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AUTHENTICATION

We declare that this work was done under our supervision according to the procedures described herein and that the report represents a true and accurate record of the results obtained.

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CONTENTS

GROWER SUMMARY

Headline

The current state of virus health of the UK pea crop is unknown. Investigations into pea affecting viruses have been carried out in other countries but this has been sporadic. Emerging viruses have been identified in northern Europe, but at present these viruses are not known to occur in the UK.

Background

This work was undertaken as a response to the perceived lack of knowledge regarding the virus health of UK pea crops and potential management actions which could be taken to mitigate viral threats to those crops.

Summary

Pea (*Pisum sativum*) is an important legume crop which is grown worldwide for consumption by humans and animals. Pea plants also form a key part of cereal rotations partly to act as a break crop to help manage disease, but also to improve soil fertility as a consequence of nitrogen fixing (Congdon et al., 2017b; Coutts et al., 2008). Using peas, or other legumes, in rotation can greatly reduce the need for application of pesticides and synthetic nitrogen fertilizer (Cernay et al., 2015). The European Union is looking to increase the production of legume crops in order to reduce negative impacts on the environment from use of fertiliser and also to reduce imports of soybean from America (Cernay et al., 2015). However, changing the crops grown in an area can lead to changes in pathogen pressure, which in turn make predicting diseases more difficult.

The range of viruses infecting peas

There are a broad range of viruses which are known to infect pea. The web-source 'Plant Virus Online' (Brunt et al., 1996) lists 124 viruses which have the ability to infect peas, however, only 43 of these viruses were reported occurring from natural infections with the remainder having pea listed as an experimental host. However, there is a lack of recent survey reports covering either the United Kingdom (UK) or the European Union (EU) which means the current health status of pea crops is unknown. Seven viruses were reported to occur in peas in the UK, with early confirmed reports dating back to 1964. Two of these viruses are known to be seed-borne and regular diagnostic testing is carried out to help ensure high seed health. One of these viruses, *Pea seed-borne mosaic virus* (PSbMV) has been the subject of a recent in-depth studies in Australia (Congdon et al., 2017a; Congdon et

al., 2017b; Congdon et al., 2016a; Congdon et al., 2016b, 2017c) which have resulted in a greater understanding of the epidemiology and control of PSbMV outbreaks in pea crops in the Mediterranean-type climate of south-west Australia. These studies have highlighted that wind-mediated plant-to-plant contact may exacerbate outbreaks of this virus, a factor not previously considered for this virus in the UK. Additionally, a predictive model was devised from these studies which may be applicable to UK PSbMV outbreaks, however, this would need to be investigated in UK climatic and agronomic conditions.

Diagnostics and control strategies

There were limited reports on the use of molecular diagnostics in investigations of pea viruses. The majority of work has used ELISA based testing, however, these methods will not be sensitive or specific enough should future investigative work seek to monitor aphid transmission factors. Additionally, given the current status of pea viruses in the UK is unknown, should novel or unusual symptoms present as part of any future symptomatic survey, technology is now available to determine the identity of diseases of unknown aetiology.

There were also limited reports on effective control measures. Where these do occur specifically for peas they are focussed on either chemical control or cultural approaches (e.g. seed fractionation to reduce PSbMV inoculum). In many cases the control measures listed have been applied for pea affecting viruses in other crops, or have been applied more generally to reduce aphid transmitted viruses (e.g. the use of mineral oils). These approaches may hold some value for reducing the virus risk to UK pea crops but further investigation would be required into their efficacy and practical application. Part of such an evaluation would need to include a study to ascertain the viruses to prioritise for control as this is not currently known.

Emerging threats?

