E-PREP IMPACT REPORT

COMBINED BACTERIAL AND VIRAL INFECTION EPIDEMICS: EXAMINING THE EVIDENCE AND APPROPRIATE RESPONSES TO PROTECT CROP HEALTH (E-PREP).

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Photo: Sugar beet clamp. © James Bell

About E-Prep

The E-Prep team are funded by UKRI under the project titled "*Combined bacterial and viral infection epidemics: Examining the evidence and appropriate responses to protect crop health (E-Prep)*" **MR/Z50581X/1**. The project began on 1st September 2024 and is due to complete its objectives the 31st May 2025. Twelve investments were made by UKRI of which E-Prep is the only project wholly dedicated to plant health.

This seed funding is phase one of a flagship investment to better prepare for future epidemics as part of the UKRI Tackling Infections strategic theme. The purpose of the nine-month project is to assemble a core team and identify a challenge area that would benefit from an interdisciplinary approach.

E-Prep Vision and Aim

Our vision is to tackle the core topics of vector-borne viral and bacterial diseases in agriculture and horticulture. We use sugar beet as an exemplar system in which Virus Yellows (VY) and Syndrome Basses Richesses (SBR), a proteobacterium and phytoplasma complex, threaten UK and European productivity. The main project aim is to create a roadmap for future research, growers, business and policy.

E-Prep Stakeholders' event

E-Prep team hosted a stakeholders' event at Friends House on the January 10th, 2025. The event comprised E-Prep team members, see below, and key stakeholders in agriculture. The facilitator for the event was Seth Reynolds, an independent consultant.

E-Prep Team

E-Prep Team members funded by MR/Z50581X/1

Project lead		
Prof. James Bell	Keele University	Entomologist
Project co-leads		
Dr Lawrence Bramham	Rothamsted Research	Virologist
Prof. Chris Bass	University of Exeter	Molecular entomologist
Dr Junfeng Gao	University of Aberdeen	Agri-Robotics
Dr Jennifer Hodgetts	Animal and Plant Health Agency	Phytoplasma research
Dr Alice Milne	Rothamsted Research	Mathematician
Prof. Damian Maye	University of Gloucestershire	Social science
Prof. Alan Stewart	University of Sussex	Entomologist
Dr Trisna Tungadi	Keele University	Virologist

For transparency, we include Dr Sara Vestergren, a psychologist formerly Keele University now Limerick University, who is associated with the project and contributed to the report but is not funded by MR/Z50581X/.

Letters of Support

E-Prep received letters of support during the MR/Z50581X/ funding process from four partner organisations, which are:

- Dr Deborah Hemming, Scientific Manager, Vegetation-Climate Interactions group, Met Office Hadley Centre, Fitzroy Road, Exeter, UK.
- Professor Kerstin Krüger, KWS SAAT SE & Co. KGaA, Grimsehlstraße 31, 37574 Einbeck, Germany.
- Manuela Schieler, Central Institute for Decision Support Systems in Crop Protection (ZEPP), Rüdesheimer Straße 60, D-55545 Bad Kreuznach, Germany.
- Professor Mark Stevens, Head of Science, British Beet Research Organisation, Centrum, Norwich Research Park, Norwich, UK.

Purpose of the E-Prep Friends House event

The purpose of the stakeholder event was to identify grower activities, scientific tools and social and policy devices that are needed to improve the timeliness of first detection and containment of a plant disease. Further, the purpose extended to identifying mitigation strategies to avoid a multi-bacterium, multi-virus epidemic. This accords with UKRI's seed funding purpose for the '*planning and hosting of workshops and meetings to explore for example, research challenges and approaches*'.

Media

Ahead of the event, Farmers Weekly ran an article titled '*Project aims to tackle emerging sugar beet disease*' published here. Keele University also ran an article ahead of the event titled '*Keele researcher preparing agriculture to withstand viral and bacterial diseases*', published on Keele's website here.

E-Prep Report

This report and its recommendations fulfil E-Prep's aim to create a roadmap for future research, growers, business and policy. We are committed to complete attendee anonymity beyond those named above. Therefore, we purposely exclude attendee names, photos featuring individuals from the event, attribution of comments or views made by individuals, and any reference to companies, their products and services. Apart from those listed above, the remaining exception is British Sugar because of their strategic role in sugar beet as the sole producer and their partnership with over 2,300 growers and customers. When we refer to the word 'industry', we are referring principally to British Sugar, BBRO, which is jointly funded by British Sugar and the National Farmers' Union (NFU), and the sugar beet growers they represent.

Disclaimers

The views expressed and recommendations made in this report are solely the work of the E-Prep team. The information contained herein and the recommendations that are made are based on the best available data at the time of publication but may not be entirely accurate or complete.

We are committed to creating a roadmap for future research, growers, business and policy. We state 23 E-Prep recommendations to best prepare the UK for a plant health epidemic, a strategic need. We use sugar beet as a model system and recognise that every field of sugar beet is different and every year that passes is different to the ones that went before.

Thus, readers should instead seek independent professional advice before making any decisions. Growers and their crop consultants should conduct thorough crop inspections to support the decision-making process. This report is for informational purposes only and does not constitute professional advice.

Photo: Sugar beet. The E-Prep event used a range of props to explain the problems facing the industry. © Damian Maye

INTRODUCTION

Sugar Beet

Sugar beet (*Beta vulgaris* subsp. *vulgaris*) accounts for 20% of the world's sugar production. In GB approximately 2,300 growers sow sugar beet on 100,000 ha of arable land, producing 8 million tonnes of sugar beet annually for processing at four sugar beet factories at Bury (Suffolk), Cantley & Wissington (Norfolk) and Newark-on-Trent (Nottinghamshire). British Sugar produces 1.2 million tonnes of sugar per annum from those four factories with almost no waste. The sugar beet industry supports up to 9,500 jobs and currently meets half of domestic sugar demand.

Figure: NFU sugar beet map, illustrating the locations of the four sugar beet factories. The British Sugar headquarters is based in Peterborough. ©NFU Sugar

Sugar beet provides an ideal model system to explore complex multi-virus, proteobacterium + phytoplasma, multi-vector, multi-host dynamics in which pathogens manipulate both plant host and vector to enhance transmission[1,2].

Definitions

For the purposes of this report, we define an epidemic as:

'A quickly developing and then a sudden, unexpected increase in the vector-borne disease intensity in the host population over space and time, representing a regional or national threat to plant health'.

