different times, the seed rate was adjusted with the drill date (AHDB, 2021). Only drill date and seed rate were changed in this scenario. The drill dates examined were: 1) an early sow date (1 September @ 220 plants/m²), 2) a middle sow date (30 September @ 300 plants/m²) and 3) a late sow date (30 October @ 300 plants/m²) (KWS, 2023). The impact on BYDV was considerable; with the early sow date the entire crop was infected by the end of October and a spray recommended on 13 October (Fig. 72). With the mid sow date, a spray was delayed for ten weeks (end of December) when crop infection was 15%. Crop infection was negligible and no spray was predicted at all by end of December in the late sow date.

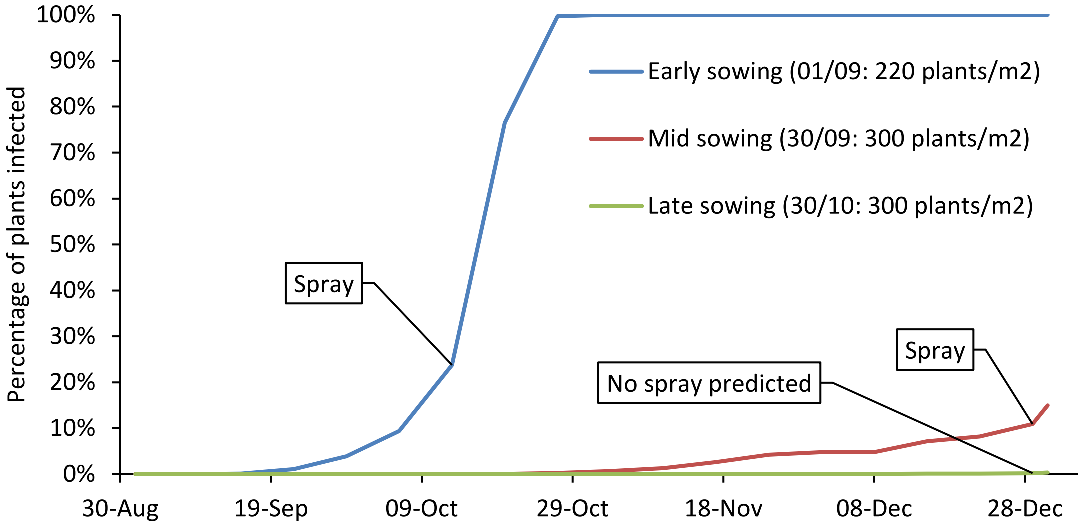

Figure 72. The effect of different drill dates and seed rates on ACroBAT predictions for insecticide sprays and the spread of infection when untreated.

Treatment costs

As spray recommendations in ACroBAT are based on the trade-off between treatments costs and expected yield loss, changes in either the cost of a treatment or grain price can have an important impact. The next two scenarios consider the impact of changes in both variables. Treatment costs comprise the insecticide cost and the spray operation cost to the farmer or contractor. Here we explore the effect of increased agrochemical costs. Pyrethroids are relatively cheap; lambda-cyhalothrin is listed in Redman (2019) at £3.40/ha, though other pyrethroids may be cheaper. Although alternatives to pyrethroids are not available in winter cereals, those in other arable crops are several times more expensive than the pyrethroids in those crops. Four treatment costs were examined in this scenario: 1) £13.94 (the current pyrethroid baseline, i.e. £3.40 plus spray operation costs), 2) £20.54 (insecticide cost = £10), 3) £30.54 (insecticide cost = £20) and 4) £40.54 (insecticide cost = £30). These reflect the potential costs of insecticide. All other parameters remained the same. The impact on the timing of the spray recommendations can be seen in Figure 73; scenarios 1 and 2 both produced recommendation on 20 October when 8% of the crop was infected, was 8% and scenarios 3 and 4 on 27 October when 14% of the crop was infected. This shows that more expensive insecticides will delay the treatment threshold so that yield loss will be greater but the economic outcome would remain the same, as the reduction in income would be offset by the increase in treatment costs.

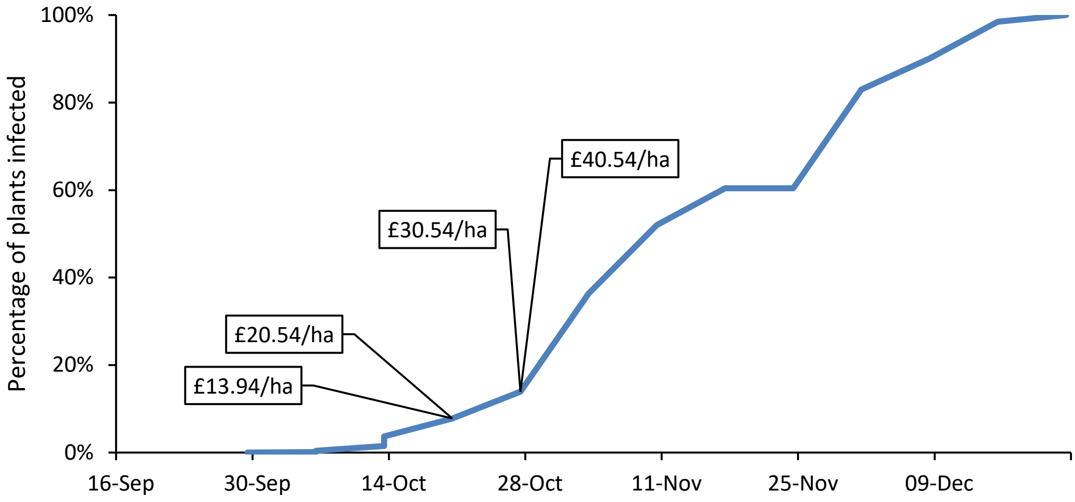

Figure 73. The effect of increasing treatment costs on ACroBAT spray prediction and the spread of infection when untreated.

Grain prices

As with treatment costs, changes in grain price effect ACroBAT's prediction timing. Here we examine the effect of three grain prices experienced in recent years (AHDB, 2023d): 1) the five-year average of £200/t (the baseline), 2) the five-year low of £130/t and 3) the five-year high of £350 /t. All other parameters are unchanged. With a grain price of £350 t/ha a spray was recommended on 3 November when just 3% of the crop was infected (Fig. 74). At £200/t of grain the spray recommendation occurred on 10 November at 5% crop infection, but at £130/t of grain a spray was delayed until 17 November when crop infection was 11%.

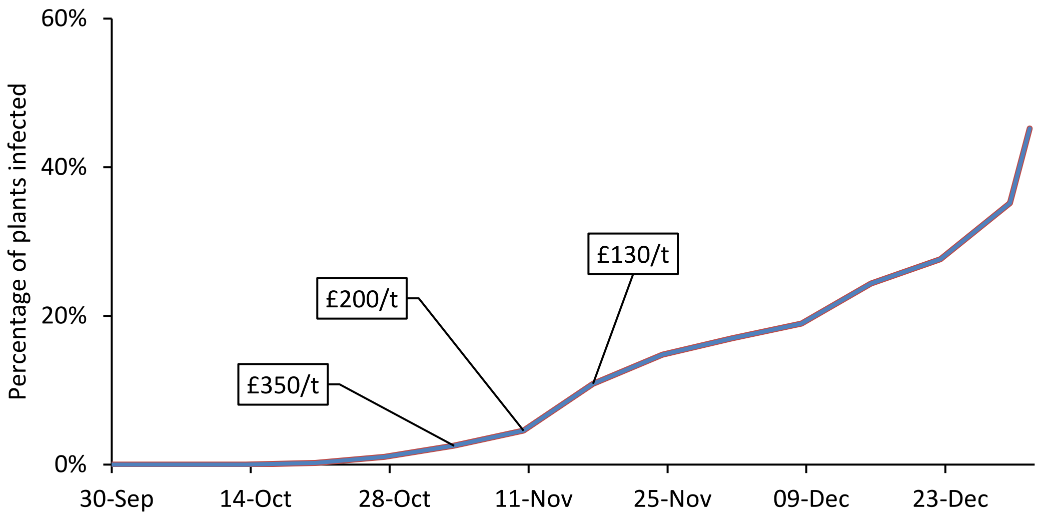

Figure 74. The effect of grain prices on ACroBAT spray prediction and the spread of infection when untreated.

4.3.2. User consultation

Workshops to guide the development of ACroBAT were conducted on 10 March 2021 and 3 March 2022. These were virtual workshops carried out online because of restrictions due to the Covid-19 pandemic. The benefit of virtual workshops is that they allowed participation from growers/advisors from across the country. Feedback on the DSS was provided by 21 and 22 individuals at each workshop respectively. This feedback indicated that there was a strong interest in DSS for BYDV (95%), that 65% had used T-sum and 75% planned to use it in future. Those that did not plan to use T-sum cited the inability to account for aphid pressure, lack of cost-benefit analyses for spray decisions and having had a bad experience with the tool as reasons for not intending to use it.

In the development of new DSS, feedback showed a strong preference for DSS that:

- directly supported decision-making and improved IPM.
- provided easily interpretable and extractable data.
- was developed by independent experts.
- was available on handheld devices.
- had ongoing support.

Preference was also shown for DSS that provided cost-benefit analyses. In terms of the input data for ACroBAT, similar numbers were willing to input all the data needed (55%) as opposed to a simplified set of input data where some data was input using defaults (45%). 95% of participants opted for a feature in which input data for specific fields could be saved between use of the DSS. In terms of the outputs of ACroBAT, 30% preferred to have the full model outputs (e.g. spray recommendation, risk level, aphid numbers etc.), 50% preferred to have information on the risk and whether a spray is recommended, and 20% preferred a simple message indicating whether a spray is recommended or not. Overall, it was felt that the lack of *S. avenae* in the model was considered moderately important. Regarding the ACroBAT cultural control DSS, 79% felt that the use of dummy data (e.g. five-year averages), to allow the comparison of different BYDV management strategies in advance of the autumn, would be useful.

4.3.3. Validation of the ACroBAT cultural control DSS

The cultural control version of ACroBAT was validated using observed BYDV symptoms from 24 untreated strips and eight untreated tramlines in DSS and DSS x variety tramline trials. Predictions of the proportion of crop infected with BYDV at GS39 made by ACroBAT were found to be significantly correlated with observations of BYDV infection at GS39, with the majority of variance accounted for in the model (df = 1, adjusted R^2 = 72.2, P = <0.001) (Fig. 75).

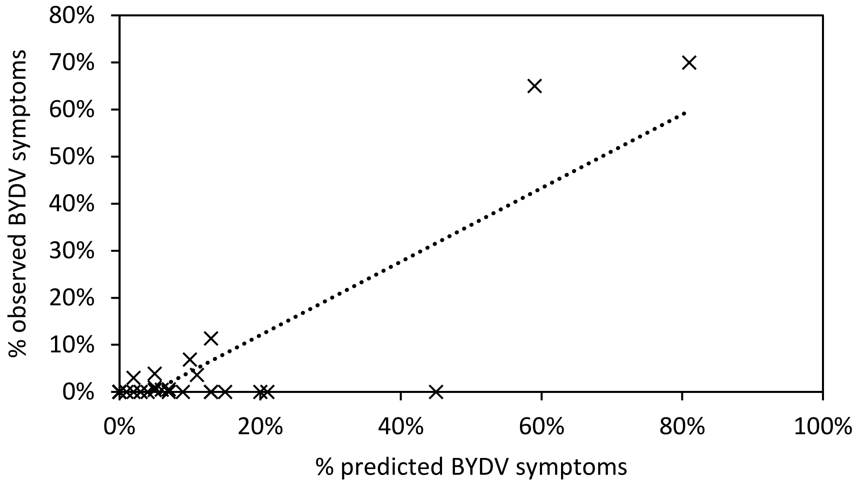

Figure 75. The comparison between the percentage of crop infected at GS39 predicted by the ACroBAT cultural control DSS and the observed percentage of crop infected. y = 0.78x – 0.04. SED = 0.09.

4.3.4. Validation of the ACroBAT spray DSS

DSS tramline trials in 2020/21

In Trial 1 (Yorkshire), feed wheat was sown on 9 September. ACroBAT advised the first spray on 4 October and the host farmer applied the spray on 6 October. The T-sum tool recommended a spray date of 9 October and the tramlines were sprayed the same day. One further ACroBAT spray and two T-sum sprays were made in this trial. Only three BYDV vectors were recorded in the autumn of 2020. All three were *R. padi*, recorded in the untreated tramlines. There was a significant difference between the number of aphids per plant between the treatments (df = 2, F = 3.35, p = 0.042) (Fig. 76). No symptoms of BYDV were recorded in any treatment in the trial. There was a significant difference in yield, with the untreated tramlines lower than the ACroBAT and T-Sum tramlines by 0.4 t/h and 0.5 t/ha respectively (df = 2, F = 15.88, P = <0.001) (Fig. 77). The benefit of using DSS in this situation, assuming a £200/tonne grain price, and a £14 treatment cost (machinery, labour and product), over untreated would be £50/ha when using ACroBAT and £62/ha when using T-sum. Note: these cost assumptions will be applied to the trials below.

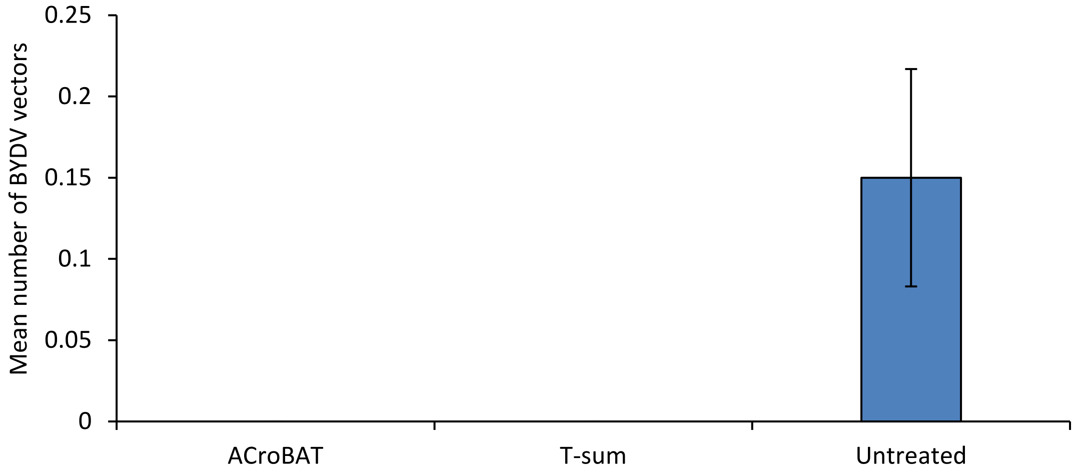

Figure 76. The mean number of BYDV vectors recorded in the tramline trial 1, Yorkshire, in autumn 2020. Bars represent the standard error of the mean.

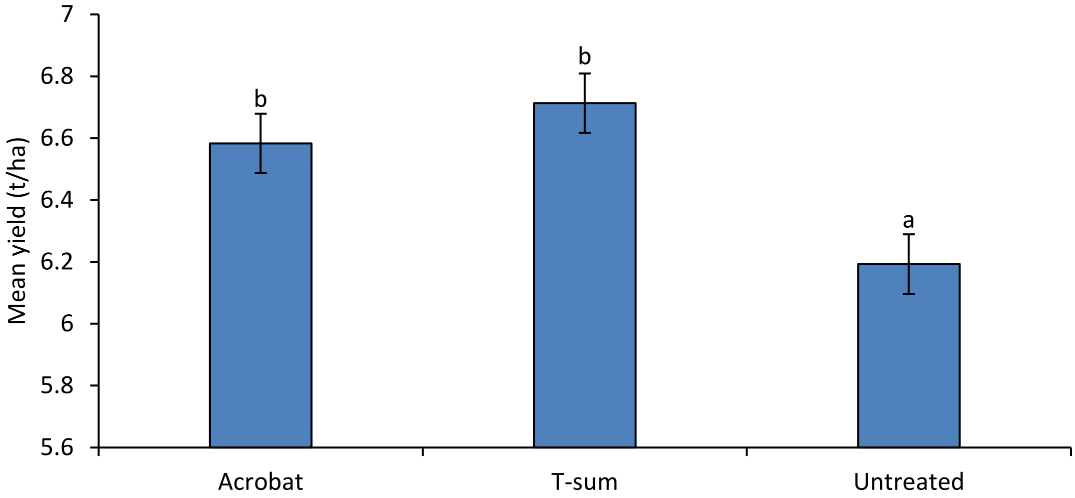

Figure 77. The mean harvested yield for tramline trial 1, Yorkshire, in 2020/21. Bars represent the standard error of the mean. Bars followed by different letters are significantly different (P <0.05).

At Trial 2 (Yorkshire), winter barley was drilled on 7 October. The first spray was recommended on 9 November by ACroBAT and was applied on 11 November. The T-sum tool recommended a spray on 15 November and was applied on 20 November. One more T-sum spray was applied before GS31. There was a significant difference in aphid numbers (df = 2, F = 3.82, P = 0.025), with a total of five *R. padi* observed in the untreated tramlines but none elsewhere (Fig. 78). There were no significant differences between BYDV symptoms, with the mean area with symptoms in untreated tramlines at less than 1%, and yield (P<0.05). The economic outcome for this trial is that ACroBAT provides an economic benefit of £3/ha over the untreated and T-sum £4 t/ha over the untreated.

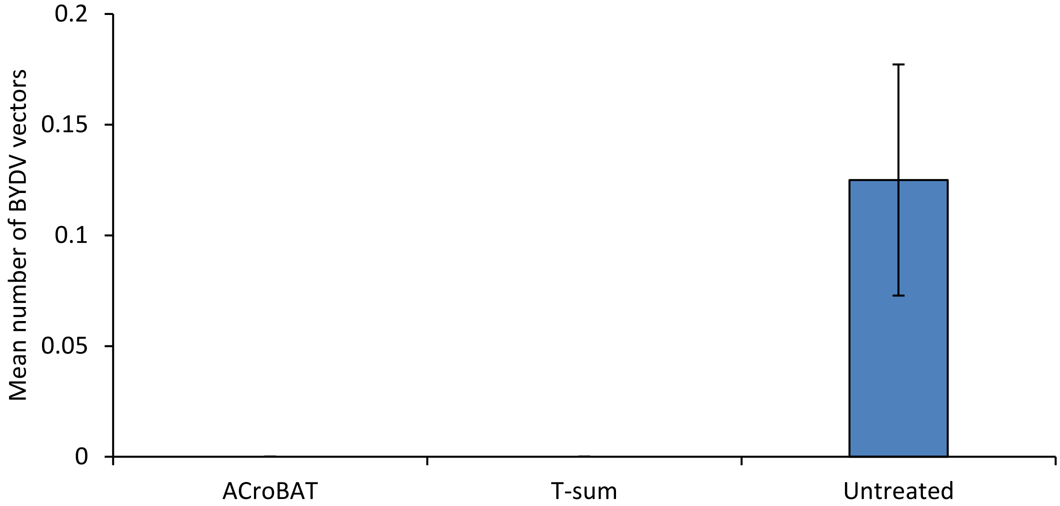

Figure 78. The mean number of BYDV vectors recorded in the tramline trial 2, Yorkshire, in autumn 2020. Bars represent the standard error of the mean.