Several viruses have been reported from European pea crops which have not yet been detected in the UK. Of greatest significance are the newly emerging genus of nanoviruses, primarily *Pea necrotic yellow dwarf virus* (PNYDV). This virus was initially reported from a single province of Germany in 2009, and by 2017 has been found in all pea growing regions of Germany as well as being detected in Austria and The Netherlands from a range of leguminous crops (Gaafar et al., 2016; Gaafar et al., 2017; Grigoras et al., 2010; Steinmöller et al., 2016). This aphid-transmitted virus, and more broadly this emerging group of viruses poses a potential risk to peas should it establish in the UK as they have been recorded causing significant damage to pea crops where they occur.

Conclusions

The primary conclusion of this study is that investigations should be carried out to ascertain the current state of the UK pea crop with respect to virus infections. To ensure outputs are of use to growers any future work should be considered under a programme which addresses the fundamental principles of plant virus management:

- **Plant clean seed**: As part of any future research programme input seed stocks should be surveyed to ensure the assumed high virus health status of input seeds is reflected in the seed being planted. This work should focus on the known seed borne viruses *Pea seed-borne mosaic virus* (PSbMV) and *Pea early-browning virus* (PEBV).

- **Grow in absence of virus reservoirs**: With limited information available on the presence and incidence of pea viruses it should be a priority to baseline current virus populations affecting pea crops. Such work should focus on those viruses known to occur in UK crops such as *Bean yellow mosaic virus* (BYMV), *Bean leaf-roll virus* (BLRV), *Pea enation mosaic virus* (PEMV), *Pea early browning virus* (PEBV), *Pea seed borne mosaic virus* (PSbMV), *Broad bean true mosaic virus* (BBTMV) and *Pea streak virus* (PeSV), but should also include testing to ensure that emerging viruses from Europe, such as the nanoviruses, are not establishing in the UK.

- **Grow in absence of vectors**: Any future survey programme should include an aphid monitoring programme and diagnostics should be developed to allow for aphids to be tested for the presence of viruses supporting epidemiological study.

- **Isolate from similar crops**: If surveillance is carried out into the viruses present in crops, this should be initially carried out on a regional basis and near neighbour crops could be compared for relative virus presence and incidence.

- **Use resistant (or tolerant?) varieties**: Field survey should include a review of resistance status of any cultivars surveyed and this information can be used to assess the relative virus health of crops.

Ultimately a decision support system for the industry would be required to allow the prediction of virus outbreaks and assess the risk of virus in individual crops. Assessing the applicability of existing models may facilitate the development of such a system but at present the knowledge gaps regarding the UK pea crop pathosytem may be too great for such models to be of immediate use.

Financial Benefits

Given the high degree of uncertainty around what viruses are present, their incidence and impact and the complication of potential multiple infections in a crop it is difficult to give any indication of potential financial benefits at this point. Work in Australia estimated yield losses from PSbMV at between 13%-25%, but this was influenced by the inoculum level in input seed and whether prevailing conditions were conducive to aphid transmission of the virus.

Action Points

There are no action points for growers arising from this review.

SCIENCE SECTION

Introduction

Pea (*Pisum sativum*) is an important legume crop which is grown worldwide for consumption by humans and animals. Pea plants are also form a key part of cereal rotations partly to act as a break crop to help manage disease, but also to improve soil fertility as a consequence of nitrogen fixing (Congdon et al., 2017b; Coutts et al., 2008). Using peas, or other legumes, in rotation can greatly reduce the need for application of pesticides and synthetic nitrogen fertilizer (Cernay et al., 2015). The European Union is looking to increase the production of legume crops in order to reduce negative impacts on the environment from use of fertiliser and also to reduce imports of soybean from America (Cernay et al., 2015). However, changing the crops grown in an area can lead to changes in pathogen pressure, which in turn make predicting diseases more difficult.

There are a broad range of viruses which are known to infect pea. The web-source 'Plant Virus Online' (Brunt et al., 1996) lists 124 viruses which have the ability to infect peas, however, only 43 of these viruses were reported occurring from natural infections with the remainder having pea listed as an experimental host. In most cases, the limiting factor to an experimental host being a natural host is opportunity, and there will be some barrier to transmission between natural and experimental hosts within the virus-vector-host relationship. As plant viruses require some form of vector to mediate onward transmission vector specificity can limit the spread of viruses between susceptible hosts of different botanical species. In other cases, the limiting factor may be one of climate, seasonality, geography or some other agro-ecological barrier which means that potential hosts of different botanical species are isolated from each other spatially or temporally.