Virus Yellows

Biology

Aphids are the primary vectors of plant viruses and their movement, reproduction, host plant selection and feeding behaviour determine rates of virus spread.

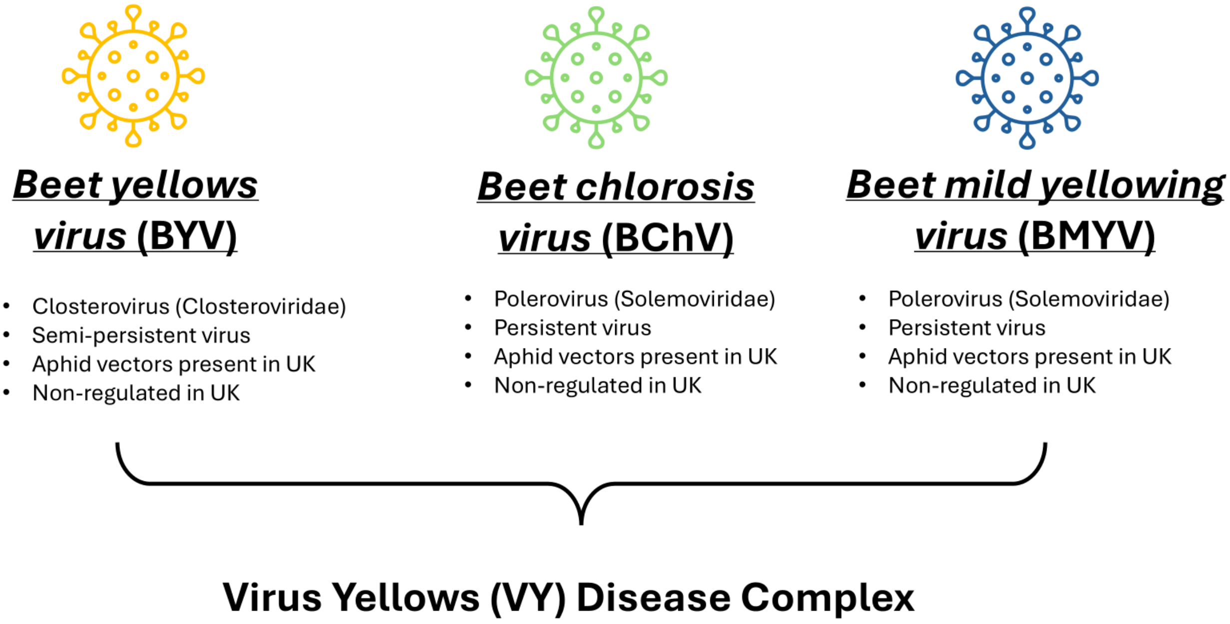


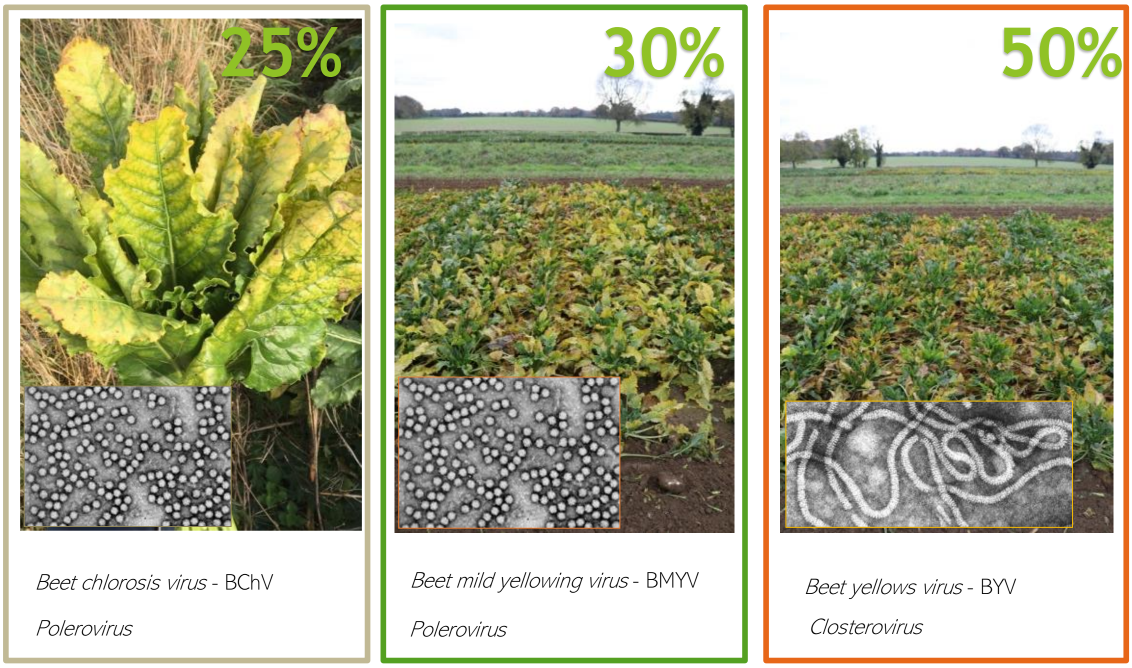
Figure: Virus yellows complex. ©E-Prep.

Aphid-vectored viruses include *Beet mild yellowing virus* (BMYV) and *Beet chlorosis virus* (BChV) which are persistent and belong to the *Polerovirus* (Solemoviridae formerly Luteoviridae) family, which has repeatedly been shown to affect attraction, arrestment, or preferred settling of aphid vectors[1,2]. These viruses are known to be vectored by two key UK aphid species, *Myzus persicae,* and, to a lesser extent, *Macrosiphum euphorbiae*[3]. Once infected with BChV and BMYV, these two aphids remain infected with these viruses for their whole lifespan. Another aphid-vectored virus, *Beet yellows virus* (BYV), a semi-persistent *Closterovirus* (Closteroviridae) is more damaging to UK agriculture even though it only persists within the aphid host for a matter of days[3]. Again, the main vector is *M. persicae*, but another aphid species, *Aphis fabae,* can also contribute to BYV transmission. Pre 2020, BBRO 'Goliath' field trials showed yield losses of up to 20% from BMYV and 54% from BYV. The three viruses, BMYV, BChV and BYV are known collectively as 'Virus Yellows' (VY).