At Trial 3 (Suffolk), winter wheat was sown on 28 September. The first spray was recommended by T-sum on 30 October and applied on 11 November. ACroBAT followed with a spray decision on 15 November, applied on 20 November. One more T-sum recommendation was made on 11 January but the host was not able to apply due to poor field conditions. Just two *R. padi* were recorded, both in the untreated tramlines, but this did not produce a significant difference between treatments ($P<0.05$). There was a significant difference in the percent of tramline area with BYDV symptoms ($df = 2$, $F = 3.91$, $P = 0.026$), with the untreated having more symptoms (4%) than the T-sum (0.4%) (Fig. 79). There was a significant difference between the yields ($df = 2$, $F = 52.4$, $P = <0.001$), with the untreated being significantly less than the T-sum (-0.3t/ha) which was significantly less than ACroBAT (-0.4t/ha) (Fig. 80). After treatment costs, T-sum and ACroBAT provided a benefit over the untreated of £51/ha and £139/ha respectively.

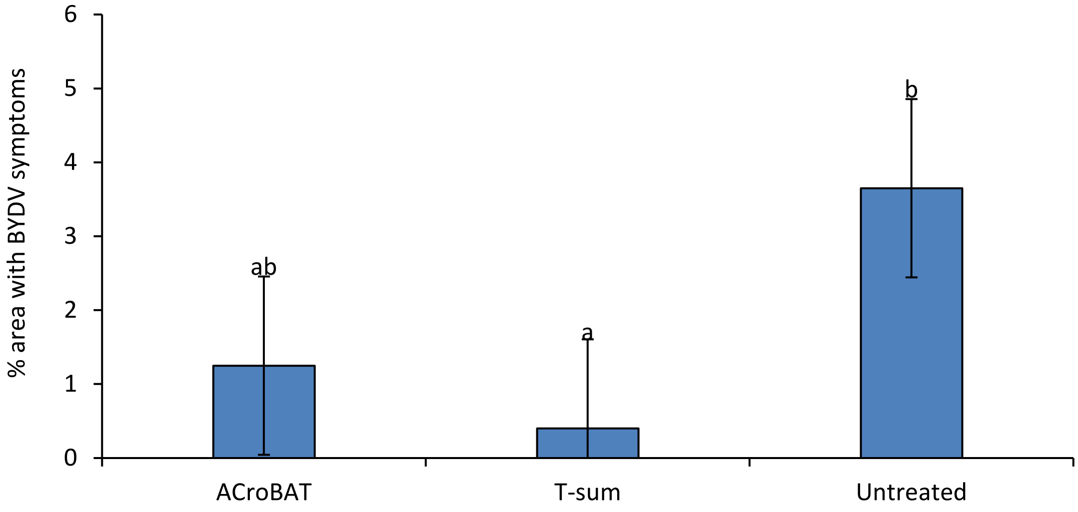

Figure 79. The mean area of tramline with BYDV symptoms in tramline trial 3, Suffolk, in spring 2021. Bars represent the standard error of the mean. Bars followed by different letters are significantly different (P <0.05).

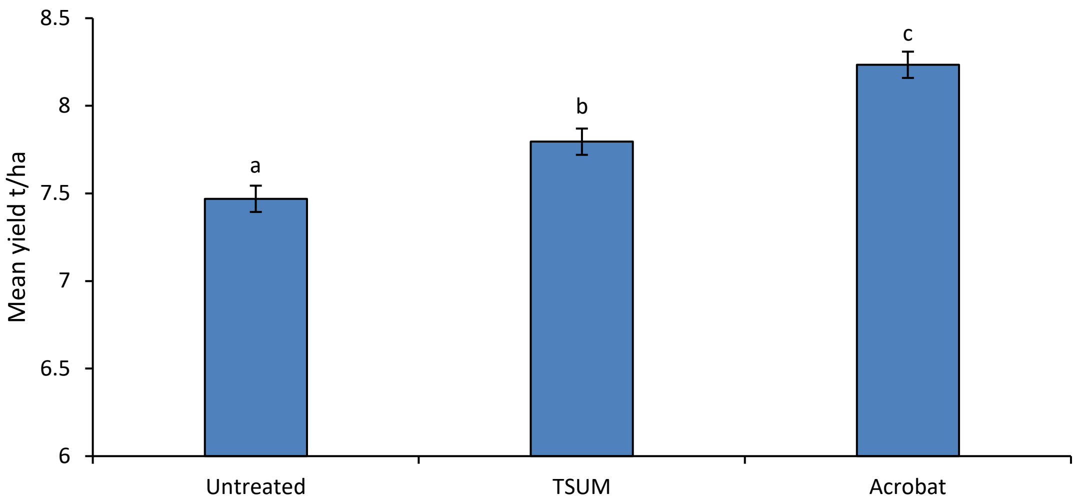

Figure 80. The mean harvested yield tramline trial 3, Suffolk, in 2020/21. Bars represent the standard error of the mean. Bars followed by different letters are significantly different (P <0.05).

In trial 4 (Devon), winter wheat was drilled in late September. The field used was a replacement site for a later drilled field where an incorrect spray application provoked the change in site. This change did not affect model decisions. The first spray recommendation came from the T-sum tool on 30 October and was sprayed on 5 November. ACroBAT produced a recommendation to spray on 9 November and was sprayed the following day. There was a second recommendation made for each model in January but, because of wet field conditions, the sprays were applied in late February. No aphids were found in the trial at any assessment timing. BYDV symptoms were observed in all three treatments, but the mean percentage of area was under 0.1% for all treatment and there were no significant differences between them (P<0.05). The T-sum tramlines (6.8t/ha) yielded significantly higher than the ACroBAT (6.2 t/ha) or untreated (6.4 t/ha) tramlines (df = 2, F = 17.68, P = <0.001) (Fig. 81). ACroBAT in this situation resulted in an economic reduction compared to the untreated of £9/ha, while T-sum provided a benefit compared to the untreated of £86/ha.

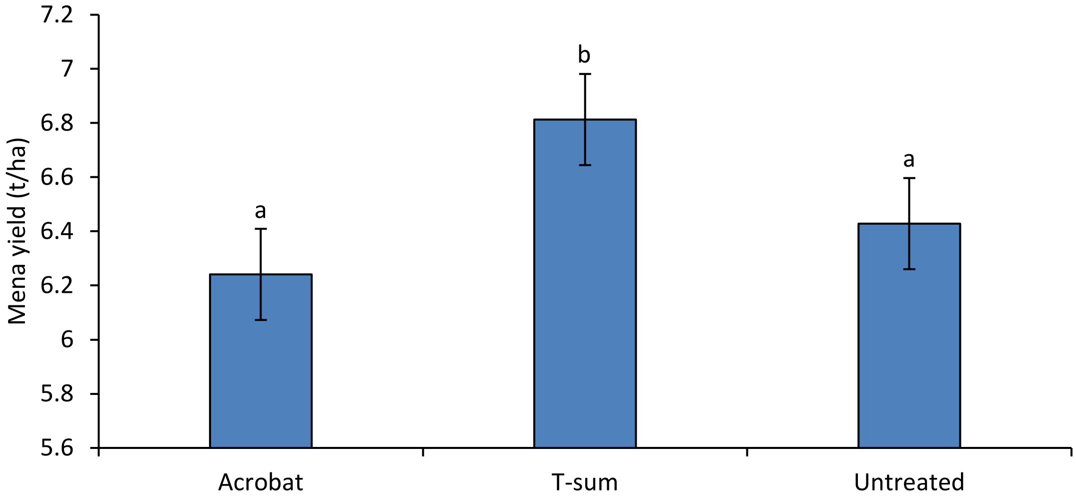

Figure 81. The mean harvested yield for tramline trial 4, Devon, in 2020/21. Bars represent the standard error of the mean. Bars followed by different letters are significantly different (P <0.05).

DSS tramline trial cross-site analysis 2020/21

Across the four tramline trials in 2020/21, aphids of both species were only recorded in untreated tramlines. Two *S. avenae* were recorded the trial in Suffolk, whereas *R. padi* was recorded in the other three trials in Yorkshire and Suffolk. There was a significant difference between treatments in terms of mean BYDV counts (df = 2, F = 5.23, P = 0.005) (Fig. 82), with numbers being significantly greater in the untreated than the ACroBAT and T-sum treatments.

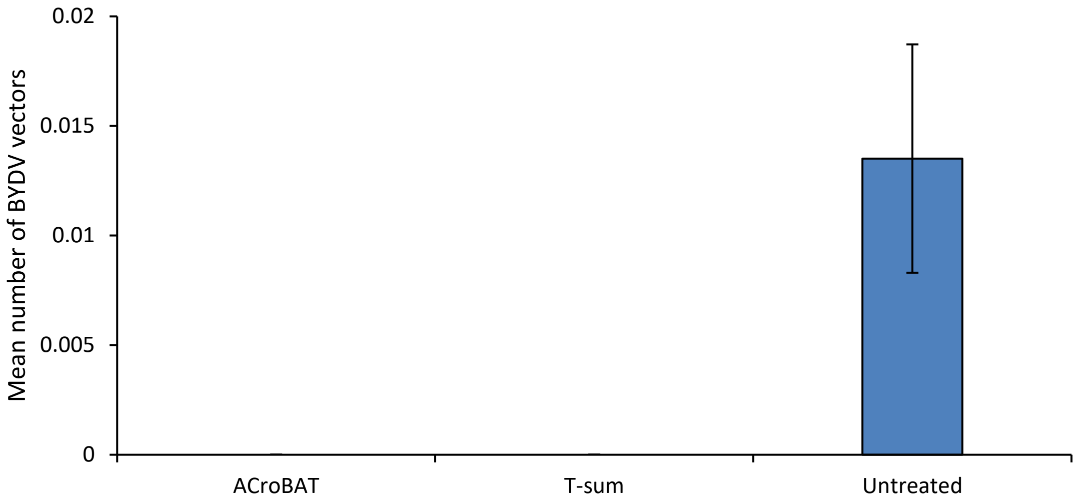

Figure 82. The mean number of BYDV vectors recorded in tramline trials in autumn 2020. Bars represent the standard error of the mean.

The mean levels for observed BYDV symptoms were low across the different treatments, with a high of 1.5% of the untreated area with BYDV. T-sum had significantly reduced BYDV symptoms when compared with untreated whilst ACroBAT was not significantly different from T-sum or untreated (df = 2, F = 3.34, P = 0.038) (Fig. 83).

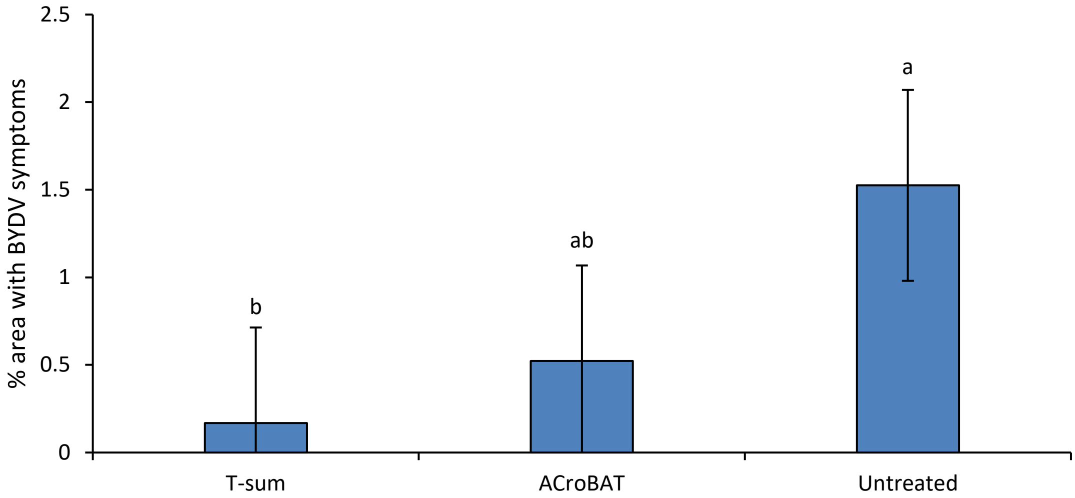

Figure 83. The mean area of tramline with BYDV symptoms in tramline trials in 2020/21. Bars represent the standard error of the mean. Bars followed by different letters are significantly different (P <0.05).

There was a significant difference between the yields, with tramlines treated with aphicides recommended by T-sum (6.9 t/ha) being higher than ACroBAT (6.7 t/ha) and untreated (6.6 t/ha) (df = 2, F = 16.18. P = <0.001) (Fig. 84). On average, T-sum recommended 1.5 times more aphicide applications than ACroBAT however, due to one T-sum recommended application being cancelled due to weather conditions the actual difference is T-sum recommending 1.3 times more sprays than ACroBAT. Calculated from mean yield from the four trials in 2020/21, the benefit of ACroBAT over untreated was £1.40/ha, and T-sum provided a benefit of £37/ha.

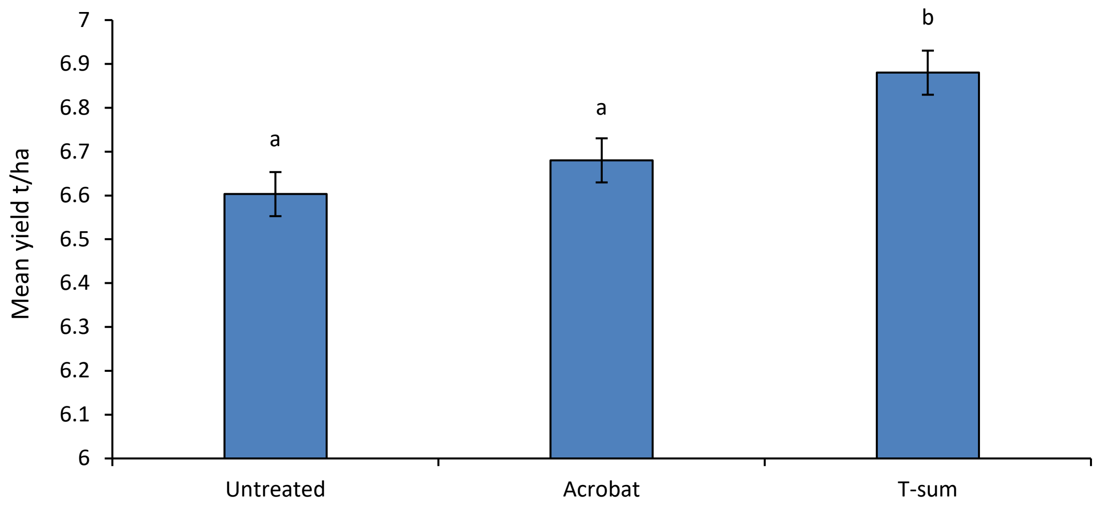

Figure 84. The mean harvested yield for tramline trials in 2020/21. Bars represent the standard error of the mean. Bars followed by different letters are significantly different (P <0.05).

DSS tramline trials in 2021/22

Trial 5 (Yorkshire) was drilled with winter barley on 20 September. The first recommendation for sprays was with ACroBAT on 20 October, sprayed on the same day, followed by T-sum on 21 October, which was sprayed on 25 October. One more ACroBAT recommendation and two more T-sum recommendations were made before GS31. A total of 330 aphids were observed in the trial, one of which was *S. avenae* and the rest *R. padi*. The untreated had 323 aphids and so this treatment had significantly more than the other treatments (df = 2, F = 12.27, P = <0.001) (Fig. 85). There was also a highly significant difference between the percentage of BYDV symptoms (df = 2, F = 10.81, P = <0.001), with more seen in the untreated (4%) than the ACroBAT (0%) and the T-sum (0.2%) treatments (Fig. 86). Yield was significantly lower in the untreated (6.2 t/ha) than the ACroBAT (6.7 t/ha) and the T-sum (6.7 t/ha) treatments (df = 2, F 18.73, P = <0.001) (Fig. 87). The use of ACroBAT and T-sum in this situation provided an £85/ha and £74/ha benefit over the untreated respectively.

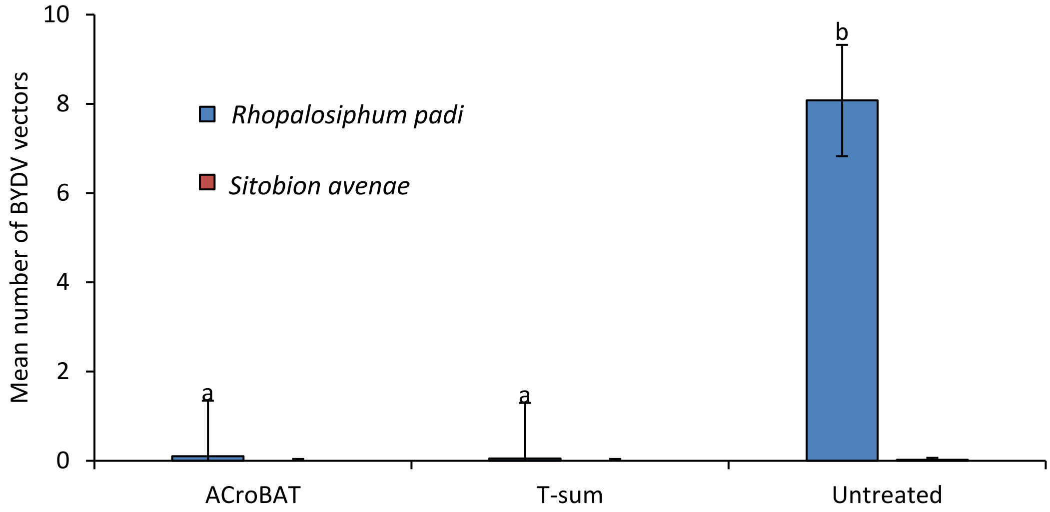

Figure 85. The mean number of BYDV vectors recorded in tramline trial 5, Yorkshire, in autumn 2021. Bars represent the standard error of the mean. Bars followed by different letters are significantly different (P <0.05).

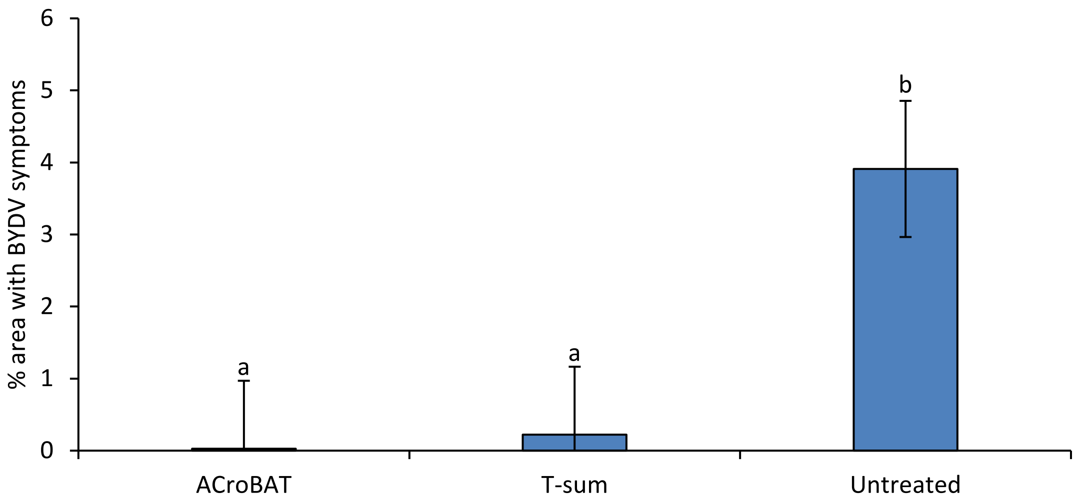

Figure 86. The mean area of tramline that had observed BYDV symptoms in tramline trial 5, Yorkshire, in spring 2022. Bars represent the standard error of the mean. Bars followed by different letters are significantly different (P <0.05).