The earliest comprehensive report on the status of pea viruses in the UK came from Hagedorn (1958), who made observations of diseases on peas across several European countries (England, West Germany, The Netherlands, Switzerland and Sweden). As this report was based on symptomatic observation it includes descriptions such as 'enation mosaic', 'mosaic', 'pea streak', 'pea stunt disease' and 'top yellows'. Whilst some of these symptoms may be indicative of infection with some viruses, the reported diseases were not supported by effective diagnostics and therefore it is unknown which viruses were present in the field at the time. It is also not known whether infected plants were only infected with a single virus or whether there were multiple viruses present. Based upon more recent work it is possible to deduce that 'Top yellows' may be *Bean leaf roll virus*; 'Pea stunt' is likely to be *Red clover vein mosaic virus*; and 'Enation mosaic' is probably *Pea enation mosaic virus*. However, both

‘Pea streak’ and ‘Mosaic’ are symptoms associated with several viruses and cannot be taken as being necessarily indicative of infection with a particular virus.

Disease incidence surveys have always had a challenge of how to best express disease levels both within and between crops, for instance how to compare a few fields in one region with a high percentage of infection with another region where many fields are infected, but at a low level of prevalence. Hagedorn (1958) observed the incidence of disease multiple fields in each country, recording the severity of infection in each field from ‘trace’ (less than 1% infected) through to ‘very severe’ (26% or more infected). In the report the author states that observations were conservative and only counted plants which were obviously infected. Often the symptoms caused by viruses are confused with those caused by water stress, herbicide damage and nutrient deficiencies, this has led to underestimates of viruses in many plants including legumes (Latham and Jones, 2001). Some viruses produce very mild symptoms, or can even be latent in the season of infection, which would be underreported without supporting diagnostic testing. Hence, Hagedorn (1958) gives a ‘snap shot’ of virus diseases occurring in Europe at the time, though specific disease incidences will be underestimates of actual virus incidence as his observations will likely have missed infected plants. Even with these caveats applied, this report still forms the most comprehensive UK and/or Europe-wide survey of pea viruses to date. An overview of the findings of this report are given in Table 1. This represents the first reports of ‘pea stunt’ and ‘top yellows’ in England. It is also apparent from these data that the levels of all the viruses appeared markedly similar throughout Northern Europe.

Table 1. Table of virus incidence in five European countries taken from (Hagedorn, 1958). Percentage reported is number of fields which had the virus present, regardless of severity.

	% Fields affected with virus like symptoms				
Country (number of fields visited)	Enation mosaic	Mosaic	Streak	Stunt	Top yellows
England (14)	100	29	71	7	43
The Netherlands (25)	72	36	56	4	56
West Germany (11)	64	64	36	18	45
Sweden (22)	5	9	5	5	N/A
Switzerland (39)	31	3	46	15	23

Through the 1960s and 1970s several pea infected viruses were also confirmed as occurring in the UK such as *Red clover mottle virus* on red clover (Sinha, 1960), *Pea early-browning virus* on pea (Gibbs and Harrison, 1964), *Red clover vein mosaic virus, Clover yellow vein virus* and *White clover mosaic virus* in white clover (Gibbs et al., 1966). However, since no subsequent surveys of viruses in pea crops have been conducted, the current incidence and importance of viruses in the UK pea crop is not known. Occasionally pea samples are submitted to the plant clinic(s) at Fera and PGRO with symptoms consistent with virus infection but these appear to be of an unknown aetiological cause (e.g. see Figure 1).

Figure 1. Peas exhibiting symptoms consistent with virus infection such as ‘tennis balling’, but of unknown cause (Picture: Fera Science Ltd).