Photo: *Myzus persciae*, the peach-potato aphid. ©James Bell

Epidemic

Virus Yellows last reached epidemic levels in the UK in 2020. Virus incidence rose to 100% in parts of Cambridgeshire during the BYV 2020 epidemic, contrasting with European virus dynamics[4]. The economic cost to sugar beet growers was estimated to be £67 million in losses[4,5]. As a result of the 2020 epidemic, in 2021 Defra initiated a policy response to authorise neonicotinoid seed coatings, an effective aphicide that is only authorised if there is a danger as evidenced by an independent prediction of virus incidence above a set Defra threshold[6]. Derogations were reviewed annually from 2021-2024 but in January 2025, the UK government decided not to grant emergency authorisation for the use of the neonicotinoid insecticide. This decision was based on assessments of environmental, health, and economic risks and benefits. The assessments highlighted the need to 'protect bee health'[7]. Given this change in policy the need for 'integrated pest management (IPM)' techniques have never been greater. The challenge is now regionwide management. However, Bell[4] showed how unpredictable aphid field counts across the region can limit large-scale strategies for control.



Slide: Virus impact on sugar beet yield by virus type. ©BBRO. Closterovirus image courtesy of ICTVonline.org

Status

The three viruses, BMYV, BChV and BYV, known collectively as VY, are routinely recorded in Great Britain, Northern Ireland and the EU. The viruses do not appear on the Plant Health Risk Register and are not notifiable or regulated because they are widespread and common in GB. Thus, VY is not subject to plant health controls or biosecurity measures, such as quarantining.

Syndrome ‘basses richesses’

Biology

Syndrome ‘basses richesses’ (SBR) refers to a reduced sugar beet disease that is caused by the combined infection of ‘*Candidatus* Arsenophonus phytopathogenicus’ and ‘*Candidatus* Phytoplasma solani’, known collectively as SBR *sensu stricto*. Historically, single ‘*Ca*. A. phytopathogenicus’ infections have been reported as SBR, however the SBR definition provided above reflects the contemporaneous scientific literature, and thus SBR defined as single infection with ‘*Ca*. A. phytopathogenicus’ is not valid use for the purposes of this report.

Arsenophonus bacteria are γ-3-proteobacteria, and one of the most widespread insect endosymbiotic genera. The endosymbiont host range comprises insects and other arthropod groups, such as arachnids, but has also twice undergone a shift to become a plant phloem pathogen; ‘*Ca*. A. phytopathogenicus’ (Morganellaceae) that infects sugar beet and potatoes[9,10], and ‘*Ca*. Phlomobacter fragariae’ infecting strawberry. Other plant pathogens of the γ-3-proteobacteria include diseases such as *Xylella fastidiosa*, a devasting disease of olive trees, and the citrus canker disease *Xanthomonas citri*[11].

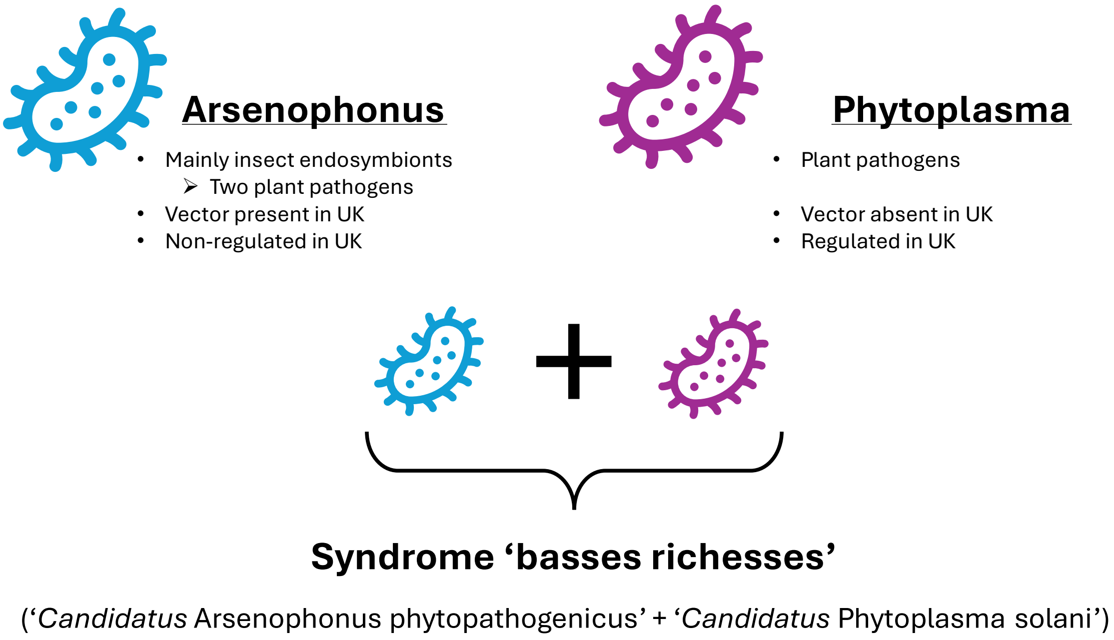


Figure: SBR components. ©E-Prep

‘*Ca*. Phytoplasma solani’ (Acholeplasmataceae), often described by its common name of ‘Stolbur phytoplasma’, is a plant pathogenic bacterium which lacks a cell wall and causes yellowing of leaves and a disruption of sugar metabolism[10]. ‘*Ca*. P. solani’ has a diversity of hosts, many of which are either ‘dead-end’ hosts (see Quaglino[10]), or effective weed species hosts that act as disease reservoirs. However, ‘*Ca*. P. solani’ alone (i.e. single infection) notably causes major diseases throughout Europe, including

'Stolbur' in potato and tomato[13,14], 'Bois Noir' in grapevine, and rubbery taproot disease (RTD) in sugar beet. One of the first countries to experience an outbreak of RTD was Serbia in 2018-2019[12].

Pentastiridius leporinus (Cixiidae), the reed planthopper, is typically associated with common reed (*Phragmites australis*) in natural habitats[15]. It is the only known vector of SBR *sensu stricto* that it is capable of transmission of both '*Ca*. A. phytopathogenicus' and '*Ca*. P. solani' to sugar beet[13,14].

Photo: Reed planthopper *Pentastiridius leporinus*. ©ZEPP.

However, a confusing SBR host-plant picture is developing because the phytoplasma is vectored by other planthoppers, such as *Hyalesthes obsoletus* and *Reptalus panzeri*, but these species are thought to be not capable of vectoring the *'Ca*. A. phytopathogenicus', based on current data[13,14]. As such, these infections are not considered SBR *sensu stricto*, because they are the sole infection with *'Ca*. P. solani'.