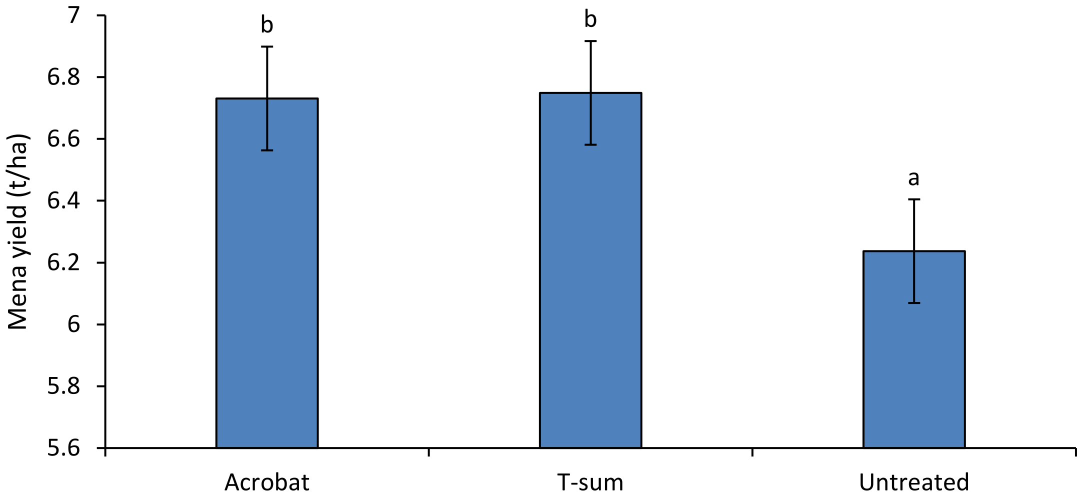

Figure 87. The mean harvested yield for tramline trial 5 in Yorkshire in 2021/22. Bars represent the standard error of the mean. Bars followed by different letters are significantly different (P <0.05).

Trial 6 (Suffolk) was drilled with winter wheat on 12 October. The first recommendation for spraying was with T-sum on 21 November and applied the following day. One further T-sum recommendation was made on 26 January, with the spray applied on 5 February. ACroBAT did not recommend any sprays for the duration of the trial. No aphids were observed in the trial. BYDV symptoms were observed in all treatments, but the mean percentage was all under 1% and were not significantly different (P<0.05). There was not a significant difference between the yields of each treatment (P<0.05). In this situation, T-sum resulted in a loss of £6/ha compared to the untreated, whereas ACroBAT produced a benefit of £8/ha compared to the untreated.

Trial 7 (Devon) was drilled with winter barley on 5 October. The first aphicide recommendation was from T-sum on 31 October and applied the following day. ACroBAT's first recommendation was on 12 November and applied the same day. Two more T-sum recommendations were made; the final recommendation on 3 January was applied two weeks late due to wet conditions preventing travel on fields. ACroBAT made one more prediction to spray on 2 February, this spray was applied on 28 January due to forecasted rain. No BYDV vectors were found and there was not a significant difference between the percentage of BYDV in each treatment (P<0.05), with a maximum of 0.5% area with symptoms. There was a significant difference between the yields of each treatment however, with T-sum (7.2 t/ha) being significantly higher than the untreated (7 t/ha) or ACroBAT (6.9 t/ha) (df = 2, F = 6.96, P = 0.001) (Fig. 88). In this trial, ACroBAT resulted in a loss of £7/ha over untreated, while the T-sum resulted in a gain of £42/ha compared to the untreated.

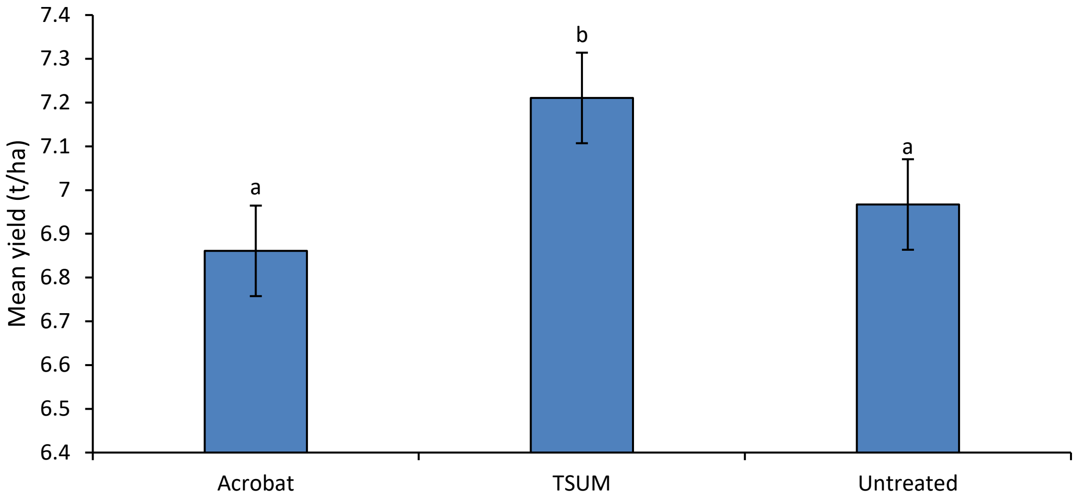

Figure 88. The mean harvested yield for Trial 7 in Devon in 2022. Bars represent the standard error of the mean. Bars followed by different letters are significantly different (P <0.05).

DSS tramline trial cross-site analysis 2021/22

In the three tramline trials in 2021/22, aphids were only found in Trial 5 in Yorkshire. As such cross-site analysis is not possible for aphids. For observed BYDV symptoms, there was a significant difference between the mean percentage of area with BYDV symptoms in untreated tramlines (1.6%) against the percentage of area with BYDV symptoms in tramlines treated according to both ACroBAT (0.3%) and T-sum (0.4%) (df = 2, F = 7.6, P = <0.001) (Fig. 89).

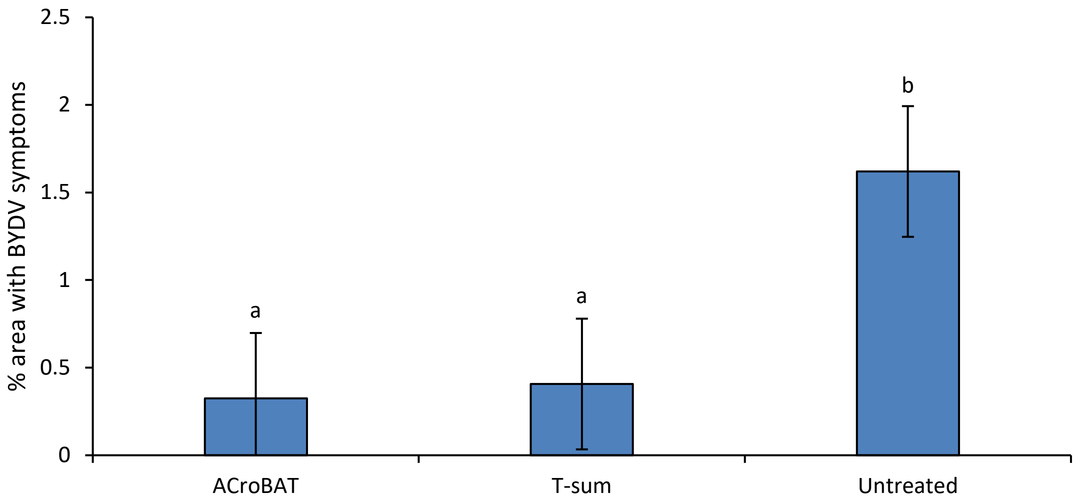

Figure 89. The mean area of tramline that had observed BYDV symptoms in tramline trials in 2021/22. Bars represent the standard error of the mean. Bars followed by different letters are significantly different (P <0.05).

There was a significant increase in the mean yield of tramlines that received aphicide applications with timings recommended by ACroBAT (6.7 t/ha) and T-sum (6.8 t/ha) when compared to the mean yield of untreated tramlines (6.5 t/ha) (df = 2, F = 9.05, P = <0.001) (Fig. 90). Across all three tramline trials, T-sum recommended twice the number of sprays as ACroBAT. As such, the overall economic benefit of T-sum is £20 /ha over untreated and ACroBAT provides a benefit of £21 /ha over untreated.

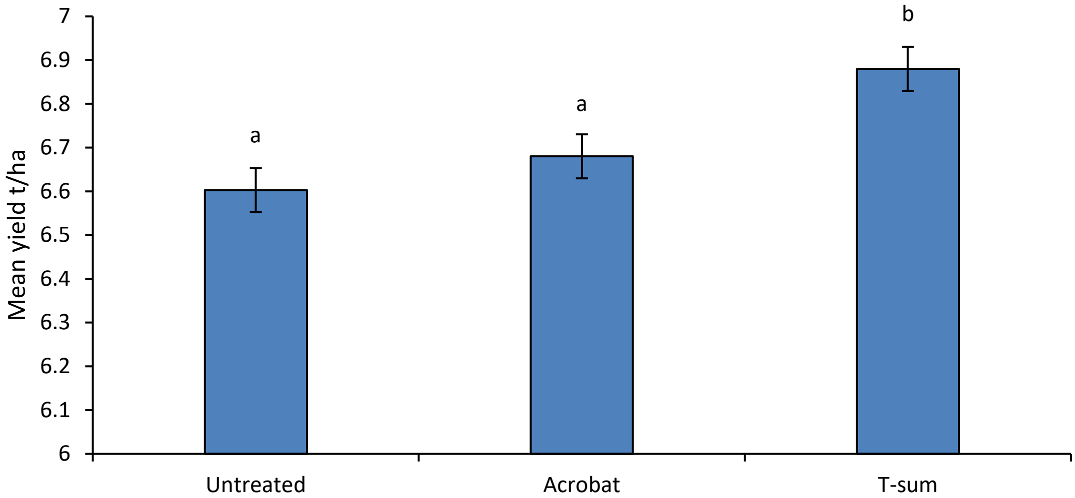

Figure 90. The mean harvested yield for tramline trials in 2021/22. Bars represent the standard error of the mean. Bars followed by different letters are significantly different (P <0.05).

DSS x variety tramline trials 2020/21

Four DSS x variety tramline trials were established in autumn 2020 in Devon. These were arranged in pairs, with one pair near Starcross (Starcross 1 and 2) and the second near Kenton (Kenton 1 and 2). All trials were drilled on 28 September. The Starcross trials were sown with the susceptible barley variety, KWS Funky, and the tolerant barley variety, KWS Amistar. The Kenton trials were sown with the susceptible barley variety, KWS Funky, and the tolerant barley variety, LG Rafaela. All trials received recommendations on the same dates and aphicides were applied on the same day across all four trials. The first recommendation to spray was provided by ACroBAT on 26 October and was applied on 5 November for the susceptible varieties and 17 November for tolerant varieties. A second spray recommendation was given on 17 January but was not applied until 26 February for all varieties due to poor travel conditions.

In Starcross 1, a total of 15 BYDV vectors were recorded (14 *S. avenae* and 1 *R. padi*) but there were no significant differences between treatments (P<0.05). BYDV symptoms were significantly different between treatments (df = 1, F = 8.61, P = 0.006) (Fig. 91) with the highest in untreated Funky (18%), followed by Funky with aphicide applications recommended by ACroBAT (2%). The tolerant variety Amistar had low observed BYDV symptoms, at 1% in untreated tramlines and no observed symptoms in tramlines where aphicides were applied according to ACroBAT.

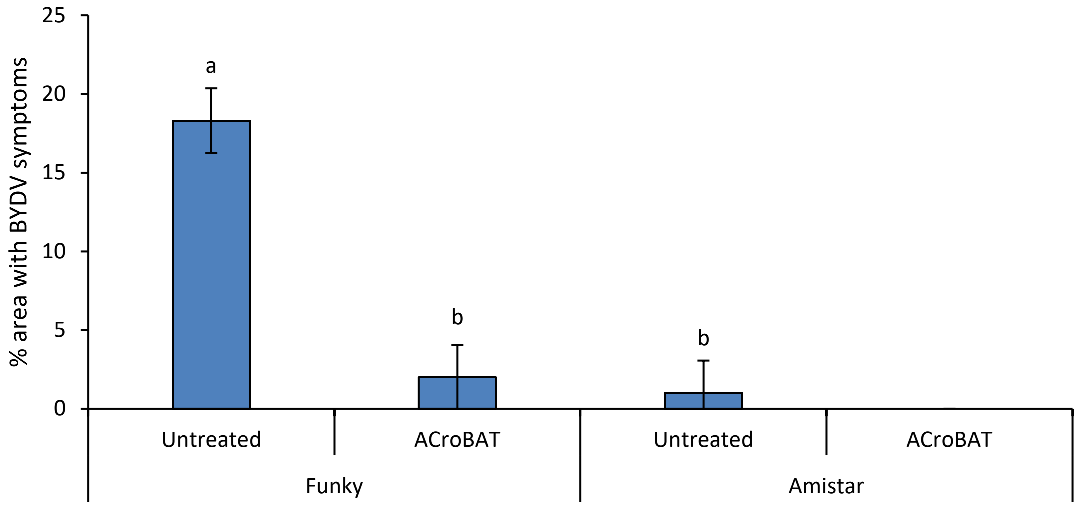

Figure 91. The mean area of the tramline with BYDV symptoms in Starcross 1, Devon, in spring 2020. Bars represent the standard error of the mean. Bars followed by different letters are significantly different (P <0.05).

Yield was also significantly different between treatments (df = 1, F = 69.87, P = <0.001) (Fig. 92) with the highest in tolerant Funky, in tramlines treated with aphicide according to ACroBAT (7.5 t/ha), followed by untreated Amistar (6.2 t/ha), Amistar plus ACroBAT (6 t/ha) with untreated Funky resulting in the lowest yield of 5.3 t/ha. In estimating the economic benefits of using DSS, the cost of purchasing tolerant varieties has not been included, instead costs are provided separately for each variety. Assumptions for these are as before, with grain prices at £200/t, and a treatment cost of £13.94. In Funky, using ACroBAT provided a benefit of £401 over untreated. Whereas in Amistar, ACroBAT produced a loss of £83 when compared to untreated.

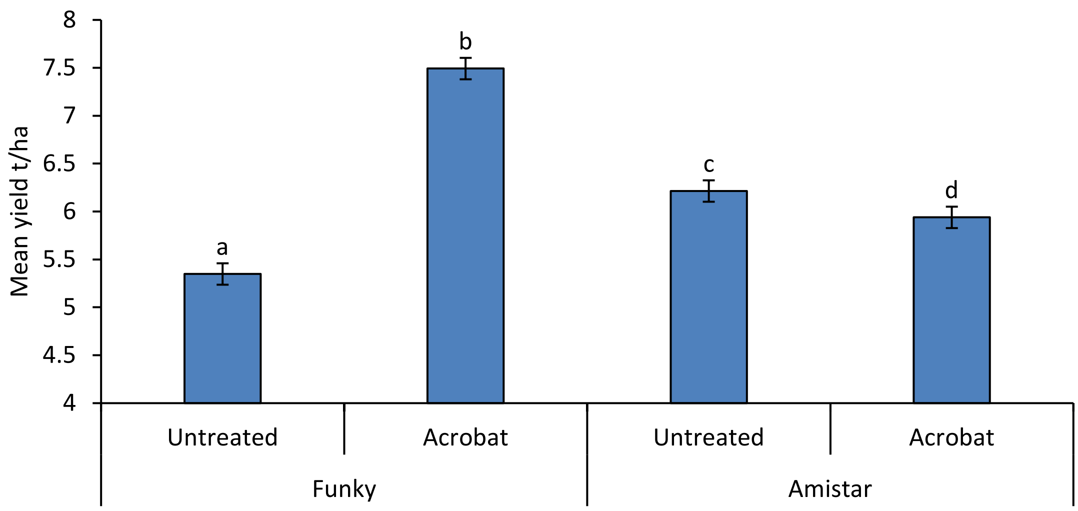

Figure 92. The mean harvested yield for Starcross 1, Devon, in 2020. Bars represent the standard error of the mean. Bars followed by different letters are significantly different (P <0.05).

In Starcross 2, no aphids were recorded in any of the treatments. There was a highly difference between treatments in the percentage of BYDV symptoms observed (df = 1, F = 13.22, P = <0.001) (Fig. 93). The highest mean percentage of area with BYDV symptoms was as expected in untreated Funky (2.1%), in untreated Amistar the area with symptoms was 0.6%. In Funky where insecticide was applied according to ACroBAT, the mean percentage of area with BYDV was 0.8%, there were no symptoms in Amistar where aphicides had been applied.

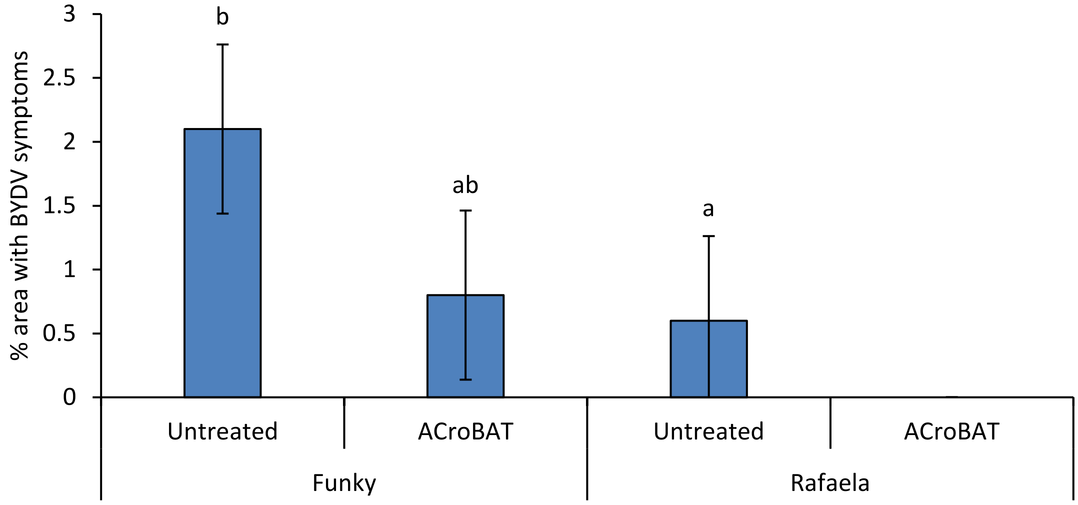

Figure 93. The mean area of the tramline that had observed BYDV symptoms in Starcross 2, Devon, in spring 2020. Bars represent the standard error of the mean. Bars followed by different letters are significantly different (P <0.05).

Yield was highest among the treatments in Funky where aphicides had been applied according to ACroBAT (7.6 t/ha). The second highest was in Amistar, also where spray decisions were provided by ACroBAT (6.8 t/ha). Untreated yields for Funky were 6.4 t/ha and for Amistar were 6.6. t/ha. There was a significant difference between treatments in terms of yield (df = 2, F = 26.7, P = <0.001) (Fig. 94). The economic benefit that could be gained from using ACroBAT was £207/ha in the susceptible variety Funky when compared to untreated. In tolerant Amistar the benefit of ACroBAT over untreated is £27 /ha.