There is a similar situation in Europe with little recent data regarding the breadth of pea virus infections. Where surveillance activity has been carried out this has been in relation to the emergence of a new and damaging genus of legume affecting viruses, the *Nanoviruses* (Grigoras et al., 2014). This is in response to a finding of a new virus *Pea necrotic yellow dwarf virus*, which spread throughout Germany and has recently been found in the Netherlands and Austria (Gaafar et al., 2016; Gaafar et al., 2017). However, these surveys were not broad ranging in scope, but instead focused on this novel emerging virus genus looking at the presence of these in legumes in some European countries. Limited surveys on viruses of legumes have also been performed in New Zealand (Fletcher, 1993) and North Africa and West Asia (Makkouk and Kumari, 2009).

The other area where there has been a concentration of recent work is Australia where the pulse industry has been growing steadily since the 1980s. Areas previously used for farming cereals and sheep are now been used to grow a range of legumes. The alternative crop legume program in West Australia promoted the use of legumes, other than narrow-leaved lupin, which are more suited to growing in shallow, fine, alkaline soils (Latham and Jones, 2001). This promoted surveys looking at the incidence of viruses in peas and other legumes, to determine their importance. This information has then then been used to both predict and control these viruses (Congdon et al, 2017).

Materials and methods

A literature search was undertaken to try to ascertain current knowledge of pea viruses around the world, and to relate these to the state of knowledge of the viruses affecting the UK pea crop. The literature search utilised several sources to identify relevant literature principally Google Scholar, Web of Science, CAB-Abstracts and the CABI Crop Compendium. In addition to formally published scientific literature (i.e. book chapters and journal papers) other sources of information included conference proceedings, publicly available project reports, and a PhD thesis. The literature search focused on the following areas:

- Establishing which viruses which had been previously reported from UK pea crops.
- Viruses present in the UK which can affect peas, but had not previously been reported from pea crops in the UK.
- Pea affecting viruses present in Europe, and subsequently the rest of the world, which are not currently present in the UK
- The epidemiology of each of these viruses
- The incidence and impact of pea viruses including potential for yield and quality losses, where reported.
- Detection methods.
- Control methods being utilised
- The application of models for the prediction of outbreaks and potential losses.

Results

Descriptions of Pea viruses

Plant Virus Online (Brunt et al., 1996) lists 124 viruses as being able to infect peas, however literature on natural infections could only be found on around 40 viruses. The following section contains tables of pea affecting viruses accompanied by brief descriptions for each of these viruses.

Some broad host range viruses such as *Tobacco rattle virus* have been reported as having pea as a susceptible host. However, for this virus pea is only a 'local lesion host' on mechanical inoculation (Robinson, 2003). As the infection is localised and does not develop systemically viruses such as this have been discounted from this review as pea does not constitute a host in the sense of a virus source for onward transmission.

As previously discussed viruses require vectors for transmission, in some cases there may be also a second dispersal route which mediates the movement of the virus into a crop. In the case of viruses where seed transmission is deemed to be the primary dispersal route, and vector transmission is of secondary importance these are listed under the dispersal route, rather than the mode of transmission.

The mode of transmission listed for each aphid transmitted virus is related to the specific mechanism of transmission and this can in turn be taken as an indication of the rapidity of a transmission event:

Non-persistent transmission occurs where the virus particles adhere to the inside of the aphid stylet during feeding. This mode of transmission is characterised by rapid acquisition and transmission, typically in less than a few minutes. This means that the action of 'probe feeding' by the aphid trying to find a suitable host plant can be enough for onward transmission. This mode of transmission is also characterised by the least virus-vector specificity and viruses with this mode of transmission often have a broad suite of potential aphid vectors. In many cases it has been noted that the efficiency of transmission will vary between species and between biotypes of each species (Congdon et al., 2017b; Fox et al., 2017). This rapid acquisition and transmission inevitably means that viruses with this mode of transmission can present challenges to traditional aphicide based virus management as transmission is often more rapid than the chemical knockdown of the aphid vector.