<u>Epidemic</u>

SBR is outbreaking in Europe and major losses have occurred in Germany, Switzerland and France that are at epidemic levels. *Pentastiridius leporinus* (Hemiptera: Cixiidae) is the most important vector of SBR in sugar beet. Symptoms of yellowing and necrosis are visually indistinguishable from other yellowing diseases, such as VY or rubbery taproot disease (RTD) that affects sugar beet in eastern Europe. However, in the UK, if drought nor VY yellows can be attributed to the appearance of a patchy but widespread yellowing of sugar beet in July-August, it may indicate SBR infection.

Photo: Symptoms in carrots and red beet, with *Pentastiridius leporinus* larvae pictured on red beet. Originally provided as a slide for the E-Prep meeting by Manuela Schieler. ©Agrarservice Hessen Pfalz GmbH.

Recent reports from Europe have identified both bacterial components with an expanded host range, including carrots and red beet that show rubbery root symptoms typical of *'Ca*. P. solani' infection. *'Ca*. P. solani' and *'Ca*. A. phytopathogenicus' has also been found in potatoes[13,14]. This expanded host range will further confound accurate diagnosis of the geographic and host range, with a different phytoplasma, *'Ca*. P. asteris' (Aster yellows phytoplasma) and another proteobacteria, *'Ca*. Liberibacter solanacearum', both causing disease in carrots, being present in Europe, and causing similar foliar symptoms.

Status

The UK Plant Health Risk Register records the risk rating of '*Ca*. P. solani' as 60, a mid-range score (1-125), which may need revision. The current score is primarily based on the risk to potatoes and tomatoes, without considering SBR and the sugar industry. '*Ca*.

P. solani' is a regulated quarantine pest in Great Britain and a regulated non-quarantine pest in Northern Ireland and the EU.

The proteobacterium '*Ca*. A. phytopathogenicus' is thought to be absent from the UK, but present but not regulated in EU. Although not regulated, the disease does satisfy the criteria required for quarantine pest status in GB. It is unclear from the Plant Health Risk Register what action (if any) would be taken if '*Ca*. A. phytopathogenicus' was identified in Great Britain.

These scores and status feature in our recommendations.

EPIDEMIC PREPAREDNESS

The 2020 VY prevalence in England was 38.1%, equivalent to a disease incidence of 40 billion infected sugar beet plants[4]. The disease intensity rose to 100% in some parts of Cambridgeshire[4] . This epidemic is sometimes described incorrectly as an 'outbreak'. We distinguish between a pandemic, epidemic and outbreak and examine models for the temporal rates of increase of the disease incidence in Appendix 1.

Photo: Virus yellows in sugar beet. © James Bell

MODULES

The E-Prep event was structured into three modules that follow a logical and sequential pattern of the threat to plant health during an epidemic as it is first observed in the field and then attempts to outbreak across a larger area. For all three modules we consider both the vectors and the pathogens separately.

- First Detection
- Containment
- Mitigation

The overall aim of using this structure was to inform current levels of epidemic preparedness and then to identify strategic needs and methods for a successful campaign. Needs and methods are identified and captured in our 'Recommendations'.

First Detection

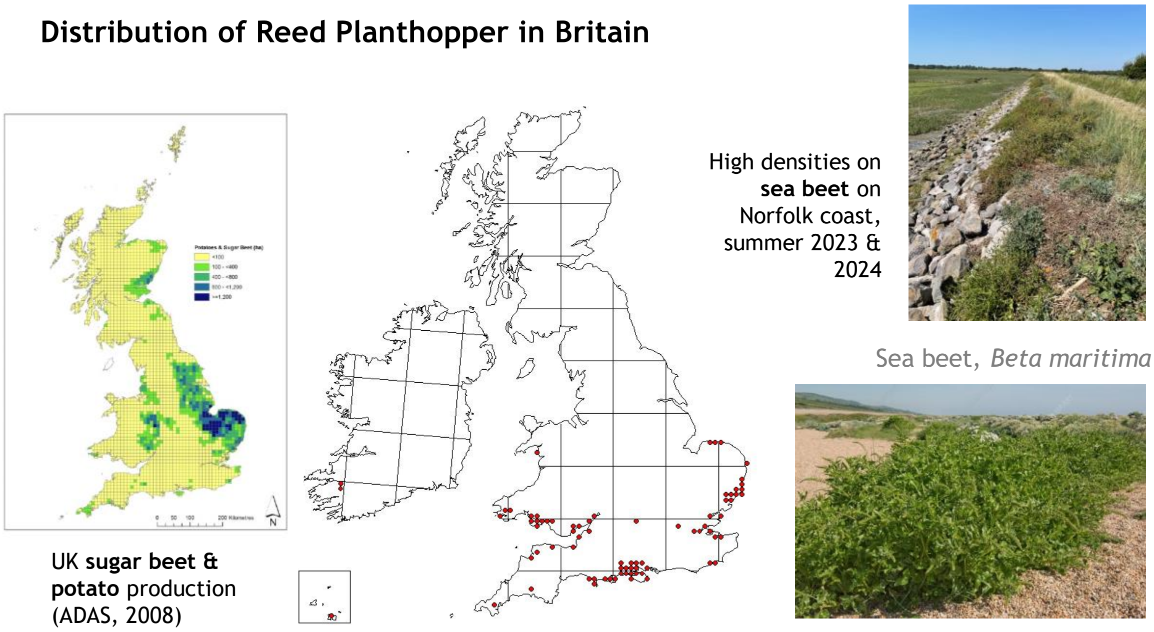
The team considered the following scenario to capture the first detection challenge: '*The vector and yellowing disease are believed to have arrived in the UK. Based on ad-hoc reports prevalence is 1 in 1000 hectares/1 billion plants but this is not confirmed. Location data is sketchy, but Norfolk is the prime suspect.*'

Photo: BBRO's yellow water trap network. ©BBRO

Citizen Science

Van Den Bosch[16] suggested that the only feasible way to achieve the sampling effort needed for early disease detection is to involve volunteers, such as citizen scientists. Due to a lack of citizen scientist expertise needed to detect and diagnose the type of yellowing, the false-positive and false-negative rate would be extremely high and consequently, without molecular diagnostics, involvement in citizen scientists is likely to be less productive.