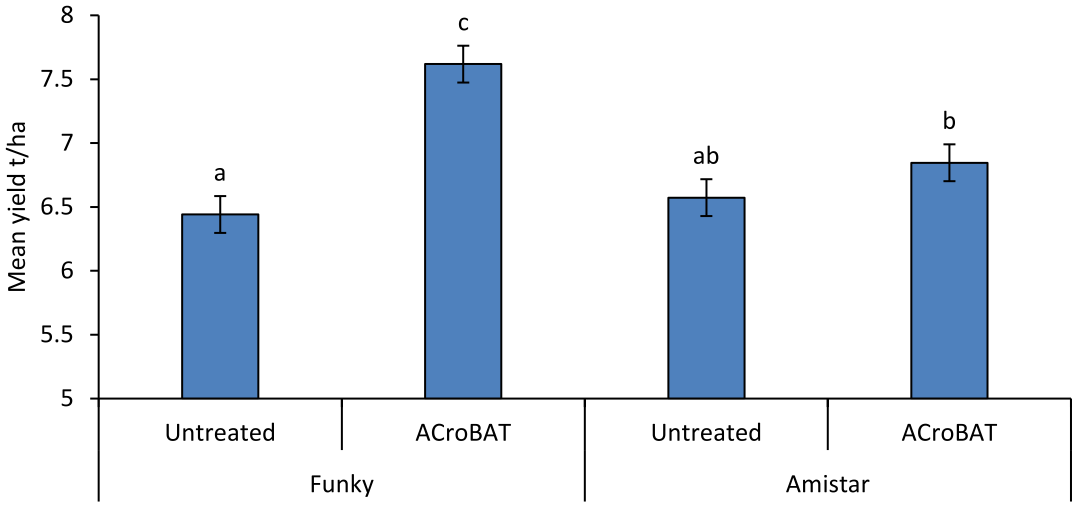

Figure 94. The mean harvested yield for Starcross 2, Devon, in 2020. Bars represent the standard error of the mean. Bars followed by different letters are significantly different (P <0.05).

In Kenton 1, a total of four aphids were recorded in untreated tramlines, three in Rafaela and one in Funky. There was a significant difference in aphid numbers were found between treatments and varieties (df = 1, F = 4.8, P = 0.035) (Fig. 95). Significant differences were also found in BYDV symptoms (df = 1, F = 15.42, P = <0.001) (Fig. 96) with untreated Funky having the highest area with BYDV (11.4%). This was significantly greater than untreated Rafaela (1.8%), Funky combined with ACroBAT (0.7%) and Rafaela combined with ACroBAT (0.4%). There were no significant differences in yield between the treatments (P<0.05), with untreated Funky having the lowest yield (6.3 t/ha) and Rafaela sprayed according to ACroBAT the highest (6.5 t/ha). In Funky, the use of ACroBAT did not provide an economic benefit, instead resulted in a reduction of minus £7/ha against untreated. Using ACroBAT in Amistar did produce a benefit over untreated of £8/ha.

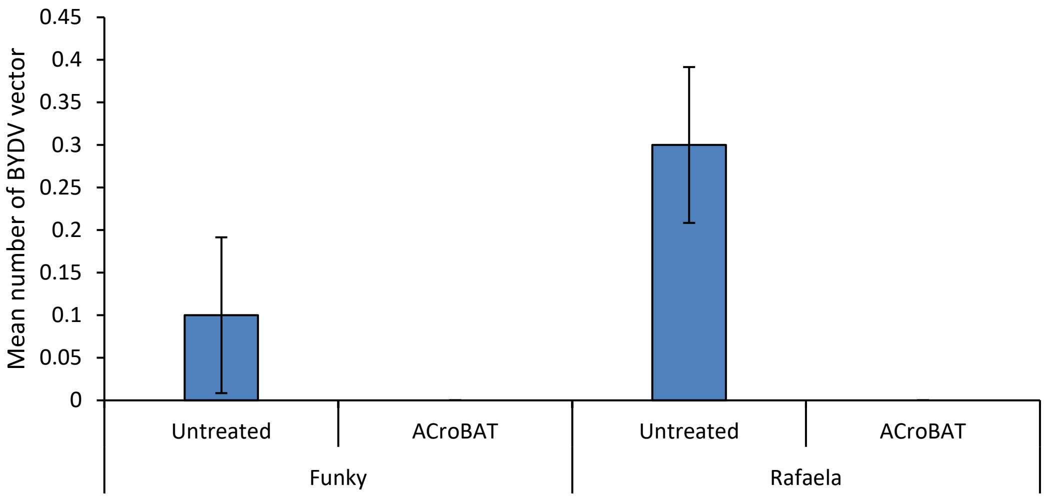

Figure 95. The mean number of BYDV vectors recorded in the Kenton 1 tramline trial, Devon, in 2020. Bars represent the standard error of the mean. Bars followed by different letters are significantly different (P <0.05).

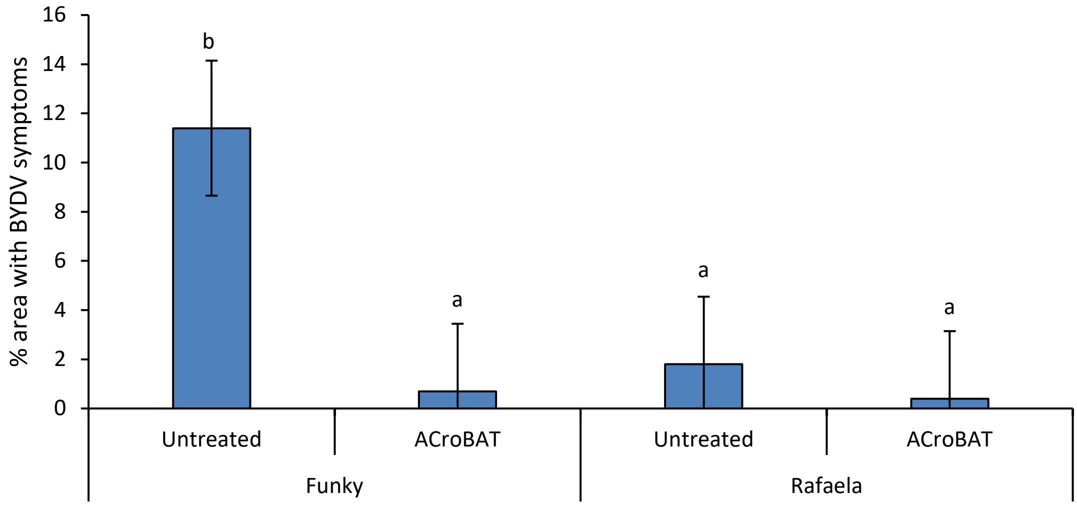

Figure 96. The mean area of tramline that had observed BYDV symptoms in Kenton 1, Devon, in spring 2021. Bars represent the standard error of the mean. Bars followed by different letters are significantly different (P <0.05).

In Kenton 2, there was no significant differences between treatments for aphids (P<0.05) as only a single aphid was recorded in untreated Rafaela. For BYDV symptoms, untreated Funky had the greatest percentage of area with BYDV (7%), followed by untreated Rafaela (1.6%). Use of ACroBAT reduced BYDV symptoms to 0.4% in Rafaela and no symptoms were observed in Funky There was a significant difference between treatments (df = 1, F = 9.7, P = <0.001) (Fig. 97).

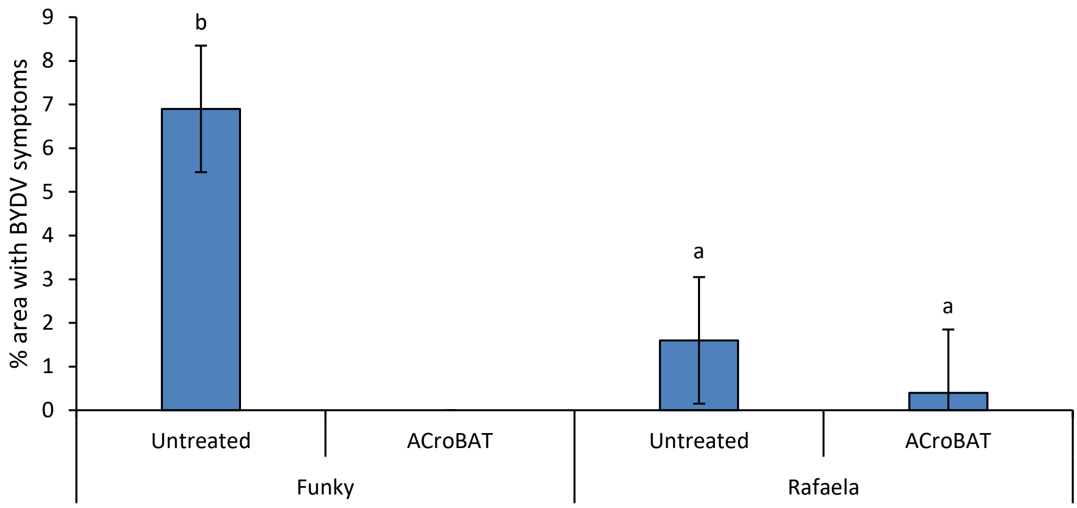

Figure 97. The mean area of tramline that had observed BYDV symptoms in Kenton 2, Devon, in spring 2021. Bars represent the standard error of the mean. Bars followed by different letters are significantly different (P <0.05).

The highest yield in this trial was Funky where ACroBAT had recommended aphicide applications (6.7 t/ha), followed by untreated Rafaela (6.6 t/ha). These not significantly more than Rafaela where ACroBAT had recommended sprays (6.5 t/ha), but they were significantly greater than untreated

Funky (6.2 t/ha) (df = 3, F = 4.17, P = 0.006) (Fig. 98). In Funky, the use of AcroBAT provided a benefit over untreated of £70/ha. In Rafaela, there was a reduction of £47/ha when compared to untreated.

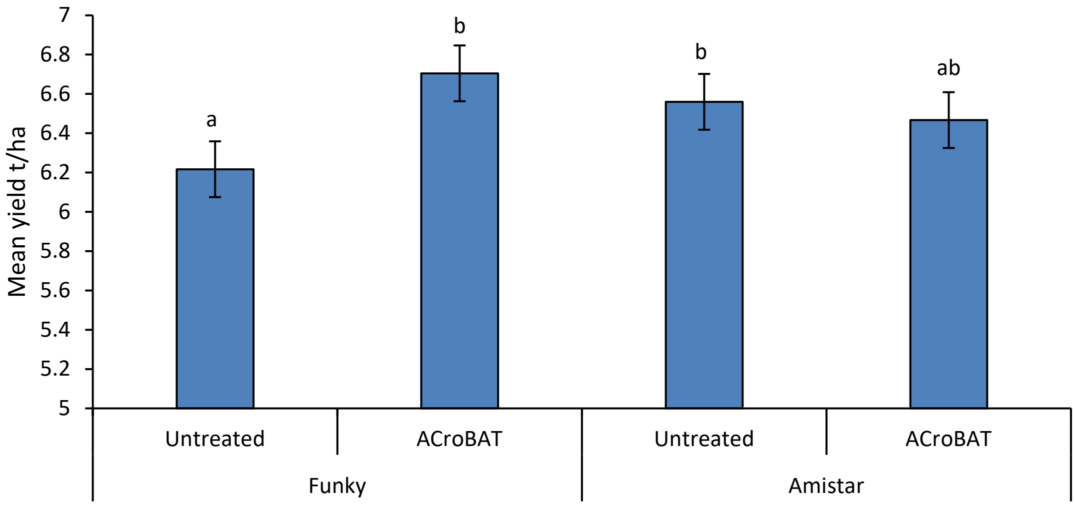

Figure 98. The mean harvested yield for Kenton 2, Devon, in 2020. Bars represent the standard error of the mean. Bars followed by different letters are significantly different (P <0.05).

DSS x variety tramline trials cross site analysis 2020/21

Across the four tramline trials combining the use of ACroBAT with varietal tolerance there was a significant difference between the number of *R. padi* found in untreated tramlines and in tramlines where sprays had been applied according to ACroBAT (df = 1, F = 6.41, P = 0.012), but there was not a significant difference between treatments for *S. avenae* (P<0.05) (Fig. 99). There was not a significant difference between varieties for either aphid species (P<0.05).

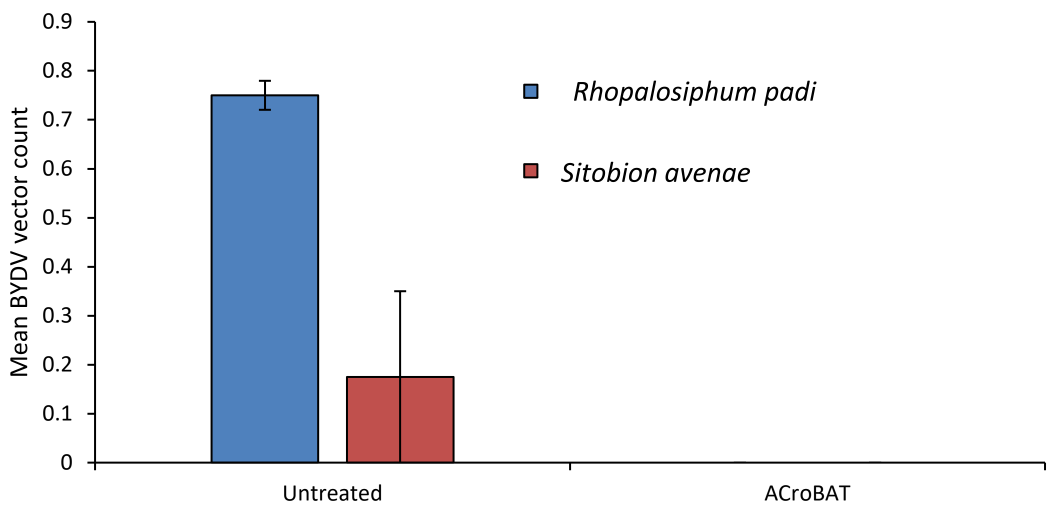

Figure 99. The mean number of BYDV vectors recorded across the DSS x variety tramline trials in 2020/21. Bars represent the standard error of the mean.

For observed BYDV symptoms, there was a significant difference between the mean percentage of area with BYDV between untreated (5.5%) and where ACroBAT had recommended sprays (0.5%) (df = 1, F = 25.95, P = <0.001) (Fig. 100). There was also a highly significant difference in BYDV symptoms between varieties, with Funky (5%) being significantly higher than Amistar (0.4%) and Rafaela (1%) (df = 1, F = 10.87, P = <0.001) (Fig. 101).

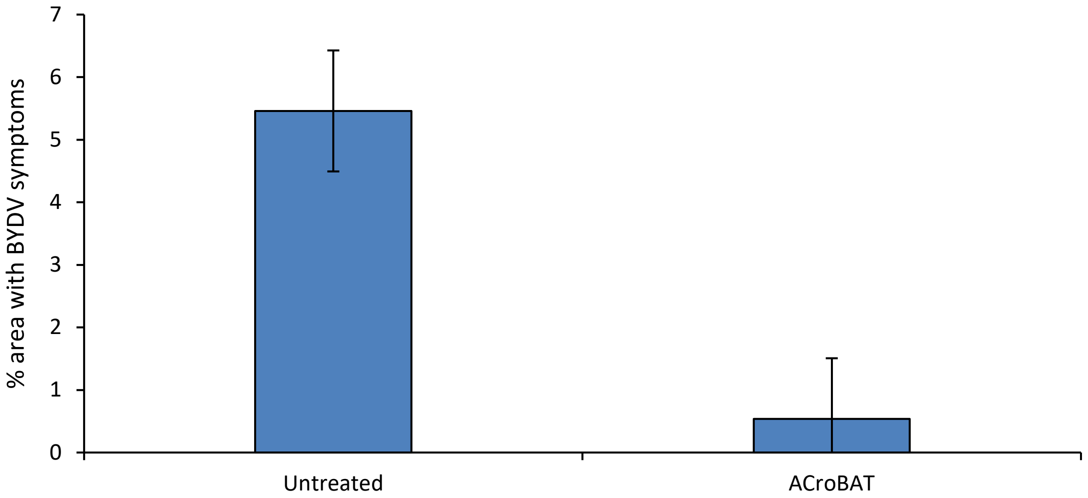

Figure 100. The mean area of tramline that had observed BYDV symptoms between treatments across the DSS x variety tramline trials in 2020/21. Bars represent the standard error of the mean.

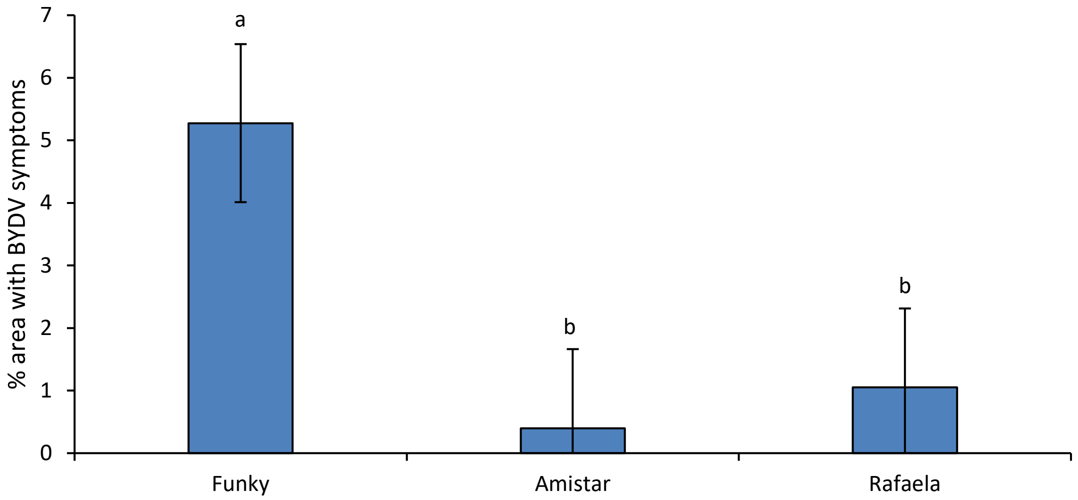

Figure 101. The mean area of tramline that had observed BYDV symptoms between varieties across the DSS x variety trials in 2020/21. Bars represent the standard error of the mean. Bars followed by different letters are significantly different (P <0.05).

With yield, there was a significant difference between using ACroBAT (6.7 t/ha) and untreated (6.2 t/ha) (df = 1, F = 85.79, P = <0.001) (Fig. 102). There was not a significant difference between the varieties used, with Amistar bearing the highest mean yield (6.6 t/ha) followed by Funky (6.5 t/ha) and Rafaela (6.5 t/ha). ACroBAT provided an economic benefit of £72/ha over untreated in these trials.