Persistent transmission refers to transmission which occurs after the virus has passed through the aphid mid-gut and has become circulative. Viruses with this mode of transmission typically have much longer times required for acquisition of the virus by the aphid vector, and have a 'lag' phase whilst the virus becomes circulative in the aphid. This means there may be several hours between the initial vector feed and the vector being able to transmit that virus onward. This time lag means that aphid transmitted viruses should be able to be managed through chemical control. Because this type of transmission depends on a specialised close inter-relationship between the aphid and the virus (and even a symbiotic bacterium e.g. (Bouvaine et al., 2011) the number of species able to transmit a given virus tends to be limited.

Pea affecting viruses present in the United Kingdom

The viruses listed in Table 2 are the seven viruses which have been recorded in the UK occurring on pea crops. Table 3 lists those viruses which have been recorded as present in the UK, and are known to infect pea crops elsewhere, but have not been previously reported from peas within the UK. Below each table the viruses are listed with a brief description to accompany the information listed in the table.

Table 2. Table of viruses known to occur in pea crops in the UK. Vectors listed in bold are present in the UK.

Virus	**Acronym**	**Spread / mode of transmission**	**Vector**	**Reference**
Seed-borne dispersal				
Pea early-browning virus	PEBV	Nematode transmission	***Paratrichodorus anemones, P. pachydermus, Trichodorus primitivius, T. viruliferous***	(Boulton, 1996; Gibbs and Harrison, 1964; Wang et al., 1997)
Pea seed borne mosaic virus	PSbMV	Aphid transmission: Non-persistent Wind-mediated (plant to plant) transmission	***Macrosiphum euphorbiae*, *Myzus persicae***, ***Acyrthosiphon pisum***, *A. craccivora,* ***Aphis fabae****, Dactynotus escalanti,* ***Rhopalosiphum padi***	(CABI, 2015) (Congdon et al., 2016b)
Transmitted by aphids				
Bean leaf roll virus	BLRV	Persistent transmission	***A. pisum,*** *A. craccivora,* ***M. persicae***	(Cockbain and Gibbs, 1973; Koike et al.,

				2007; van Leur et al., 2013)
Bean yellow mosaic virus	BYMV	Non-persistent transmission (Seed transmission is thought to be uncommon)	***A. pisum, M. euphorbiae, M. persicae, A. fabae***	(Sutic et al., 1999)
Pea enation mosaic virus	PEMV	Persistent transmission	***A. pisum, M. euphorbiae, M. persicae***	(Cockbain and Gibbs, 1973; Smith, 2012; Sutic et al., 1999)
Pea streak virus[1]	PeSV	Non-persistent transmission	***A. pisum***	(Biddle and Cattlin, 2007)
Transmission (other)				
Broad bean true mosaic virus	BBTMV	Transmitted by weevils	***Sitona lineatus***, ***Apion vorax***	(AC-Diagnostics; Gibbs and Paul, 1970)

[1] PeSV No confirmed formal report of PeSV in UK, See table 2.

Bean leaf roll virus (BLRV), also known as 'pea leaf roll virus' is a *Luteovirus* which causes stunting, chlorosis of upper leaves and leaf roll. The virus causes a disease known as 'Pea top yellow virus' (Cousin, 1997). BLRV is persistently transmitted by *Acyrthosiphon pisum*, *Aphis craccivora* and *Myzus persicae* but is not transmitted by seed (Freeman and Aftab, 2011; Koike et al., 2007).

Bean yellow mosaic virus (BYMV) also known as Pea common mosaic virus and Pea mosaic virus is a *Potyvirus* (Freeman and Aftab, 2011; Sutic et al., 1999; Taylor and Smith, 1968). In pea, BYMV causes a mild mottle and vein chlorosis and can cause necrosis in the stem. BYMV is non-persistently transmitted by many aphids including *Macrosiphum euphorbiae, A. pisum, M. persicae* and *Aphis fabae* (Sutic et al., 1999). BYMV can be transmitted by seed but this is uncommon (Bos, 1970).