However, the citizen is extremely well placed to survey sea beet and common reed for the SBR vector *Pentastiridius leporinus*. The citizen science community has already provided data on the presence of the reed planthopper via the NBN gateway and the national recording scheme for planthoppers. The planthopper show a strong coastal pattern probably in association with its coastal host, sea beet (*Beta maritima*) a congener to commercial sugar beet. *Pentastiridius leporinus* is likely under recorded on common reed as this is a difficult and sometimes inaccessible habitat to sample. The planthopper may be climate limited. However when the climate warms, it may spread northwards towards Hull where sea beet is present.



Distribution of Reed Planthopper in Britain

High densities on **sea beet** on Norfolk coast, summer 2023 & 2024

Sea beet, *Beta maritima*

UK **sugar beet & potato** production (ADAS, 2008)

Figure: SBR components. ©E-Prep

Trajectory Models

Long-distance migration events can be predicted using the Met Office's 'NAME' model which has been successful at understanding the threat posed by *Culicoides* midges, vectors of blue tongue[17]. Hemming[18] provides an overview of various modelling approaches and datasets potentially useful for plant and animal biosecurity.

Insect Traps and Trapping

Whilst we have the Rothamsted Insect Survey's 12.2 m suction-traps which provide daily counts for aphids during the growing season and thus provide a rich data source for virus yellows modelling. Cixiids are not well represented in those traps. Instead, BBROs yellow water trap network provides a better estimate of plant hopper presence. Bressan[15] showed that if sticky traps were placed on or near sugar and close to ground level, these traps were effective at capturing flight activity. ZEPP also use this methodology in Germany.

Photo: Sticky traps placed close to the canopy. ©Central Institute for Decision Support Systems in Crop Protection/ZEPP/NIKIZ

Biochemical and Molecular Assays

ELISA, lateral flow, LAMP, RPA, PCR, qPCR tests are available for detecting VY (BMYV, BChV, BYV) and LAMP, RPA, PCR, qPCR are available for detecting SBR ('*Candidatus* Arsenophonus phytopathogenicus' and '*Candidatus* Phytoplasma solani'). Though, these assays are not all necessarily recognised to the level of EPPO (European and Mediterranean Plant Protection Organisation) standards (see Recommendations). Similarly, a range of confirmatory assays are available to identify *Myzus persicae* and *Pentastiridius leporinus*, though these can both be determined using taxonomic methods.

Photo: 12.2m suction-trap, Rothamsted. © James Bell

AI, Robotics and UAVs

Robotics and particularly UAVs (i.e. drones) offer huge surveillance and monitoring opportunities to precision agriculture and simultaneously also pose substantial skills, logistic and analytical expertise challenges and cost burdens. These are echoed in the EPSRC UK-RAS Network's white papers '*Training the UK Agri-food Sector to Employ Robotics and Autonomous Systems* - 2023' and '*Agricultural Robotics* – 2018'.

The most widely deployed technology for surveillance and monitoring are UAVs equipped with imaging sensors. UAVs are routinely deployed by BBRO and research organisations to capture symptomatic yellowing and other environmental factors. The Modified Normalized Difference index (mND_{blue}) performs significantly better than other indexes tested for detecting a change in sugar beet chlorophyll content[19]. Recent research in collaboration with BBRO, funded by BBSRC BB/X005313/1 shows that mND_{blue} detects symptoms of BYV disease better than NDVI when validated by ground level molecular diagnostics (Beale *et al*. in prep). UAVs do not replace the need for crop inspections or molecular tests[20]. The role of drones and more generally image processing has recently been reviewed[21].

Photo: Husky robot with RGB-Depth camera scanning sugar beet plants, University of Lincoln. © Junfeng Gao

Incorporating AI, particularly machine learning algorithms, enhances the capabilities of UAVs and robotics in disease monitoring and surveillance. AI-powered image processing techniques allow for the automatic identification and counting of aphids from water pan trap imagery in sugar beet fields[22]. Deep learning models, trained on vast amounts of drone-acquired imagery, can improve the precision and speed of disease progress assessments. These AI-driven systems also enable continuous, real-time data analysis, providing actionable insights that can be directly integrated into decision-making processes. As such, AI not only augments the capabilities of UAVs but also helps overcome some of the analytical challenges by streamlining the interpretation of complex data sets. The integration of AI into UAV-based agricultural surveillance systems thus offers significant potential to increase efficiency and reduce the reliance on traditional, labour-intensive diagnostic methods. For example, AI can be used to recognise the presence of sea beet in field surveys, helping to reduce the workload of agronomists by allowing citizen scientists to validate findings and contribute to the confirmation process. This crowdsourced validation process enables faster and more efficient monitoring while ensuring expert resources are focused on more complex tasks.

Conclusions

Finding a diseased plant in amongst one billion healthy plants is an enormous challenge that cannot be solved by one approach in isolation. While AI, UAVs, and robotics offer great potential to revolutionize plant monitoring, they must be integrated within a comprehensive strategy to be truly effective. Our conclusion is that the best chance of establishing the presence of a disease is to conduct both field scouting and deploy routine molecular assays at all four sugar beet factories' warehouses, as elaborated in the report's recommendations. Once the presence of the SBR/RTD disease or individual proteobacteria or phytoplasma is confirmed from a sample taken from a lorry, the farm location will be known from the stub card. At that point, the surveillance methods that will be most useful include biochemical and molecular analysis, insect trapping, and deployment of drones once expression of leaf yellowing is observed. Importantly, the role of AI in this surveillance process extends beyond just yellowing detection. It also enhances decision-making by offering predictive insights, such as identifying areas at high risk of infection based on environmental factors, historical data, and real-time monitoring. Throughout the process, engagement and communication to instil trust and cooperation must take place (see **Mitigation**). Building trust and cooperation among stakeholders, including farmers, researchers, and industry experts, will be essential to the successful implementation and adoption of these technologies. As new methods and tools, such as AI, UAVs, and robotics, are introduced, clear communication and transparency will help foster confidence in the system, ensuring its success and long-term sustainability.

Containment

Containment for plant health, sometimes referred to as phytosanitary containment, is a set of measures and restrictions to control the movement of plants, plant pests, and pathogens. The large majority of successful phytosanitary containment measures are horticultural and under glass or other closed systems, which is a much more manageable proposition when the cost justifies the outcome. Here we consider field-based containment measures.