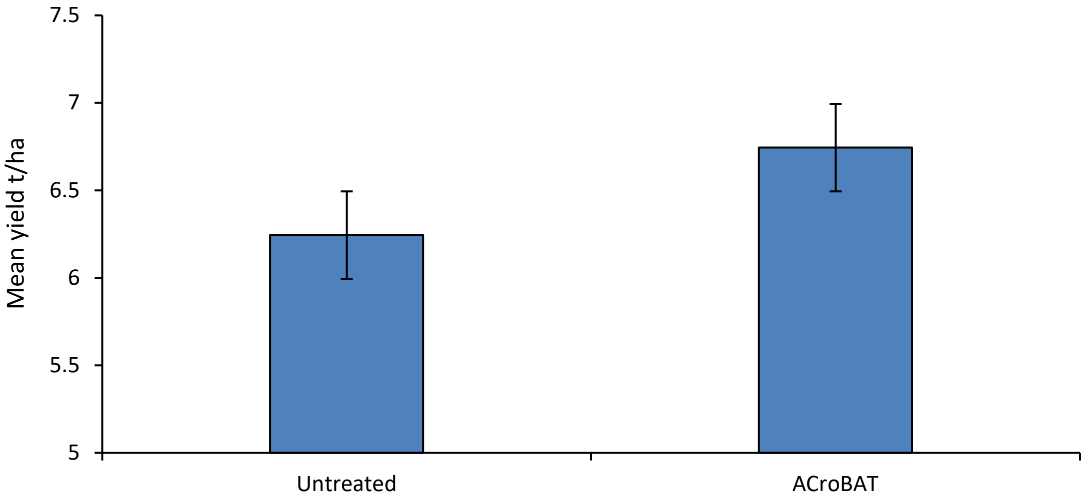

Figure 102. The mean harvested yield for DSS x variety tramline trials in 2020/21. Bars represent the standard error of the mean.

DSS x variety tramline trials 2021/22

Four DSS x variety tramline trials were established in autumn 2021. These were arranged in pairs in Ashcombe, Devon. Ashcombe 1 was sown with BYDV susceptible variety, KWS Orwell, and BYDV tolerant variety, LG Rafaela, on 12 October. A single insecticide application was recommended by ACroBAT on 15 December and applied on the same day. No aphids were found in the trial at either assessment timing. There was not a significant difference in the percentage of area with BYDV symptoms between treatments (P<0.05), varieties (P<0.05) or the interaction between them (P = >0.05). The highest mean yield was in tramlines of Orwell that received aphicide applications recommended by ACroBAT (7.7t/ha) (Fig. 103). This is significantly more than tramlines of untreated Rafaela (7.5 t/ha) but not significantly more than Rafaela with ACroBAT (7.6 t/ha) (df = 3, F = 7.59, P = <0.001). Untreated Orwell yielded lowest at 7.3 t/ha which was significantly less than other treatments. In Orwell, the economic benefit of using ACroBAT was £45/ha. In Rafaela, ACroBAT resulted a reduction of £2/ha against untreated.

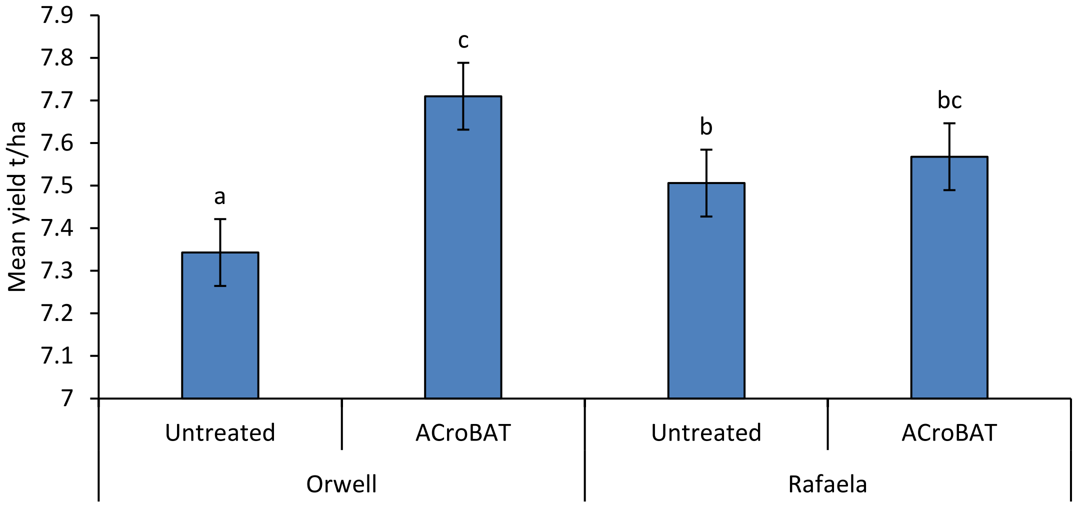

Figure 103. The mean harvested yield for Ashcombe 1 in 2021/22. Bars represent the standard error of the mean. Bars followed by different letters are significantly different (P <0.05).

Ashcombe 2 was sown with KWS Orwell and LG Rafaela on 12 October. A single insecticide application was recommended by ACroBAT on 15 December and applied on the same day. No aphids were found in the trial at either assessment timing. There were no significant differences in BYDV symptoms between the treatments (P<0.05), with the highest levels seen in Orwell with ACroBAT (1.9%) and the lowest in untreated Rafaela (0%). There was a significant difference in yield between the treatments (df = 3, F = 4.12, P = 0.007), with yield in Rafaela with aphicides applied according to ACroBAT (7.6 t/ha) being significantly higher than Orwell with ACroBAT (7.2 t/ha) and untreated Rafaela (7.2 t/ha) (Fig. 104). ACroBAT provided an economic benefit for Rafaela over untreated of £67/ha, but in Orwell ACroBAT resulted in a reduction against untreated of £45/ha.

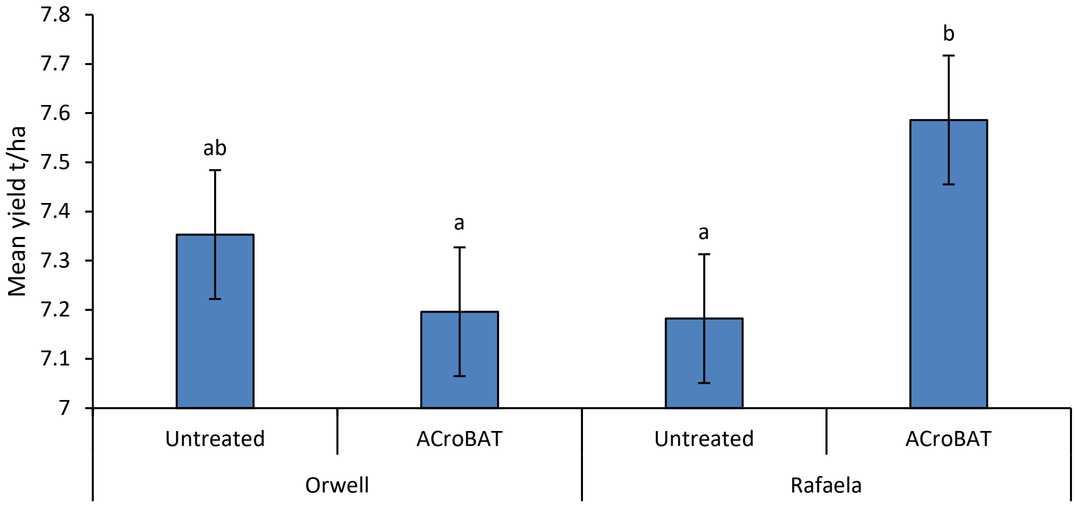

Figure 104. The mean harvested yield for Ashcombe 2 in 2021/22. Bars represent the standard error of the mean. Bars followed by different letters are significantly different (P <0.05).

Ashcombe 3 was sown with KWS Orwell and BYDV tolerant variety, KWS Feeris, on 12 October. A single insecticide application was recommended by ACroBAT on 15 December and applied on the same day. No aphids were recorded in the trial at either assessment timing. There were no significant differences in BYDV symptoms between the treatments ($P<0.05$), with the highest levels seen in Orwell sprayed according to ACroBAT (0.5%) and the lowest in Feeris sprayed according to ACroBAT (0%). There was a significant difference in yield between the treatments (df = 3, F = 9.36, P = <0.001), with Orwell with AcroBAT (7.6 t/ha) being higher than untreated Feeris (7.3 t/ha), which in turn was significantly higher than untreated Orwell (7.1 t/ha) (Fig. 105). The economic benefit of using ACroBAT in Orwell was £80/ha over untreated, whereas in Feeris the benefit was £10/ha greater than untreated.

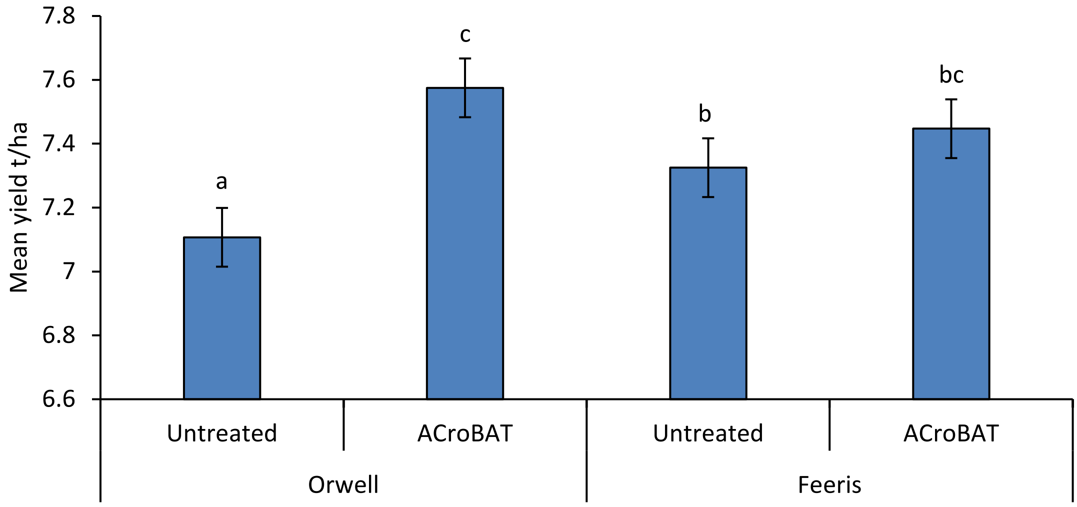

Figure 105. The mean harvested yield for Ashcombe 3 in 2021/22. Bars represent the standard error of the mean. Bars followed by different letters are significantly different (P <0.05).

Ashcombe 4 was sown with KWS Orwell and KWS Feeris on 12 October. A single insecticide application was recommended by ACroBAT on 15 December and applied on the same day. No aphids were recorded in the trial at either assessment timing. There was a significant difference in observed BYDV symptoms between the treatments (df = 3, F = 3.31, P = 0.02) (Fig. 106), with Orwell sprayed according to ACroBAT greater than Feeris sprayed according to ACroBAT and untreated Feeris.

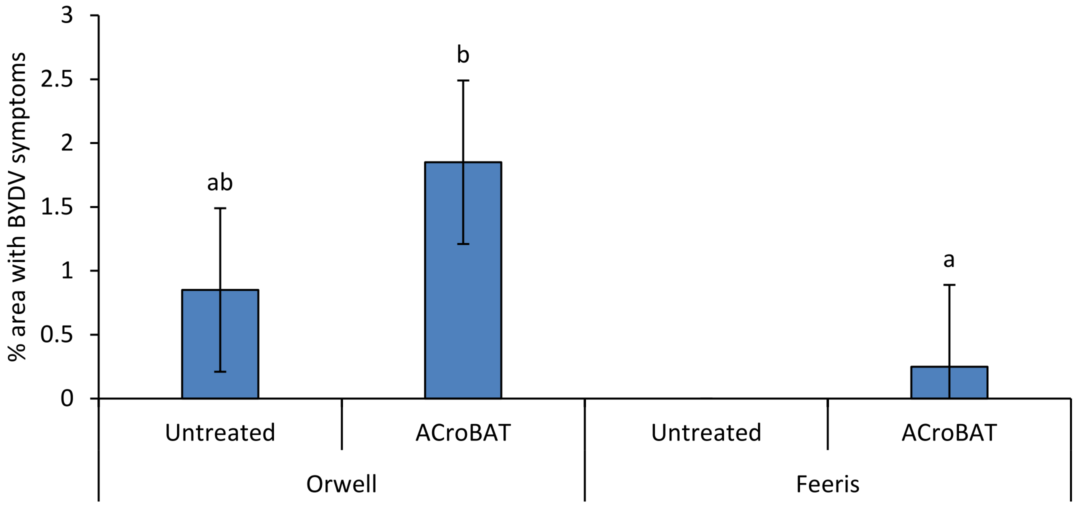

Figure 106. The mean area of tramline that had observed BYDV symptoms in Ashcombe 4 in 2021/22. Bars represent the standard error of the mean. Bars followed by different letters are significantly different (P <0.05).

There was also a significant difference in yield between the treatments (df = 3, F = 48.57, P = <0.001). The highest yield was from Feeris combined with ACroBAT (7.7 t/ha), followed by Orwell with ACroBAT (7.6 t/ha), untreated Feeris (7.5 t/ha) and untreated Orwell (7.2 t/ha) (Fig. 107). ACroBAT does provide an economic benefit over the untreated when used in Orwell (£62/ha) and in Feeris (£7/ha).

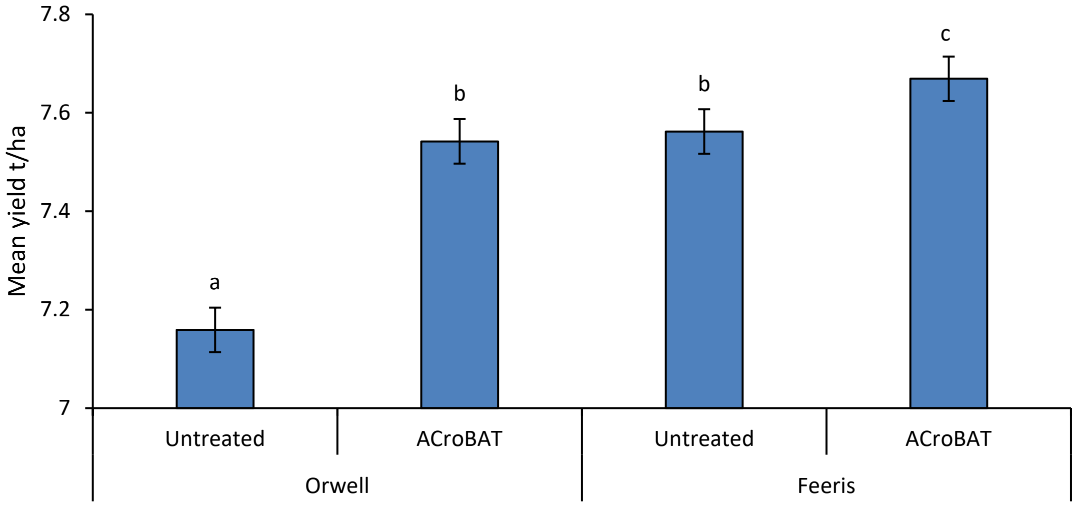

Figure 107. The mean harvested yield for Ashcombe 4 in 2021/22. Bars represent the standard error of the mean. Bars followed by different letters are significantly different (P <0.05).

DSS x variety tramline trials cross site analysis 2021/22

Across the four DSS x variety tramline trials, no aphids were recorded at any point. For observed BYDV symptoms there was not a significant difference between using ACroBAT (0.5%) and untreated (0.4%) however there was a significant difference between the susceptible variety Orwell (0.7%) and the tolerant varieties Feeris (0.1%) and Rafaela (0.2%) (df = 2, F = 6.69, P = 0.001) (Fig. 108). In testing the interaction between variety and the use of ACroBAT there were significant differences (df = 5, F = 3.28, P = 0.007) but all were under 1% of the area with infection (Fig. 109).

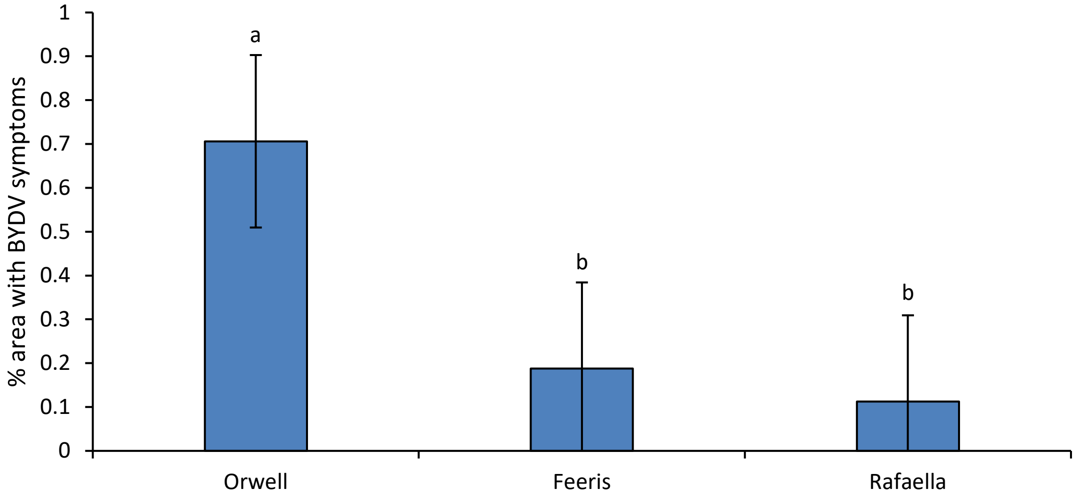

Figure 108. The mean area of tramline that had observed BYDV symptoms between different varieties in the DSS x variety tramline trials in 2021/22. Bars represent the standard error of the mean. Bars followed by different letters are significantly different (P <0.05).

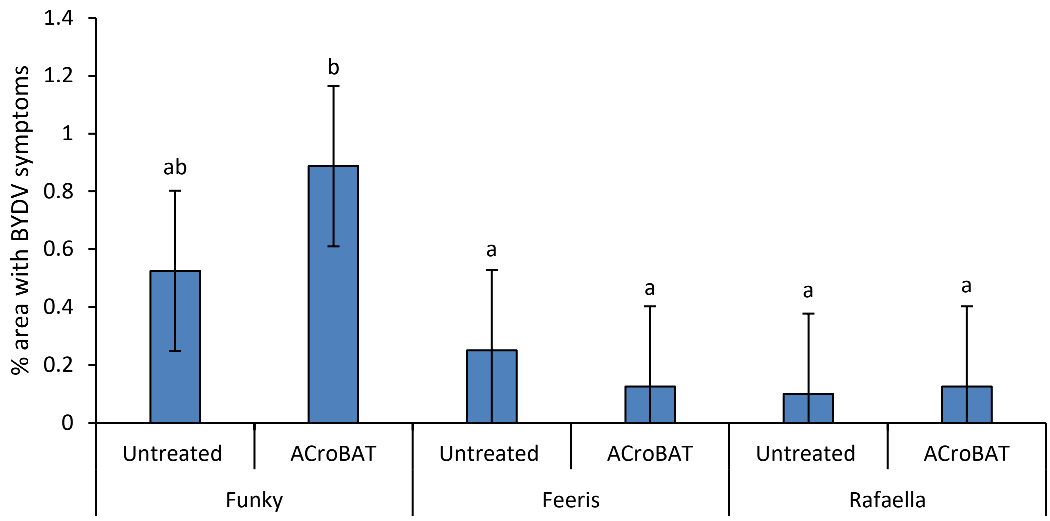

Figure 109. The mean area of tramline that had observed BYDV symptoms according to treatment and varietal interaction in the DSS x variety tramline trials in 2021/22. Bars represent the standard error of the mean. Bars followed by different letters are significantly different (P <0.05).