Broad bean true mosaic virus (BBTMV) previously reported as 'Echtes Ackerbohnenmosaik-Virus' (EAMV) is a *Comovirus* which causes chlorosis, leaf distortion,

vein clearing and later in infection can cause necrosis of the stem and the plant to become bushy (Sutic et al., 1999). BBTMV is transmitted by weevils *Sitona lineatus* and *Apion vorax* but was not found to be spread by aphids or pollen beetles (Cockbain et al., 1975). BBTMV is seed-borne on field bean (Jones, 1978).

Pea enation mosaic virus (PEMV) is an *Enamovirus* which causes distortion of leaves, pods and stem, vein clearing, mottling and stunting of the plant (See Figure 2). PEMV also causes proliferations on the underside of leaves which are called enations (Cousin, 1997; Sutic et al., 1999). PEMV is transmitted by aphids in a persistent manner by *A. pisum, M. euphorbiae* and *M. persicae* (Smith, 2012).

Figure 2. *Pea enation mosaic virus* showing veinal chlorosis/clearing and mottling (Picture courtesy of PGRO)

Pea early-browning virus (PEBV) is a *Tobravirus* which causes necrosis on leaves, stem and pods (See Figure 3) and causes the seed coat to be wrinkled and green/grey in colour (Boulton, 1996; Sastry, 2013; Sutic et al., 1999). PEBV is transmitted by seed and nematodes. In England they are transmitted by *Paratrichodorus anemones*, P. pachydermus, *Trichodorus primitivius* and *T. viruliferous* (Goodey, 1963; Sutic et al., 1999; Wang et al., 1997).

Figure 3. Pea plants with necrotic leaves caused by infection with *Pea early browning virus* (Picture courtesy of PGRO)

Pea seed-borne mosaic virus (PSbMV) is a *Potyvirus* which can cause mosaic, distortion of leaves and pods and stunting of the plant (Koike et al., 2007) but these symptoms are often subtle and hard to spot in the field (Coutts et al., 2009). PSbMV can also cause discolouration and necrotic rings on pea seed, which in the past have been mistakenly attributed to other causes such as environmental stresses or fungal disease (Coutts et al., 2008). PSbMV is primarily spread by seed, plants grown from infected seed act as a primary source of inoculum. Virus from these infected plants may then spread to neighbouring plants wind-mediated plant to plant contact before onward transmission by aphids (Congdon et al., 2016b). PSbMV is non-persistently transmitted by many aphids, including *M. euphorbiae, M. persicae*, *A. pisum*, *A. craccivora, A. fabae, D. escalanti* and *R. padi* (Khetarpal and Maury, 1987; Rao et al., 2008).

Pea Streak Virus (PeSV) is a *Carlavirus.* The virus is mainly transmitted by the pea aphid (*Acyrthosiphon pisum*) (Biddle and Cattlin, 2007). It causes severe necrotic streaking (brown/dead tissue) of stems and petioles. Tops of plants may be mottled or chlorotic. Pods remain unfilled with pit marks on the surface (See Figure 4) and there is a purple discolouration of pods. Symptoms appear later in the growing season when pods are formed but not filled. If infection is early plants become severely affected and may die before flowering (Bos, 1973).

Figure 4. Pitting on pod surface caused by infection with Pea streak virus (picture courtesy of PGRO).

Table 3. Viruses which are found in the UK and can infect peas, but have not been reported from UK pea crops.