The following containment measures were considered:

1. **Removal and burn**. The team drew on three examples: 1. Asian Longhorn Beetle (*Anoplophora glabripennis*) that was brought under control by incineration of infected plant and insect material[23]. 2. Huanglongbing (‘*Candidatus* Liberibacter asiaticus /africanus/americanus’) vectored by the Asian citrus psyllid (*Diaphorina citri*) which had limited success. Huanglongbing (HLB) was first detected in Florida in 2005. Despite aggressive containment efforts, HLB proved difficult to manage due to the rapid spread of the psyllid and the asymptomatic nature of early infections, which hindered timely intervention that aimed to remove all symptomatic trees and strategically placed uninfected trees[24]. 3. The false Columbia root-knot nematode (*Meloidogyne fallax*) was controlled by removal and disposal of infested plant material. Rotations are unlikely to be successful, so infested fields were committed to black fallow (uncultivated) for a period of at least two years[25].
2. **Buffer Zones**. The IPPC definition of a buffer zone is ‘an area surrounding or adjacent to an area officially delimited for phytosanitary purposes in order to minimize the probability of spread of the target pest into or out of the delimited area, and subject to phytosanitary or other control measures, if appropriate.’[26] The team considered Italy’s buffer zone response to contain *Xylella fastidiosa* epidemic, a bacterial disease vectored by the meadow spittlebug (*Philaenus spumarius*) to olive trees[27].
3. **Innovation.** The team considered two cooperation strategies: 1. The recent successful control of invasive Asian hornet in the UK (*Vespa velutina nigrithorax*) using citizen scientists and local beekeepers that acted as reporting scouts for the National Bee Unit (NBU) who then promptly eradicated the nests[28] 2. Bluetongue virus vectored by biting midges (*Culicoides* sp). The Bluetongue disease control framework shares information and expertise between government, the Animal and Plant Health Agency, stakeholders and industry (partnership model) for effective first detections[29].

Conclusions

1. **Removal and Burn:** Sugar beet cannot be easily eradicated in situ without widespread disturbance of the soil and plant tissue that would spread the infection. Sugar beet cannot easily be incinerated in situ without damage to the soil and even if this were the case, planthopper larvae penetrate 30 cm into the soil and would not be destroyed easily by any control method.
2. **Buffer Zones:** For effective containment of an insect-vector borne disease, the dispersal kernel needs to be known to create a robust buffer zone. The dispersal kernel of *Pentastiridius leporinus* would need to capture its migratory capacity, thought to be at least farm-to-landscape scale for individual planthoppers.

However, most insect pest migrations have a leptokurtic distribution that captures extremely long-distance flights as a long 'fat' tail for an unknown proportion of the individuals[30]. The leptokurtic distribution is appropriate for aphid migrations (i.e. frequencies higher than expected close to source and in the tail and lower than expected at intermediate distances) but it is unknown if this distribution is appropriate for planthoppers. Another constraint is effectively demarking a buffer zone when the full list of *P. leporinus'* possible plant hosts is not well documented. The likely impact of a large migration and a polyphagous habit is that the buffer zone would occupy a considerable area which could be difficult to manage. The report also highlights the need for careful people management, particularly supporting positive engagement (see **Innovation**). Other factors to consider are highlighted by EPPO[26].

3. **Innovation:** Containment could be blended with a mitigation strategy. For example, grower-led buffer zones in which novel rotations (e,g, non-crop Sustainable Farming Incentive (SFI) agreements) operate to control the vector below threshold levels. This buffer zone could be monitored by a third party who would build trust and a willingness to cooperate whilst avoiding that would otherwise lead to reputational damage for the grower. Resilience could be bolstered by requiring growers within a buffer zone to only use resistant varieties when they become available, until the threat has passed, thus avoiding chronic infections. Here, it is important to recognise that tolerant varieties, although symptomless, may still act as disease reservoirs, potentially maintaining chronic field infections. Payments could be made to those who experience substantial economic losses, based on field surveys, re-enforcing the principle of shared responsibility. Most of these elements are expressed in the Australian '*Emergency Plant Pest Response Deed* (EPPRD)'. A containment strategy should be designed early in the preparedness cycle. This could take the form of a stakeholder group (including industry, policy and research expertise) that considers roles, responsibilities and knowledge gaps. It recognises a need for pre-emptive action to plan for SBR or a combined threat, considering containment alongside detection and mitigation[31,32].

Mitigation

The team considered the following scenario to capture the mitigation challenge '*Outbreaks are now regular and so we move to mitigating the impacts by keeping the diseases to minimal levels'*. Topics were wide ranging but included plant breeding, IPM strategies and genetic control and how these might cause unintended consequences, may have several barriers to uptake and implementation, or need cooperation mechanisms for successful widespread adoption.

Plant Breeding

Plant breeding includes the use of genomics, genetic engineering, cell and tissue culturing as well as traditional crossing and breeding. Successful varieties which have a licence to be grown in the UK are highlighted in BBRO's recommended list (RL). Even with the latest genomic tools, the time taken for a new variety to be considered is about 10 years of plant breeding development (Kerstin Krüger *pers comm*). Further, combining two tolerant disease traits (e.g. SBR and RTD resistance) into one variety, is a major research challenge but needed for combined infection epidemics.

In terms of tolerance to vector-borne pathogens, KWS Maruscha, tolerant of BMYV, and KWS Josephina tolerant of SBR (see KWS varieties). New VY/SBR/RTD varieties from other seed companies will undoubtedly be in development but are not commercially known.

Alternative Control

BBRO have been experimenting with alternative methods to insecticides, such as attractants and alternative hosts (aka push-pull principles using brassica buffer strips), beneficials (beneficial insects, particularly natural predators, parasites and parasitoids), camouflage (use of cover crops, such as barley, wheat and rye or the use of food dyes to change the appearance of the crop), deterrents and repellents (natural plant extracts, some of which work well in other systems (garlic, neem). These are all examples of various integrated pest management (IPM) strategies which have been successfully deployed in other systems. Generally, the overall message is that no one strategy is sufficient to provide complete protection, but a range of management strategies are needed for effective control. Verheggen[33] reviews alternative interventions in sugar beet.

Genetic Control

RNA silencing-based genetic resistance has been demonstrated in bean, papaya, pepper, plum, potato, squash, and tomato[34]. In sugar beet, rhizomania resistant plants have been produced against beet necrotic yellow vein virus (BNYVV), through conventional or transgenic breeding, the latter using RNAi interference to prevent expression of harmful traits[35,36]. In the lab, programmed cell death has been demonstrated in aphids[37]. The difference between the two approaches is that RNAi may turn-off a gene without causing cell death. Programmed cell death is controversial method of insect control and not yet available in the UK for use against vector-borne diseases. RNAi shows promise.