For yield, there was a significant difference between using ACroBAT (7.5 t/ha) and untreated (7.3 t/ha) (df = 1, F = 46.17, P = <0.001) (Fig. 110). This was also the case with varieties, whereby Orwell (7.4 t/ha) yielded significantly lower than Feeris (7.5 t/ha) and Rafaela (7.5 t/ha) (df = 2, F = 5.92, P = 0.003) (Fig. 111).

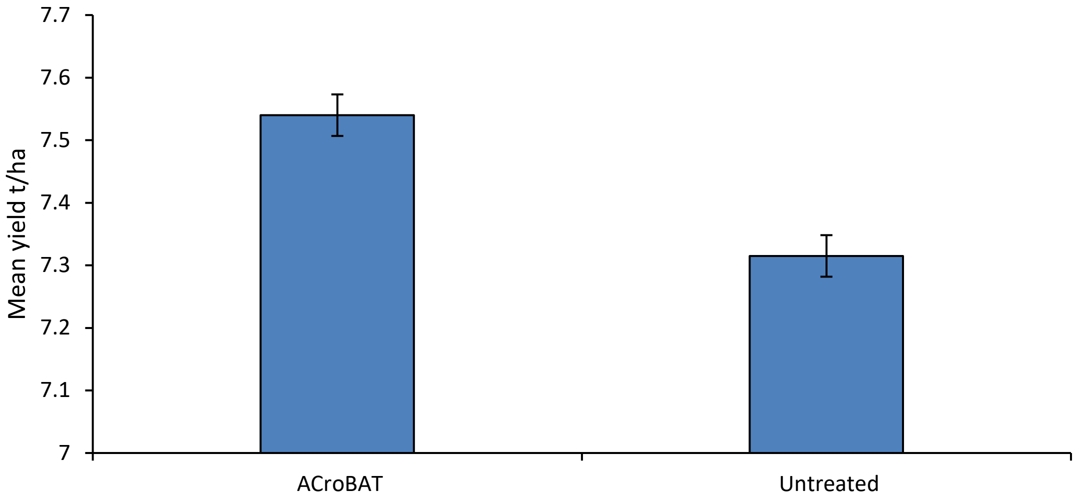

Figure 110. The mean harvested yield when using ACroBAT or untreated in the DSS x variety tramline trials in 2021/22. The bars represent the standard error of the mean.

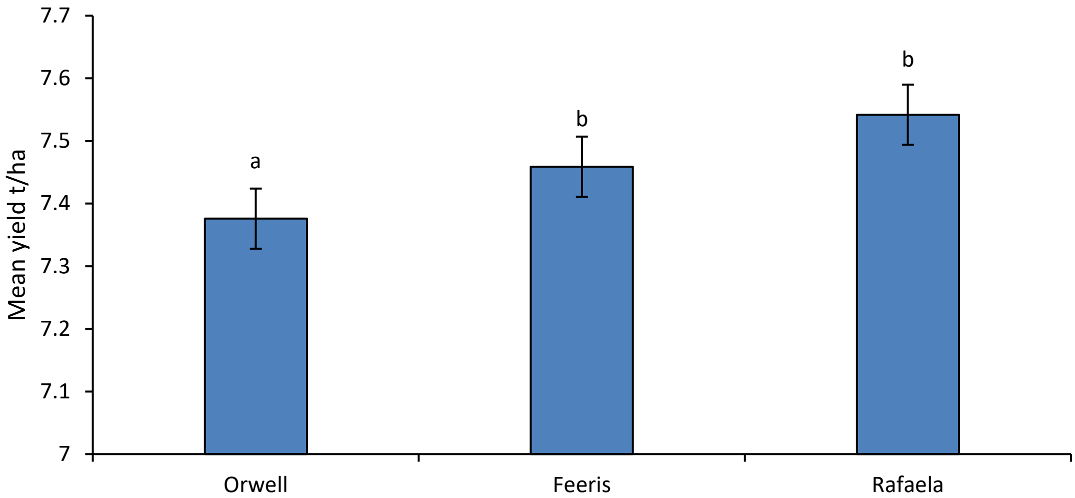

Figure 111. The mean harvested yield between varieties in the DSS x variety tramline trials in 2021/22. Bars represent the standard error of the mean. Bars followed by different letters are significantly different (P <0.05).

The interaction between ACroBAT and varietal tolerance on yield was also significant (df = 5, F = 12.47, P = <0.001). All three varieties with ACroBAT yielded highest, with Rafaela (7.6 t/ha), Feeris (7.6 t/ha) and Orwell (7.5 t/ha) yielding significantly higher than untreated Orwell (7.2 t/ha) and Feeris (7.4 t/ha) (Fig. 112). In economic terms, ACroBAT provided a benefit over untreated when used with Orwell (+ £40/ha) and Feeris (+ £29/ha) but resulted in the same price with Rafaela.

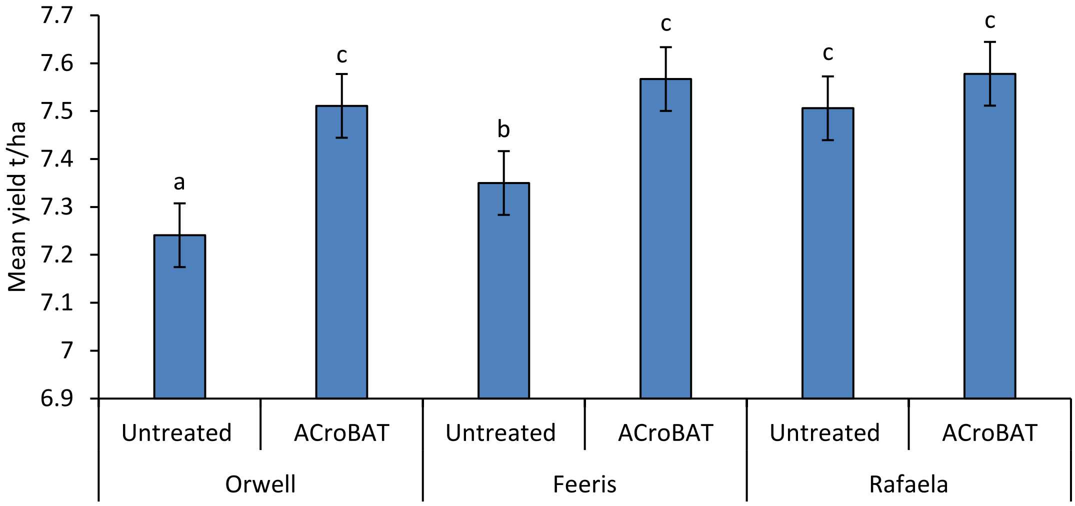

Figure 112. The mean harvested yield between treatments in the DSS x variety tramline trials in 2021/22. Bars represent the standard error of the mean. Bars followed by different letters are significantly different (P <0.05).

Inoculated plot trial

In the inoculated plot trials, the first spray recommendation came from T-sum on 16 October, applied on 18 October. Followed by a recommendation from ACroBAT on 20 October, applied the following day. In total there were three recommendations to spray from T-sum and two from ACroBAT. 28,000 aphids were inoculated into the trial on 5 October, at the first assessment of aphid numbers on 14 October this had reduced to 2,139. There was not a significant difference between treatments or varieties ($P<0.05$). At the next assessment on 21 October, a total of 77 aphids were recorded, again there was not a significant difference between treatments or varieties ($P<0.05$). There were no significant differences between the aphid counts in the four subsequent assessments, not when data was combined across all assessments.

Inoculating with viruliferous aphids resulted in high levels of BYDV symptoms in the plot trial. At the first assessment for BYDV symptoms on 12 December, the highest percentage of BYDV was in untreated Funky (40%) and the lowest in Rafaela with ACroBAT (28%), although there were no significant differences between the treatments ($P<0.05$). In the spring assessment, untreated Funky had the highest BYDV (30%) and Rafaela with ACroBAT the lowest (13%) again. This time Funky had a significantly higher percentage of BYDV symptoms (24%) than Rafaela (15%) across the spray treatments (df = 1, F = 18.25, P = <0.001). Within Funky, the treatment that resulted in the lowest BYDV symptoms was T-sum (20%). In Rafaela, plots sprayed monthly (calendar spray) had the highest percentage of symptoms (16%). There was a significant difference between the interaction of treatments and varieties at this assessment (df = 7, F = 3.53, P = 0.005) (Fig. 113), with the untreated having significantly more BYDV than Funky/T-sum, untreated Rafaela, Rafaela/T-sum and

Rafaela/calendar sprays, which in turn had significantly more BYDV than Rafaela/ACroBAT (Fig. 113).

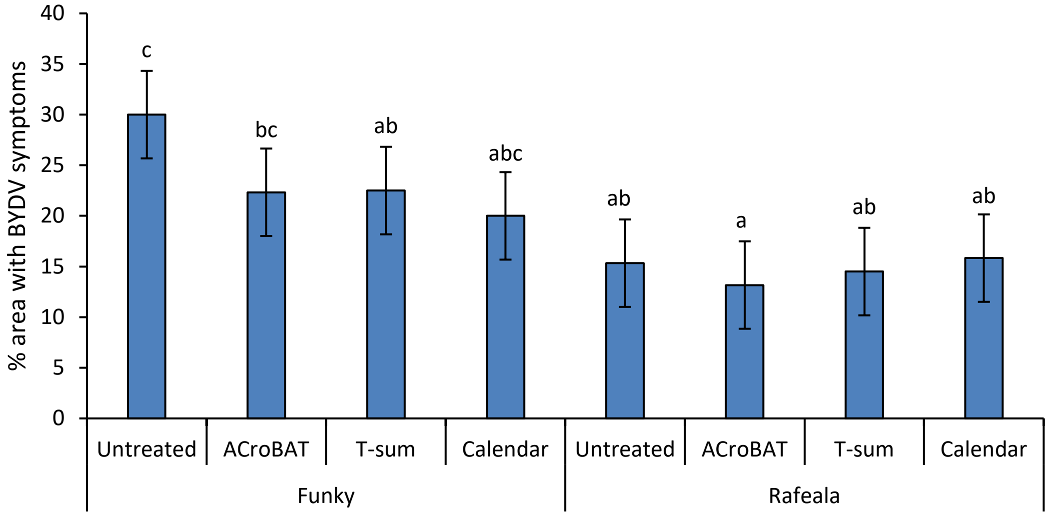

Figure 113. The percentage of BYDV symptoms according to treatment and variety in the March assessment. Bars represent the standard error of mean. Bars followed by different letters are significantly different (P<0.05).

The differences between observed BYDV symptoms were supported with drone image analysis. In January there was not a significant difference between treatments (P<0.05) but there was a significant difference between varieties (df = 1, F = 34.61, P<0.001) where green leaf area was higher in plots of Rafaela (8% green area loss) than in Funky (15% green area loss). The interaction between all treatments and variety was significant (df =7, F = 6.94, P = <0.001) (Fig. 114). Successive drone flights in April and June found there to be no significant difference between treatment and variety with regards to the percentage of green area in plots (P<0.05). Differences between the varieties are demonstrated in Figure 115, which shows two randomly selected untreated plots of both Funky and Rafaela. Differences between the spray treatments were not significant.

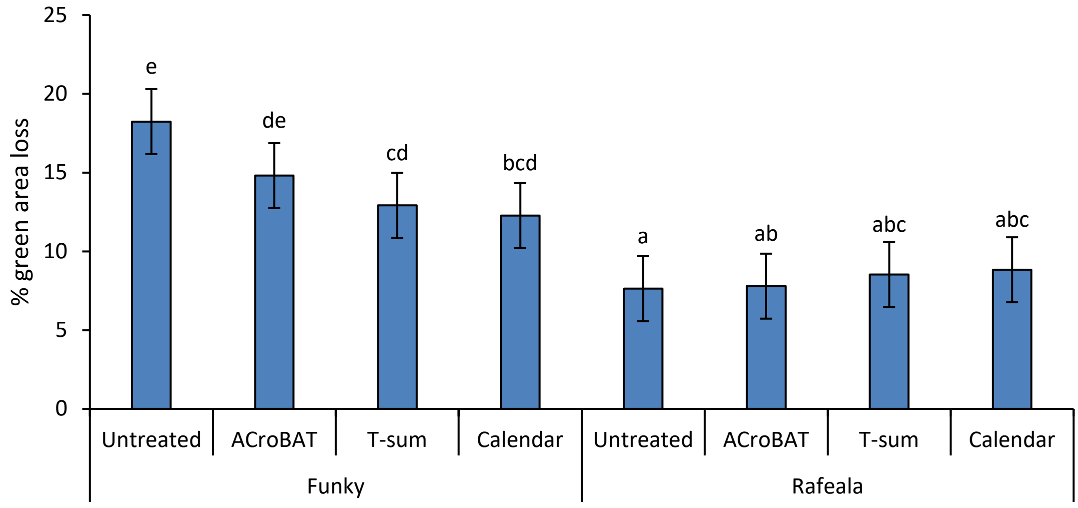

Figure 114. The percentage of green area loss per plot in the inoculated trial, as recorded by drone in January 2022. Bars represent the standard error of the mean. Bars followed by different letters are significantly different (P<0.05).

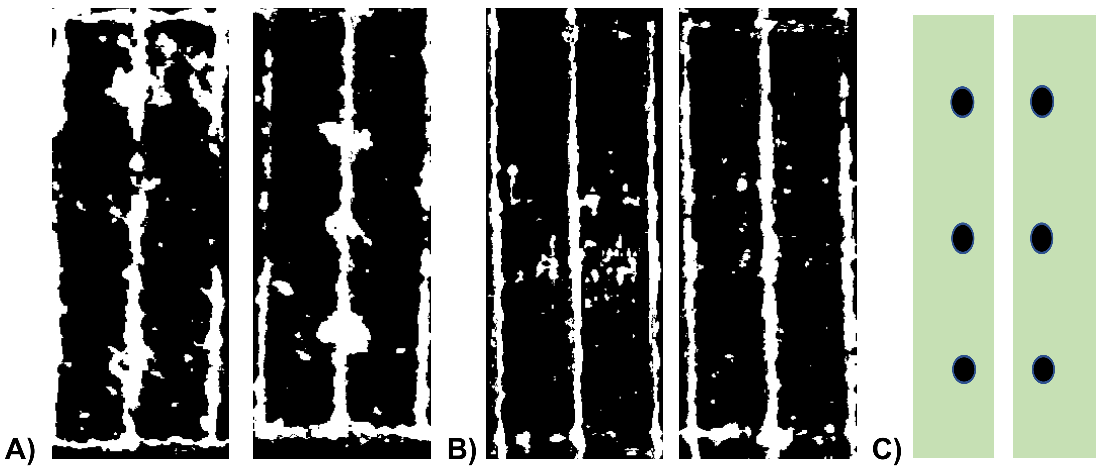

Figure 115. Green area analysis results from drone imagery captured in May 2022 (GS52), showing two plots of KWS Funky (A) and two plots of LG Rafaela (B). White areas indicate a lack of green plant material, representing either bare ground or dead plants. C) Plot design with inoculation points.

Analysis of yield found significant differences between spray treatments in Funky (df = 3, F = 4.6, P = 0.007), with the untreated significantly lower than the three spray treatments (Fig. 116). Differences between spray treatments in Rafaela were not significant, nor were differences between varieties across spray treatments (P<0.05). The highest yield was seen in Funky with sprays as guided by T-sum (7.5 t/ha) and the lowest was in the untreated Funky (6.1 t/ha). To establish the economic benefit of the different treatments the cost of purchasing tolerant varieties has been omitted and only the cost of applying insecticide at a field level according to the different treatments have been included. Within Funky, the use of ACroBAT would result in a £186/ha increase over the untreated, T-sum would add £54/ha over untreated and the calendar spray would produce a net loss of £67/ha against the untreated. In Rafaela, all treatments would make a loss against untreated, with ACroBAT being the lowest (£4/ha), followed by calendar sprays (£9/ha) and T-sum (£21/ha).

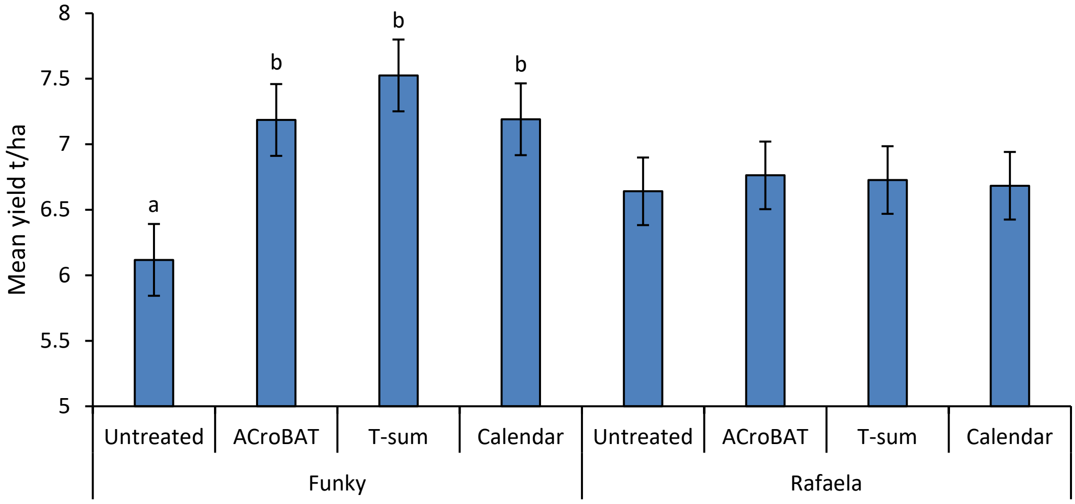

Figure 116. The mean yield for the different treatments in the inoculated trial. Bars represent the standard error of the mean. Bars followed by different letters are significantly different (P <0.05).

4.4. Discussion

4.4.1. ACroBAT

BYDV management has primarily relied on the use of insecticides to control the aphid vectors. There are cultural control approaches that can reduce risk but, other than adjusting drill date, these are not well understood or utilised. In recent years, varieties with tolerance or resistance to the virus have become commercially available, and their use represents a shift away from vector control. Nevertheless, the use of insecticides to control aphids is likely to remain the primary management method for BYDV. There are treatment thresholds available to guide insecticide use for most arable pests, but these are lacking for BYDV vectors (Ramsden et al., 2017a). Primarily, this is because of the difficulty relating numbers of BYDV vectors to damage (and, in turn, yield loss). Damage from direct feeding (e.g. removing leaf area or destroying shoots) can usually be related to the number of pests present, but this relationship is less clear with BYDV because a single aphid can infect multiple plants, all of which could suffer major impacts to development as a result. The consequence has been that the treatment threshold for BYDV vectors is their mere presence, which has often translated into prophylactic treatments due to the difficulty in monitoring for these aphids in the autumn and the relatively low cost of pyrethroids (Ellis et al., 2009).

To help predict BYDV risk and assist with management decisions, a range of models to predict have been developed since the 1980s (Salinari & Holland, 2019). That these are not currently in use in the UK is likely due to a range of factors, including resource requirements (Kendall et al., 1992), processing power available at the time, performance, trust and ease of use (Rose et al., 2016). The processing power now available on smart phones is several times that of most desktop computers in the 1990s, meaning that some older models may now not be as limited in this regard. Smart phones also improve ease of use by offering the potential to run DSS in the field. This project aimed to evaluate previously developed models, update them and assess their performance. Due to issues with all the models evaluated individually, we elected to combine several models into a single DSS named ACroBAT. The ACroBAT DSS was developed by combining three models: an aphid population dynamics model (Morgan, 2000), a BYDV epidemiology model (Kendall et al., 1992) and risk model (MAFF, 2001). It simulates the arrival of aphids, the build-up of their populations in the crop, crop plants being infected with BYDV and aphids acquiring the virus from infected plants, and assesses risk based on the proportion of the crop infected. The spray decision-support element of ACroBAT then uses the risk level to make a cost-benefit calculation to determine whether an insecticide spray is worthwhile. The cultural control element of ACroBAT can be used before sowing to predict likely levels of BYDV risk ahead and explore the impact of different cultural control approaches.

ACroBAT uses a range of agronomically important variables, including the size of the migrating aphid population, varietal choice, the proportion of migrating aphids carrying the virus, and information on crop economics. The majority of the input factors are readily available to growers/advisors, while others (e.g. migrating aphid numbers, temperature and percentage of viruliferous aphids) could be sourced externally (e.g. by linking with RIS data sources, weather applications), as occurs with the AHDB T-sum tool. ACroBAT is currently in beta-version form, with an interface suitable for research purposes but it could be readily adapted into a web or phone app service, with an improved interface. The spray DSS is designed for use once the crop has been sown and can be used as frequently as desired to provide guidance on the need for sprays and their optimal timing. The cultural control DSS is designed for use as far in advance of drilling as desired, to assist in making choices that can reduce risk, e.g. field selection, drill date and varietal choice.

Researchers have long endeavoured to include a range of relevant risk factors in DSS for estimating BYDV risk (Salinari & Holland, 2019) but it has been acknowledged that understanding the percentage of viruliferous aphids present at any one time has been a key missing element (Harrington et al., 1999; Dedryver et al., 2010). This has primarily been because ascertaining this information was time-consuming and expensive, with results taking weeks to generate, by which time the opportunity to act on them is passed. With the RT-PCR method used in this project, this data can be generated in days and relatively cheaply, allowing it to be used an input into DSS. ACroBAT is the first time this information has been used in DSS to generate guidance for growers, advisors and others in the industry. As evident from the scenario work (Section 4.3.1), aphid infectivity within the range seen in field work (Obj. 1) can have a considerable impact on the rate of crop infection, whether an insecticide is required and the timing of application.

The numbers of migrating *R. padi* can vary dramatically between years and locations, with five-fold differences in years within the last two decades and three-fold differences between regions (see Fig. 55 and 56 respectively in Section 3.4.1). Accounting for this variation in pest pressure is an important element of BYDV management. ACroBAT showed that a 95% reduction in migrating aphid numbers can delay a spray recommendation by a month and reduced infection by the end of the autumn by 74% (Section 4.3.1). The interrelationship between aphid numbers and the percentage viruliferous can have even greater impacts on risk. The scenario work (Section 4.3.1) showed that if migrating aphid numbers were low and only a small proportion carried the virus then this can result in a 96% reduction in crop infection and a spray delay of at least one month.

The inclusion of farm-specific economics is a key element of the DSS, being used in the risk sub-model in which risk is described as an economic threshold model. The farm-specific economics are used to determine the break-even incidence, i.e. the proportion of the crop infected at which it is economical to spray to prevent further infection and, in turn, yield loss. For example, the more expensive the treatment cost, the larger the break-even virus incidence. Conversely, the larger the grain price or yield, the smaller the break-even incidence. This is demonstrated in the treatment cost and grain price scenario sections (4.3.1), where more expensive insecticides both delayed sprays and increased the amount of crop that needed to be infected before a spray was recommended, while increasing grain price had the opposite effect. It's worth adding that treatment costs could be reduced if the insecticide is applied as a tank mix with a herbicide, but if this is applied at the optimum timing for weed control then this is likely to be a suboptimal timing for BYDV control (IRAG, 2021a). The interrelationship between farm-specific economics and spray recommendations is an important one; most treatment thresholds in the UK are economic thresholds, i.e. that the reduction in income due to pest damage is greater than the treatment cost (Ramsden et al., 2017a). However, very few current thresholds actually respond to changes in either crop value or treatment costs, despite both being highly variable. For example, grain price has fluctuated considerably in recent years (AHDB, 2023d), and while pyrethroids are relatively cheap, if they became unavailable (due to regulation) or ineffective (due to resistance), alternatives are likely to be several times more expensive. Thresholds are central to IPM and adapting more thresholds to be dynamic in this way could make a large difference to the number of sprays being applied.

Delaying drill date is a key tool for reducing BYDV risk. It reduces the window of aphid migration to which the crop is exposed, and it means that aphids in the crop experience lower temperatures, in turn reducing secondary spread throughout the crop. Its importance is clearly demonstrated in the scenario work (Section 4.3.1), where delaying drilling from the start of September until the of the month resulted in a 97% reduction in disease by mid-November and a delay in treating by over two months. There are trade-offs with yield to be considered when contemplating a later drill date (Plumb, 1983; McKirdy & Jones, 1997; Spink et al., 2000), although these are not always seen (McGrath & Bale, 1990; McKirdy & Jones, 1997; Royer et al., 2005). Additionally, the choice of drill date is not always simple, with rotation and weather having an important influence. The ACroBAT cultural control DSS can be useful for exploring the impact of sow date on BYDV for specific crops, while the ACroBAT spray DSS can help guide sprays in both the most vulnerable, early drilled crops and less vulnerable later drilled crops.

The relatively recent availability of barley varieties tolerant to BYDV means that plant breeding can now form part of a BYDV IPM programme. By integrating them into the DSS, their importance and interaction with other control measures can be investigated by the user. However, it is accepted their integration into the ACroBAT DSS can likely be improved, and this is achievable with additional data on yield response to the virus. Wheat lines resistant to BYDV are also now available and, with suitable datasets on yield response, these could also be integrated relatively simply. Finally, autumn and winter weather have been key drivers of changes in pest pressure in recent years, e.g. the increase in cabbage stem flea beetle larval pressure due to milder winters (White et al., 2020). It is likely that global temperatures will increase by several degrees Celsius in the next decades (IPCC, 2023), which will have important consequences for UK agriculture (Harkness et al., 2020). The scenario work done using ACroBAT (Section 4.3.1) illustrates the impact even a 10% increase in temperature will have on BYDV management, increasing the rate of crop infection and the need for insecticide applications considerably.

4.4.2. Validation of ACroBAT

The performance of ACroBAT was validated using three methodologies: comparing predicted BYDV infections with those in crops in the spring, naturally infested tramline trials and an artificially inoculated plot trial. ACroBAT was found to accurately predict BYDV infections in the spring in untreated crops, achieving a R^2 of 72.2 and accounting for the majority of the variance. As the model predicts the proportion of crop infected but was validated using visual symptoms of BYDV, it is possible that symptoms caused by something else could be mistaken for BYDV or that asymptomatic BYDV was present, either of which would mean that the accuracy of the DSS may seem to be lower than it is. Molecular tests would improve such validation. Additionally, this validation used five-year average data on weather and immigrating aphid numbers so it is possible that performance could be improved by using actual weather and aphid data from the nearest suction trap for each site. It is accepted that validation at a greater number of sites than featured here (32 crops across England)

and in years or locations with higher virus levels would improve confidence in predictions and help identify situations in which prediction is poor.

Two tramline trial designs were conducted: one in which sprays according to ACroBAT were compared with those according to T-sum and an untreated control, and the other involving BYDV-tolerant and susceptible barley varieties onto which sprays according to ACroBAT and an untreated control were overlayed. Very few aphids were seen in these trials and so the performance of the DSS cannot be evaluated in terms of aphid control, however considerable BYDV symptoms were sometimes seen despite this, demonstrating the difficulty in finding aphids even for experienced research scientists. In all trials, ACroBAT performed well compared to the untreated controls, reducing BYDV symptoms and increasing yield when anything other than negligible BYDV symptoms were present in the untreated tramlines. In the first year of DSS trials (2020/21), ACroBAT performed moderately well in comparison to T-sum, producing similar levels of BYDV control but slightly poorer yields and economic benefit (although where notable BYDV symptoms were observed, in trial 3, ACroBAT provided better BYDV reductions and higher yield). However, it should be borne in mind that the ACroBAT DSS underwent an improvement after these trials, in which the proportion of aphids in suction traps that are anholocyclic were better accounted for, resulting in ACroBAT being less conservative. This means that the version of ACroBAT tested in the 2020/21 was not the final version, being liable to overpredict risk and recommend more sprays than needed.

In the 2021/22 DSS trials, ACroBAT performed better against T-sum, producing a greater reduction in BYDV symptoms in the trial in which reasonable BYDV symptoms were recorded in the untreated tramlines. Importantly, ACroBAT recommended half as many insecticide applications as T-sum, resulting in a slightly higher economic benefit overall. In one trial, ACroBAT did not recommend any sprays at all (trial 6), something that is essentially impossible with T-sum, and no BYDV symptoms were subsequently recorded. However, T-sum did produce a significant yield increase in trial 7, despite negligible BYDV symptoms being present in the untreated control.

In the DSS x variety tramline trials, featuring tolerant and susceptible barley varieties, ACroBAT performed consistently well. In susceptible varieties, BYDV symptoms were significantly lower in all trials and yield increased in all but one trial in which BYDV symptoms were non-negligible in the untreated. The benefit of tolerant varieties is also evident in these trials, with significant reductions in BYDV symptoms and increases in yield whenever BYDV symptoms in the untreated were non-negligible. The lowest disease symptoms were generally seen when ACroBAT was used in combination with varietal tolerance, although this rarely resulted in a yield increase. Across all the trials, ACroBAT tended to provide an economic benefit.

Other than the overall satisfying performance of the ACroBAT, there were some other observations to be made from these trials. In several trials (e.g. trial 7, Ashcombe 1 and Ashcombe 3), significant yield benefits from DSS were seen despite negligible BYDV symptoms in the untreated tramlines, suggesting the possibility of asymptomatic BYDV in the untreated or incidental control of another pest due to the DSS-recommended sprays. Additionally, the difference in BYDV symptoms between trials in neighbouring fields was occasionally stark (Starcross 1 and 2), illustrating the variability in aphid pressure across small distances and the reinforcing the case for monitoring at the field level. Lastly, the majority of these trials experienced low BYDV pressure despite placing them in areas that are traditionally considered high risk, which was disappointing and made a rigorous assessment of DSS performance difficult.

It was because of the low levels of BYDV in naturally infested trials that we chose to carry out a plot trial in which viruliferous *R. padi* were artificially inoculated. In terms of the reductions in BYDV symptoms, the clearest benefit can be seen in the tolerant barley variety (Rafaela), however reductions due to the DSS or calendar spray programme were disappointing. Only T-sum resulted in a significant reduction but even this (25% reduction in disease) would be considered inadequate. Nevertheless, both DSS and the calendar spray programme resulted in significant yield benefits in the BYDV-susceptible variety, with ACroBAT providing a clear economic benefit over the alternatives. In hindsight, we are not sure that this inoculation trial was a fair test of either the ACroBAT or T-sum DSS. Both assume that crop infestation, and so primary infection, begins with relatively small numbers of alate aphids, whereas the trial begun with a relatively high numbers of apterous aphids and nymphs. We made adjustments to both models in an attempt to account for these differences but the resulting levels of BYDV symptoms leads us to believe that these adjustments were not sufficient to account for these fundamental differences from a "normal" naturally infested crop.

Overall, ACroBAT performed well in these trials. BYDV symptoms were reduced in a consistent and generally marked manner and yields improved where BYDV was present. Performance of the final version was as good as, if not better than, the T-sum tool. Importantly this was accompanied by fewer insecticide applications, which has several benefits. Firstly, the overall lower treatments costs tended to provide a greater economic benefit. Secondly, achieving the same control with fewer insecticide applications has wider benefits. Applying fewer insecticides reduces the selection pressure for stronger or new forms of resistance to appear in *R. padi* or *S. avenae* (IRAG, 2021b). Such an outcome also results in fewer impacts to non-target organisms, with the potential that this will increase populations and activity of natural enemies of BYDV vectors, in turn reducing BYDV infection further. Finally, fewer spray operations mean lower greenhouse gas emissions, e.g. due to lower diesel usage. It would be remiss to pretend, however, that this validation conclusively demonstrates that accuracy of ACroBAT; BYDV pressure was generally low in these trials. Additionally, the DSS was not well tested in early drilled crops. Both of these issues ought to be addressed.

4.4.3. Key considerations and areas for improvement

ACroBAT appears to be a useful tool, however there are several areas of the ACroBAT DSS that are worth considering.

- In general, most of the parameter values used in the models that comprise ACroBAT are based on experiments conducted in the 1970s, 80s and 90s. This does not mean that they are not relevant but certainly some warrant revisiting, for instance where crop varieties or aphids clones have changed.
- Sensitivity analysis in Morgan (2000) identified that aphid survival rates had the largest influence on predicted population dynamics, e.g. decreasing mortality by 5% will lead to a 60-fold increase in aphid density. As there was no experimental data available at the time to quantify survival, mortality rates were assumed to be a function of the number of days degrees below 2.8°C, which was derived from the effects of low temperatures in field conditions. Other studies have looked at the relationship between accumulated temperature below a theoretical threshold and aphid densities (Dewar and Carter., 1984) or examined aspects of survival in laboratory conditions (Griffiths and Wratten., 1979; Williams, 1980; Powell & Bale, 2005; Alford et al., 2014) and field conditions (Knight, 1987; Williams, 1987; Williams & Wratten, 1987; Fabre et al., 2010) but interpretation of these results is deemed complex (Knight, 1987, McDonald et al., 1997, Morgan., 2000; Alford et al., 2014). Nevertheless, this parameter may be worth further work to improve model accuracy.
- Aphid survival is also influenced by the presence of natural enemies, which is not accounted for in the model. Inclusion of natural enemies, such as Coccinellidae, would result in a net loss to the aphid population (Skirvin, 1995). However, the effectiveness of predators is dependent on both the density of the natural enemy compared to the density of the aphid population and both species having coinciding phenology (Morgan, 1990). Recent work as part of the annual Defra Survey of Crop Pests & Diseases has shown that natural enemies are present winter wheat crops in appreciable numbers in the autumn (this data will soon be available at https://www.pestanddiseasesurvey.co.uk/). Natural enemies can also impact virus transmission by affecting the between-plant movement of aphids. Depending on the natural enemy, this has been shown to increase or decrease the rate of virus spread (Lykouressis & van Embden, 1983; Bailey et al., 1995; Smyrnioudis et al., 2001). Due to the lack of suitable data at the point of model development the impact of natural enemies was not included.

- Rain and wind have been found to influence aphid survival and movement (Araya & Fereres, 1991; Bailey et al., 1995; Mann et al., 1995). However, neither are accounted for in the Morgan (2000) model as little is known about the magnitude of the impact on aphid species and the influence of other factors such as available shelter and crop growth stage (Morgan, 1990). Given the frequency of wind and rain events in the autumn, these are parameters that are worth further work to determine their importance for the DSS.
- There is no explicit temperature threshold in Morgan (2000) below which *R. padi* does not develop, reproduce, move or fly, whereas Kendall et al. (1992) assumes aphid activity to cease below 4°C. As there is now a wealth of work demonstrating the importance of temperature on development, reproduction, movement and flight in cereal aphids (Dean, 1974; Walters & Dixon, 1984; Williams, 1987; Smyrnioudis et al., 2000; Wiest et al., 2021), future versions of the model should consider making the two models consistent in this area.
- The Morgan (2000) model was only developed to predict aphid numbers for *R. padi* on barley crops. It therefore does not encompass the impact of other aphid species such as *Sitobion avenae* or population dynamics on other crops such as on wheat. Although several models for *S. avenae* exist, they primarily focus on either spring sown crops or on population dynamics in the summer (Skirvin et al., 1995; Duffy et al., 2017), and do not represent the autumn and winter dynamics sufficiently to be included in ACroBAT. While *S. avenae* tends to be less numerous than *R. padi* in the autumn, it can tolerate low winter temperatures better than *R. padi* meaning that it can be an important cause of secondary spread (Mann et al., 1995). Further work could endeavour to include *S. avenae* in the model by establishing whether reliable data for parameterising this species in autumn/winter conditions exists in the literature or, if these are not available, carrying out experiments to generate this data. However, a key challenge will be determining the arrival and presence of *S. avenae* in crops as a model input. As discussed in Section 3.4.1, this species tends to be caught at low numbers in suction traps and in-field traps, meaning that initial *S. avenae* numbers may need to be determined through laborious on-plant assessments. Harrington et al. (1999) recognised this challenge in modelling *S. avenae* and suggested seeding the model with a constant, low number of the species when suction trap catches are low.
- The Morgan (2000) model relies on suction trap data to determine alate *R. padi* immigration. Their calculation is based on work by Taylor & Palmer (1972), which is not species specific. Furthermore, work in Objective 1 suggests that suction trap data on *R. padi* numbers is only reliable up to 10-20 km away. If so, this would have a substantial impact on the number of fields likely to be further away than this (see Figure 59 in Section 3.4.3) and therefore those needing in-field monitoring to accurately determine alate immigration. Currently, the model uses only suction trap data as the input for aphid pressure, and so would need adapting to allow users to input data on aphid numbers based on in-field monitoring. Additionally, as

discussed in Section 4.2.4, the relationship used to calculate the number of anholocyclic *R. padi* (Harrington et al., 2012) is based on data from the Rothamsted suction trap and it is uncertain whether this relationship applies to other suction traps.

- The virus epidemiology sub-model (Kendall et al., 1992) relies on several parameters to fit the data, many of which were calculated from field observations of infestation between 1978-89 and validated in one locality. When describing the relationship between plant infestation and the density of aphids found in crops during the field experiments it is shown that it would only require a mean of 7 apterous aphids per plant to result in 90% of the plants infested. Future work could revisit these parameterisations and rederive the values of the aggregation coefficients from more recent field data.
- Kendall et al. (1992) uses a single value for their "infectivity of migrant aphids" input for their model. To represent this in ACroBAT, the use of the parameter "initial infectivity" was added as an input in the model to drive initiation of BYDV infection but does not change throughout the season. It is likely that Kendall et al. (1992) used a single value for this parameter due to the difficulty in establishing the proportion of aphids carrying the virus (percentage viruliferous) at the time of developing their model. The RT-PCR assay used in this project allows for percentage viruliferous to be determined throughout the season. Therefore, a future improvement would allow for the user to adjust the percentage viruliferous value on a weekly basis (or however often this information is available). Additionally, Kendall et al. (1992) always assumed at least 5% of aphids were viruliferous, presumably because of the limitations in determining the true value but also because of the importance of this value in simulating crop infection. This was not included in ACroBAT due to the availability of the RT-PCR assay but work in Objective 1 has shown that percentage viruliferous is somewhat variable over time, suggesting that in weeks in which no aphids are found to carry BYDV there are likely to be some, and so it is possibly prudent that this lower limit on percentage viruliferous should be reinstated.
- The Kendall et al. (1992) model does not include any effect of temperature, virus strain, aphid species, aphid morph and feeding duration on the likelihood of infection (Van der Broek & Gill, 1980; Gray et al., 1991; Guo & Moreau, 1996; Lowles et al., 1996; Lowles et al., 1997). All of these, especially temperature, could have an important effect on epidemiology and should be considered for inclusion in future versions of the model. BYDV infection can also encourage the development of alate aphids in *R. padi* and *S. avenae,* potentially facilitating a greater spread of aphids within a crop as crop infection increases (Gildow, 1980; Gildow, 1983; Rozo-Lopez & Parker, 2023). The effect on the speed of spread of BYDV has not been studied and future work can investigate this and its effect on vector management.
- The Yield-Virus Relationship (YVR) for each crop has an important influence on the break-even virus incidence (the economic treatment threshold). The value for barley (0.62) means

that it is more susceptible to BYDV than wheat crop (0.165). These values are fixed and based on 6 research papers for barley and 2 for wheat, all of which use data from trials occurring between 1981-1998. Further research on yield impact would allow for these parameters to be updated and model reliability to be improved. Additionally, further trial data on the YVR for resistant and tolerant varieties could allow these to be better incorporated into the model.