Human cooperation

Even amongst diverse set of stakeholders, social identity can foster a willingness to cooperate. Cooperation enables effective collective actions (e.g. area-wide control of the disease or vector). For example, the Palatinate-Hessian sugar beet growers' association are together working as a group to find tolerant or resistant potato varieties against the phytopathogens, an example of collective responsibility – they believe that the problem is theirs as custodians to solve. There are several examples of sugar beet cooperatives in the UK, including regional examples, such as Bury Beet Group, Cantley Beet Group, and national organisations, such as the BBRO and the NFU Sugar who support sugar beet growers in the UK at various spatial scales.

Conclusions

One of the most successful mitigation strategies that largely avoids unwanted environmental impacts on the wider environment, is plant breeding for disease protection. However, the pipeline to deliver is a decade long in development, which is a weakness.

The Genetic Technology (Precision Breeding) Regulations 2025, a necessary legislative tool to implement the Genetic Technology (Precision Breeding) Act 2023, is awaiting approval by Parliament. The act would allow genetic changes to the DNA of plants or animals in England and is expected to permit gene editing along with other biotechnology techniques. Modified plants will be labelled ‘precision-bred organisms’ (PBOs). If approved, this legislation would expedite the breeding process. More information can be found at FSA and Defra.

Grower-focussed groups can and have fostered innovation and then delivered relevant regional solutions for sugar beet, but this may be a fragile relationship during an epidemic. The UK sugar beet industry does have a good example of epidemic preparedness to reflect upon when the soil-borne viral disease rhizomania arrived in the UK in 1987.

Recommendations

The following recommendations are primarily aimed at the sugar beet industry, British Sugar, NFU Sugar, the BBRO and the growers they represent. Notwithstanding that effective preparedness will also require support and guidance from policymakers, particularly Defra, and strategically placed organisations such as APHA. For an effective epidemic preparedness campaign, additional support from agricultural stakeholders, such as plant breeders and academia, as well as third-party organisations, such as crop consultants and the Farming Community Network (FCN) will be required. Widespread cooperation is key to success.

Plant Health Risk Register

1. *'Candidatus* Arsenophonus phytopathogenicus' should be reviewed as potentially needing quarantine pest status in Great Britian and Northern Ireland and the Plant Health Risk Register updated.
2. The risk rating of *'Candidatus* Phytoplasma solani' should be reviewed and the Plant Health Risk Register updated.
3. The Plant Health Risk Register entry for 'Syndrome des basses richesses' (archived 13/08/2020) should be reviewed in light of current research on the disease complex, vectors and distribution.
4. The regulated non-quarantine pest in Northern Ireland should be reviewed for the Plant Health Risk Register and updated.

First Detection

5. Each year British Sugar select approximately 320 fields across the four factory areas (specific field survey) that are monitored throughout the season. These fields are inspected for pests and diseases in June and late August/early September (e.g. virus yellows) and provides one of the first opportunities to spot unusual symptoms. The British Sugar survey has been effective at spotting new invasive species such as beet moth (*Scrobipalpa ocellatella*) from 2020 onwards.
6. Molecular assays (PCR and qPCR protocols) for the independent detection of the two components of SBR 1) '*Candidatus* Arsenophonus phytopathogenicus' and 2) *'Candidatus* Phytoplasma species' should be routinely deployed at the point of intake to the factory using the existing random sugar beet sampling protocol at the tarehouse (e.g. Mahillon *et al* 2022. *Pathogens* **11**:885; Hodgetts *et al.* 2009 *Appl Environ Microbiol.* **75**:2945-50). These samples are the best opportunity to gather spatially referenced information on prevalence of all pathological aspects of SBR and sugar beet diseases (RTD) from a mixed field sample. However, random sampling of lorries would be required for this to be workable; the total number of lorries offloading sugar beet on to the pad at British Sugar factories is extremely large (circa 285,000 pa), hence the need for subsampling (e.g. one lorry per farm or one lorry per district etc).
7. Academics and industry should undertake verification/validation of a '*Ca*. A. phytopathogenicus' diagnostic assay to a recognised EPPO standard (i.e. EPPO

PM7/98). See Recommendation 6 and **Biochemical and Molecular Assays** section.

8. Long-range forward trajectory models should be deployed by the Met Office to understand the risk of *Pentastiridius leporinus* planthoppers arriving from the continent during May and June, the period of likely first detection.
9. A systematic study to establish the presence of the SBR vector *Pentastiridius leporinus* and any other cixiids in sugar beet fields should be conducted without delay. Coastal fields are a priority, especially in fields that are in close proximity to sea beet (*Beta maritima*) or common reed (*Phragmites australis*).
10. Suspected *Pentastiridius leporinus* planthoppers, especially those feeding on sugar beet, should be sent to Professor Alan Stewart, the National Recorder for Auchenorrhyncha and E-Prep project member, in the first instance (e-mail: a.j.a.stewart@sussex.ac.uk).
11. Taxonomic identification of females and nymphs of *Pentastiridius leporinus to* species level is challenging, requiring a high level of expertise. Where such expertise is not available or there is uncertainty, it is recommended that a molecular test is used (e.g. Pfitzer *et al*. 2022. *Insects* **13**: 992; Eini *et al*. 2024 *Bull Entomol Res*. **114**:309-316). This will provide high confidence that individuals are not misidentified.
12. There are no pheromones for *Pentastiridius leporinus* which would otherwise greatly assist in effective surveillance strategies. Active industrial and academic research should develop pheromones as a priority.
13. Population genetics and/or genomic surveillance should be carried out on GB *Pentastiridius leporinus* planthoppers to understand population structure and possible source populations.
14. AI-powered predictive models should be developed to analyse environmental conditions, historical data, and field observations to forecast the risk of disease *Pentastiridius leporinus* and *Myzus persicae* outbreaks. These AI models can help identify areas at high risk of infection, enabling early warning systems that can guide targeted surveillance and intervention efforts.
15. The effective integration of AI, UAVs, and robotics for first detection will require collaboration between academic researchers, industry stakeholders, and technology developers. A shared data platform should be developed where information from field sensors, drones, and molecular diagnostics can be accessed and analysed collectively. This will facilitate more efficient monitoring and response efforts across the industry.

Containment

16. The lifecycle of the SBR vector *Pentastiridius leporinus* is not well understood, particularly host-switching behaviour and host expansion from ‘typical’ hosts in natural habitats to crop hosts. Behavioural assays are needed to understand the effectiveness of any containment.