- The risk categories used in the MAFF (2001) model (see Table 17 in Section 4.2.3) relate the current level of crop infection to the break-even virus incidence. ACroBAT recommends that an insecticide application is considered when a "medium risk" is predicted. However, this category is only reached when the virus incidence is at 95% of the break-even incidence, potentially leaving little time to make a spray decision and apply the insecticide. It is possible that adjusting these categories slightly may be of practical benefit to growers, e.g. adjusting the "medium risk" category to be between 80% and 130% of the break-even incidence.
- The risk sub-model uses field location data (distance from sea and surrounding land use) to adjust the predicted risk (the proportion of crop infected). This was originally done as part of DESSAC (MAFF, 2001) to tailor their regional risk maps to specific fields. These factors are likely proxies for other causal mechanisms, e.g. coastal climate and virus pressure (Foster et al., 2004), which might be accounted for elsewhere in ACroBAT. Therefore, it is possible that this element of the model is unnecessary.
- The model does not account for the timing of virus infection, however Kendall et al. (1992) recognised that this is an important factor in determining subsequent yield loss. Infection at earlier growth stages have a greater yield impact than at later growth stages (Smith, 1967; Doodson & Saunders, 1970). This could be considered for inclusion in future versions of the model.
- There are data availability and resolution limitations in regards the ACroBAT cultural control DSS. The model was not designed to access predictive weather and aphid data through an API and therefore five-yearly averages were used as a substitute to gauge future risk. Although this is a suitable proxy for the purposes of the project, the input files will have to be updated every year to have the most recent average data, and to make sure climate and aphid trends are being captured accurately. Data availability and computational power limited the resolution of the weather data to 5 km. This had coverage for the whole of the UK so was deemed appropriate for use within the model. However, future improvements could include the capability of the farmer or user to input weather information themselves (e.g. from an onsite weather station) to increase accuracy.
- The DSS does not include a component to account for product persistence, but this can be readily included in future versions.

- As detailed in Section 4.2.4, the model switches to an adjusted T-sum model after the first spray because the MAFF (2001) risk sub-model calculates when the economic treatment threshold is reached, meaning that any further BYDV infection, no matter how minimal, would immediately be above treatment threshold. This may not be an ideal solution to this problem. An alternative would be for ACroBAT to predict a spray programme, involving multiple sprays if necessary, with the objective of avoiding the break-even virus incidence being reached. However, this would necessitate the prediction of aphid migration and weather data months in advance, which is currently not possible with any reasonable level of confidence. This means that any spray programme generated would likely be highly unreliable.
- The three models (Kendall et al., 1992; Morgan, 2000; MAFF, 2001) were devised and validated individually under different conditions. While Morgan (2000) and MAFF (2001) were designed to form part of the DESSAC DSS suite, Kendall et al. (1992) was not designed to be compatible with them. As a result, and despite good performance in the validation work, the use of ACroBAT has the potential to produce unreliable results.

4.5. Conclusions

- ACroBAT DSS is a tool allowing for simulation of BYDV disease progression and risk assessment. It comprises three previously developed models and two functions: 1) a spray support DSS, for use once the crop has been sown to provide guidance on the need for sprays and their optimal timing, and 2) a cultural control DSS, for use as far in advance of drilling as desired, to assist in making choices that can reduce risk, e.g. field selection, drill date and varietal choice.
- The model accounts for a range of important variables relevant to BYDV management, e.g. drill date, aphid pressure, the proportion of aphids carrying the virus, varietal tolerance and crop economics.
- ACroBAT was able to accurately predict BYDV symptoms in surveys of untreated crops. In tramline and plot trials, BYDV symptoms were reduced in a consistent and generally marked manner and yields improved where BYDV was present. Performance of was as good as, if not better than, the T-sum tool, but used fewer insecticides.

5. Future work

- ACroBAT has been validated in 2020/21 and 2021/22, performing well, but BYDV pressure was mostly low. It is strongly recommended that further validation take place to test the DSS, especially in early drilled crops in areas of high risk. Such an approach would give greater confidence to users, were the DSS to become widely available.
- A variety of model improvements are listed in Section 4.4.3 but below are those we consider to be the most important:
    - Include *S. avenae* population dynamics and BYDV infection. Initially identify whether suitable data exists for use in parameterisation, or else conduct experiments to generate this data.
    - Include a lower temperature threshold for aphid life history parameters, a lower limit on the percentage of viruliferous aphids and product persistence, and allow data on in-field aphids numbers and on-farm weather data to be input and the percentage of viruliferous aphids to be input weekly. All of these are relatively simple modifications.
    - Re-evaluate the Yield-Virus Relationship for each crop and for resistance and tolerant varieties. The latter especially would allow resistant/tolerant varieties to be better integrated into the DSS. Resistant/tolerant varieties are relatively new and represent potentially key components of BYDV IPM, but understanding their role and interaction with other elements of BYDV management and wider agronomy is important. Only BYDV-tolerant winter barley was included in this project, but BYDV-resistant wheat should also be included in the DSS, as such varieties are now available.
    - Reassess the simulation of aphid survival in different climatic situations, including the impact of rain on aphid survival and spread within a crop.
    - Include the impact of natural enemies. This would improve the simulation of aphid survival, and so the ACroBAT spray DSS, but could also be included in some form in the ACroBAT cultural control DSS, allowing growers to input different levels of natural enemy activity and understand the impact this would have on their risk. See below for more on natural enemies.
    - Investigate whether including timing of infection and the effect of temperature on infection can better simulate epidemiology and yield impact.
- Currently, the user interface for ACroBAT is basic, being as needed for the purposes of this research and validation. If it were to be made available to growers/advisors, the interface should be modified to improve ease of use, e.g. by allowing inputs for to be saved for different fields. Consideration should also be given to providing an option for a simplified set of inputs, with some being set to defaults, which would save time in running the model. This can include automatic inputs of weather and local suction trap data based on location. Lastly, the format in which model outputs are provided could also be improved by providing graphics of disease

progress and spray programmes. Further inclusion in networks such as IPM Decisions (https://www.ipmdecisions.net/) can increase the visibility of the DSS and assist in farm-wide use of DSS for various crops and pest problems.

- Further work is needed to continue monitoring the percentage of viruliferous aphids from more suction traps, identify risks in early sown winter cereals, and provide training on aphid identification to growers/agronomists.
- Validate the relationship between the proportion of anholocyclic *R. padi* forms and the previous winter temperature (Harrington et al., 2012) at sites other than Rothamsted.
- Investigate whether the percentage of aphids carrying the virus can be accurately predicted using an adapted version of Fabre et al. (2005), in which non-small grain cereal hosts that are more prevalent in the UK, such as perennial grasslands are included.
- Where fields are located beyond the zone of reliability of the suction traps, it should be investigated whether in-field traps are representative of a wider area or at a field scale only. Such information is important for accurate DSS predictions.
- While effective pest monitoring and DSS to support management decisions are crucial components of BYDV management, other potentially important components are less well understood. Several research priorities in this regard are:
    - Understanding the benefit and reliability of minimum tillage in reducing BYDV pressure.
    - Investigating whether intercropping or companion cropping can reduce primary infection and secondary spread of the virus.
    - Insecticide or biopesticides that are less lethal but have important sub-lethal effects (e.g. slowing reproduction or reducing movement between plants) may be just as effective as more lethal, traditional insecticides in controlling BYDV spread. Such products are also likely to have fewer non-target impacts, and so maximise natural enemy activity. The performance of such products could be readily tested using ACroBAT (e.g. by assessing the impact of a slower reproductive rate) and ultimately included in the DSS if registered.
    - Updating guidance on control of the ‘green bridge’ in light of current weed control methods.
    - Investigating the potential for trap cropping to reduce primary infection.

6. Project conclusions

BYDV control has changed dramatically in recent years, with current management little different from that forty years ago. This project aimed to improve monitoring of BYDV vectors and develop DSS to assist in management decisions. The project found that data from suction traps on aphid numbers may be reliable to nearby growers within a smaller radius than previously thought, but that in-field monitoring using water traps are an effective substitute. Monitoring of the percentage of aphids carrying the virus found this to be higher than in previous surveys and that suction trap data on this important variable is reliable to surroundings farms within a 40 km radius. These results were used to propose a BYDV monitoring scheme. A DSS, ACroBAT, was developed to guide spray decisions and the use of cultural control. ACroBAT uses a range of important input parameters for predicting risk, including aphid pressure, the percentage of aphids carrying BYDV and crop economics. ACroBAT performed well in validation work, providing effective control of BYDV, improving yields where substantial BYDV was present, increasing gross margin and recommending fewer insecticides that the T-sum DSS. ACroBAT has the potential to be a useful tool for growers and advisors. With improved monitoring, effective support for decision-making and the increased availability of BYDV tolerant/resistant varieties, the future for BYDV management is promising.

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9. Appendix

Table 1: *Site details for suction trap monitoring sites each autumn in 2019, 2020 and 2021. * represents where information is not available.*

Year	Suction trap	Location	Cardinal direction	Distance from suction trap (km)	Coded distance (km)	Crop	Variety	Sow date
2019	Broom's Barn	Feltwell	N	24	20	WB	*	11/10/2019
2019	Broom's Barn	Haddenham	NW	36	40	WW	*	21/10/2019
2019	Broom's Barn	Hollybush	SE	25	20	WW	*	10/10/2019
2019	Broom's Barn	Lidgate	SW	43.62	10	WW	*	10/10/2019
2019	Broom's Barn	Methwold	N	30	40	WB	*	03/10/2019
2019	Broom's Barn	Silver Fern	W	18	20	WW	*	10/10/2019
2019	Broom's Barn	Stetchworth	W	15	20	*	*	*
2019	Broom's Barn	Thriplow	SW	37	40	WW	*	22/09/2019
2019	Broom's Barn	West Row	NW	10	10	WW	*	20/10/2019
2019	Broom's Barn	Westhorpe	E	29	40	WW	*	18/09/2019
2019	Newcastle	Bothal	SE	8	10	WW	*	19/09/2019
2019	Newcastle	Cresswell	E	10	10	WW	*	19/09/2019
2019	Starcross	Stevens Cross	E	19	20	WB	California	23/10/2019
2019	Starcross	Bulleigh Barton	SW	20	20	WW	California	15/09/2019
2019	Starcross	Crediton	N	38	40	WW	Elation	08/10/2019
2019	Starcross	East Allington	SW	40	40	WW	*	22/10/2019
2019	Starcross	Exminster	NW	7.5	10	WW	Momento	15/09/2019
2019	Starcross	Hill Barton	N	11	10	WW	Marsdon	17/10/2019
2019	Starcross	Okehampton	NW	40	40	WW	*	01/10/2019
2019	Starcross	Shapwick Grange	E	40	40	WB	Cassia	23/10/2019
2019	Starcross	Starcross	SW	6	10	WW	*	01/10/2019
2019	Starcross	Stokeinteignhead	SW	12.5	10	WW	Graham	28/10/2019
2019	Starcross	Tedburn St. Mary	NW	20	20	WW	Costello	23/09/2019
2019	Starcross	Washfield	N	38	40	WB	Cassia	21/10/2019
2020	Hereford	Ashton	N	18	20	WW	*	01/10/2020
2020	Hereford	Bishops Frome	E	9.5	10	WW	Graham	27/09/2020
2020	Hereford	Brobury	W	24	40	WW	*	25/09/2020

Year	Suction trap	Location	Cardinal direction	Distance from suction trap (km)	Coded distance (km)	Crop	Variety	Sow date
2020	Hereford	Docklow	N	9.8	10	WW	*	16/10/2020
2020	Hereford	Droitwich	NE	37	40	WW	*	20/10/2020
2020	Hereford	Fownhope	S	14	10	WW	*	01/10/2020
2020	Hereford	Gt Witley	NE	32	40	WB	Bazooka	19/09/2020
2020	Hereford	Howcaple	S	20	20	WW	Barrel	20/09/2020
2020	Hereford	Moreton	W	6.3	10	WW	Graham	27/09/2020
2020	Hereford	Sarnesfield	NW	20	20	WW	*	13/10/2020
2020	Hereford	Suckley	E	16	20	WW	Gravity	25/09/2020
2020	Hereford	Tewkesbury	NW	33	40	WW	*	16/10/2020
2020	Starcross	Stevens Cross	E	19	20	WB	Sensation	01/10/2020
2020	Starcross	Bulleigh Barton	SW	20	10	WW	California	13/10/2020
2020	Starcross	Crediton	N	16.3	20	WB	Cassia	29/09/2020
2020	Starcross	East Allington	SW	36.5625	40	WW	Graham	28/09/2020
2020	Starcross	Exminster	NW	7.5	10	WW	Graham	16/10/2020
2020	Starcross	Hill Barton	N	11	10	WB	Idyllic	30/09/2020
2020	Starcross	Okehampton	NW	40	40	WB	Cassia	26/09/2020
2020	Starcross	Shapwick Grange	E	40	40	WB	Cassia	23/10/2020
2020	Starcross	Starcross	SW	6	10	WW	Graham	17/09/2020
2020	Starcross	Stokeinteignhead	SW	12.5	20	WB	Orwell	28/09/2020
2020	Starcross	Tedburn St. Mary	NW	20	20	WW	JB Diego	20/09/2020
2020	Starcross	Tiverton	N	38	40	WW	Theodore	26/09/2020
2020	York	East Harlsey	N	47	40	WW	*	05/10/2020
2020	York	Full Sutton	SE	8.5	10	WB	Cresswell	29/09/2020
2020	York	Gardham	SE	32	40	WB	Craft	25/09/2020
2020	York	Huggate	E	25	20	WW	*	10/10/2020
2020	York	Huttons ambo	NE	14	10	WB	*	25/09/2020
2020	York	Newton on Ouse	W	16	20	WW	Graham	25/09/2020
2020	York	Pockley	N	28	20	WB	Craft	29/09/2020
2020	York	Riccall	S	19	20	WW	*	29/09/2020
2020	York	Rudston	E	41	40	WW	Spotlight	08/10/2020

Year	Suction trap	Location	Cardinal direction	Distance from suction trap (km)	Coded distance (km)	Crop	Variety	Sow date
2020	York	Skelton	W	10	10	WW	Graham	21/09/2020
2020	York	Stockton in the Forest	SW	5	10	WW	*	21/09/2020
2020	York	Ulleskelf	SW	25	40	WW	*	05/10/2020
2021	Broom's Barn	Burnt Fen	NW	19.54	20	*	*	*
2021	Broom's Barn	Clacton	SE	61.09	40	*	*	*
2021	Broom's Barn	Cranworth	NE	45	40	*	*	*
2021	Broom's Barn	Depden	S	8.34	10	*	*	*
2021	Broom's Barn	Elmsett	SE	35.26	40	*	*	*
2021	Broom's Barn	Feltwell	N	26.48	20	*	*	*
2021	Broom's Barn	Haddenham	NW	36.18	40	*	*	*
2021	Broom's Barn	Risby	NE	3.4	10	*	*	*
2021	Broom's Barn	Stetchworth	W	14.67	10	*	*	*
2021	Broom's Barn	Thriplow	SW	37.35	40	*	*	*
2021	Broom's Barn	Westhorpe	E	29.83	20	*	*	*
2021	Broom's Barn	Westley	W	18.6	20	*	*	*
2021	Hereford	Ashton	N	17.85	20	*	*	*
2021	Hereford	Bishops Frome	E	9.11	10	WB	*	29/09/2021
2021	Hereford	Brobury	W	22.67	40	WW	*	01/10/2021
2021	Hereford	Docklow	N	9.65	10	WB	*	26/09/2021
2021	Hereford	Fownhope	S	14.15	10	WW	*	27/09/2021
2021	Hereford	Kinver	NE	8	40	WW	*	01/10/2021
2021	Hereford	Moreton	W	6.38	10	*	*	*
2021	Hereford	Overton	N	11.4	10	*	*	*
2021	Hereford	Sarnesfield	NW	19.68	20	*	*	*
2021	Hereford	Sellack	S	20.12	20	WB	Rafaela	20/09/2021
2021	Starcross	Stevens Cross	E	18.21	20	WB	Flynn	11/10/2021
2021	Starcross	Bulleigh Barton	SW	13.85	10	WB	Orwell	30/09/2021
2021	Starcross	Crediton	N	21.06	20	WW	Sundance	26/09/2021
2021	Starcross	East Allington	SW	39.33	40	WW	Graham	14/10/2021
2021	Starcross	Exminster	NW	5.0975	10	WB	Tardis	11/10/2021

Year	Suction trap	Location	Cardinal direction	Distance from suction trap (km)	Coded distance (km)	Crop	Variety	Sow date
2021	Starcross	Hill Barton	N	9.3	10	WW	Extase	01/10/2021
2021	Starcross	Okehampton	NW	40.08	40	WB	Cassia	23/09/2021
2021	Starcross	Shapwick Grange	E	34.8	40	WB	Valerie	14/10/2021
2021	Starcross	Starcross	SW	6.26	10	WB	California	*
2021	Starcross	Stokeinteignhead	SW	20.29	20	WB	California	25/09/2021
2021	Starcross	Tedburn St. Mary	NW	21.98	20	WW	Costello	22/09/2021
2021	Starcross	Washfield	N	35.19	40	WB	Flynn	22/09/2021
2021	York	Full Sutton	SE	8.34	10	WB	Orwell	07/10/2021
2021	York	Gardham	SE	31.9	40	WW	Gleam	23/09/2021
2021	York	Huggate	E	17.68	20	WW	*	10/10/2021
2021	York	Menethorpe	NE	14.77	10	WB	*	25/09/2021
2021	York	Overton	W	40.93	40	WW	*	10/10/2021
2021	York	Pockley	N	30.31	20	WB	Mountain	15/09/2021
2021	York	Riccall	S	19.63	20	WW	*	10/10/2021
2021	York	Shipton	W	10.27	20	WB	Craft	20/09/2021
2021	York	Stockton in the Forest	SW	3.8	10	*	*	*
2021	York	Thornholme	E	44.09	40	WB	Craft	14/09/2021
2021	York	Ulleskelf	SW	23.45	40	WB	*	28/09/2021
2021	York	Winton	NW	46.84	40	WB	Valerie	21/09/2021