17. Simple sticky trap monitoring close to ground level in and around infected fields has shown to be effective in France and Germany and needs to be deployed using sentinel farms from this point forward in sugar beet, carrots, potatoes and wheat fields.
18. As part of the Plant Biosecurity Strategy for Great Britain (2023-2028), SBR *sensu stricto* infection is reportable because '*Ca*. P. solani' is a regulated quarantine pest. British Sugar and BBRO need to develop a contingency plan, building upon knowledge gained from previous rhizomania contingency planning, using the Defra's template and work with Defra to understand responsibilities and approach, including plant health controls, guidance and toolkits to help growers.
19. The contingency plan, the guidance and toolkit need to be clearly elaborated to growers before an epidemic begins in order to build trust and cooperation. There is the additional need to communicate the strategy to the media and general public, to manage expectations.

Mitigation

20. The new 2025 UK sugar beet seed model may help ease the pressure on seed purchases, but there is only one variety, KWS Josephina, that is tolerant of SBR (Kr. New tolerant SBR/RTD/VY varieties are needed to be licenced for the UK to cope with expected demand during an epidemic.
21. *Pentastiridius leporinus* presents challenges to crop rotations because their plant hosts are core inclusions to most rotations used throughout the region (i.e. sugar beet, carrots, potatoes, wheat)[15]. Field trials should be conducted that develop new crop rotations using new tolerant varieties and novel crops to minimise the risk to sugar beet.

Funding

22. An industry-led seed fund to encourage the surveillance and reporting of SBR/RTD/VY diseases and their vectors should be adopted immediately to instil a collective responsibility that enables the unconditional exchange of observational data between crop consultants, growers and industry.
23. A new fund needs to be created to support growers who have experienced substantial economic impact during a plant health epidemic, especially if the infected field must be committed to bare fallow for several years. An equivalent historical scheme, the UK Rhizomania Scheme for Sugar Beet[38], compensated affected growers whilst funding research and development to reduce longer-term cost risks (e.g. new experimental rotations).
24. The next generation of funding from the Department for Environment, Food and Rural Affairs (Defra), UKRI and Innovate UK (e.g. Farming Innovation Programme; Transforming Food Production (TFP) Challenge) should prioritise landscape-level monitoring and surveillance strategies to overcome the first detection challenge that has been identified in this report (i.e. >1 billion plants).

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Photo: A new dawn. © James Bell

Appendix 1: What do we mean when we use the word ‘Epidemic’?

Plant health epidemics are poorly defined, but what is clear is that a pandemic crosses continents and therefore operates at a larger spatial scale than an epidemic that remains within the borders of a country[1]. Applying this logic to the term ‘outbreak’, leads to a definition that includes a cluster of infected fields at the farm or district level, whereas an epidemic is at least regional in its impact, crossing multiple counties or states. An outbreak may lead to a pandemic and the pandemic can then subside. Thus, the need to constantly update the threat with new epidemiological data.

For a pandemic, epidemic or outbreak, plants must be both susceptible (i.e. infected readily, thus lacking resistance) and sensitive (i.e., severe symptoms) to an infection[13]. Nutter[2] recognised value of ‘disease intensity’ to capture disease prevalence (i.e. the number of fields infected as determined from assaying individual plants within those fields, often reported as a percentage), disease severity (i.e. a measure of the symptoms of a pathogen on the plant health status, such as total area of yellowing leaves) and disease incidence (proportion of plants infected based on symptomatic expression) observed within a farm, district or region.

For pandemics, epidemics and outbreaks, there will be a rapid increase in the infection rate. In agriculture, the temporal rate of change typically is described by one of the following statistical models:

- Linear: the slope of the curve indicates a constant rate of increase of infection. The trend is not bounded by an asymptote but infinite.
- Negative exponential: A special case in which there is no secondary spread. This may indicate a failed outbreak, and thus a successful mitigation campaign.
- Exponential: The trend is without an upper asymptote meaning that carrying capacity of the host crop does not limit the rate of disease increase. Hence often only used in the early phases of an epidemic or outbreak.
- Logistic: A lower and upper asymptote is present and as such, the distribution represents well the progress of an epidemic. The curve is best described as ‘S’ shaped, in which the rate of spread develops slowly, then saturating when an increasingly limited number of susceptible plants remain uninfected.
- Gompertz: Another special case and similar to the logistic model but the S shape is skewed in time, perhaps indicating an increase plant resistance, such as that which could arise from mature plant resistance in sugar beet.

More complex epidemiological models can be found in Madden[3]

For the purposes of this report, we define an epidemic as ***“A quickly developing and then a sudden, unexpected increase in the vector-borne disease intensity in the host population over space and time, representing a regional or national threat to plant health’.***

Disease epidemics are common in agriculture and can cause huge devastation when uncontrolled. Examples include *Septoria tritici* blotch, a foliar disease of wheat, caused by the fungus *Zymoseptoria tritici.* Severe epidemics are common and reportedly decrease wheat yields by between 30–50%. Other common epidemics in cereals include yellow rust in wheat and net blotch (*Pyrenophora teres*) in barley. The severity of both epidemics varies annually, influenced by weather conditions and the prevalence of susceptible wheat varieties. Root crops also suffer from a variety of pest and disease epidemics. Potato late blight, caused by *Phytophthora infestans,* remains the single most devastating disease of global potato production. In countries where chemical control is prohibitively expensive late blight can routinely lead to over 60% yield loss. Despite access the decision support systems and effective fungicides, late-blight epidemics reportedly cost the UK potato industry £50 million per blight season. Climate change and the loss of effective insecticides mean that several vectored diseases more frequently reach epidemic levels. A key example is Barley Yellow Dwarf Virus (BYDV) which is vectored by aphids (*Rhopalosiphum padi*; *Sitobion avenae*). This disease can lead to severe yield loss cereals up to 50%.

Rarely is it the case that definitions of epidemics include quantitative assessments since there are good reasons not to have ridged criteria. The 2020 VY prevalence in England was 38.1%, equivalent to a disease incidence of 40 billion infected sugar beet plants. The magnitude of this infection is classed as borderline 'High' average crop losses (i.e. >40%) However, the disease intensity rose to 100% in some parts of Cambridgeshire[4] leading to very high crop losses (>80%)[5]. The 2020 epidemic is sometimes described incorrectly as an 'outbreak'.

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