Virus	Acronym	Distribution	Spread	Vector	Reference
Aphid transmission Non-persistent					
Alfalfa mosaic virus	AMV	Worldwide		*Acyrthosiphon pisum, A. kondoi, Aphis craccivora, A. gossypii, A. spiraecola* and *Myzus persicae*	(Bergua et al., 2014)
Bean common mosaic virus	BCMV	Worldwide	Experimental host	*A. pisum, A. fabae* and *M. persicae*	(Bos, 1971)
Beet mosaic virus	BtMV	Worldwide		*A. fabae* and *M. persicae*	(Russell, 1971)
Broad bean wilt virus 1	BBWV1	Europe, Japan, New York and Australia		*M. persicae, A. craccivora, Macrosiphum euphorbiae* and *A. fabae.*	(Taylor and Stubbs, 1972)
Broad bean wilt virus 2	BBWV2	Worldwide		*M. persicae, A. pisum* and *A. craccivora*	(Zhou, 2002)
Clover yellow vein virus	ClYVV	UK, Bulgaria, Canada, USA		*A. pisum, M. euphorbiae, M. persicae* and *Aulacorthum solani*	(Gibbs et al., 1966; Larsen et al., 2008; Pasev et al., 2014; Singh and López-

					Abella, 1971)
Cucumber mosaic virus	CMV	Worldwide		*A. kondoi, A. craccivora, A. glycines, A. gossypii, A. spriaecola, A. solani, Lipaphis erysimi, M. europhbiae and M. persicae*	(CABI, 2017a)
Lettuce mosaic virus	LMV	Worldwide	Experimental host	*A. pisum, M. persicae* and *M. euphorbiae*	(Le Gall, 2003)
Red clover vein mosaic virus	RCVMV	UK, Europe, USA, India and New Zealand	Can be transmitted by seed	*A. pisum, M. persicae, Therioaphis ononidis, Cavariella aegopodii* and *C. theobaldi*	(Fletcher et al., 2015; Varma, 1970; Varma et al., 1970)
Turnip mosaic virus	TuMV	Worldwide		*M. persicae* and *Brevicoryne brassicae*	(Tomlinson, 1970)
Watermelon mosaic virus	WMV	Worldwide		*Ageniaspis citricola, A. craccivora, A. solani, A. gossypii, M. persicae, M. euphorbiae* and *Toxoptera citricidus*	(Plantwise)
Aphid transmission: Persistent					
Beet western yellows virus	BWYV	UK, Europe, Asia, North America, Australia		*A. craccivora, A. solani, B. brassicae*, *M. orantus*, *M. persicae, A. kondoi*, *Hyperomyzus*	(CABI, 2016b)

		and New Zealand		*lactucae*, and *Therioaphis trifolii forma maculate*	
White clover mosaic virus	WClMV	UK, USA and New Zealand	Possibly seed borne	*A. pisum*	(Fry, 1959; Gibbs et al., 1966; Zhao et al., 2016)
Other mechanism of transmission					
Broad bean mottle virus	BBMV	UK and Morocco	Weevils	*Sitona lineatus*	(Fortass and Diallo, 1993; Gibbs, 1972)
Broad bean stain virus	BBSV	Europe and North-West Asia	Weevils	*Apion vorax* and *S. lineatus*	(Gibbs and Smith, 1970)
Red clover mosaic virus	RCMV	UK, Northern Europe	Vectors not known		(Valenta and Marcinka, 1971)
Tobacco necrosis virus	TNV	Worldwide	Fungus	*Olpidium brassicae*	(Kassanis, 1970)
Tobacco streak virus	TSV	Worldwide	Thrips	*Frankliniella occidentalis, F. schultzei* and *Thrips. tabaci*	(CABI, 2016f)
Tomato black ring virus	TBRV	UK, Europe and Turkey and India.	Nematodes. Also known to be seed borne.	*Longidorus attenuates* and *L. elongates*	(EPPO, 1990)

Tomato spotted wilt virus	TSWV	Worldwide	Thrips	*F. occidentalis*, *F. fusca, F. intonsa, F. schultzei, F. bispinosa, T. palmi, T. tabaci* and *T. setosus*	(CABI, 2017b)

Alfalfa mosaic virus (AMV) is an *Alfamovirus* which occurs worldwide and can infect over a hundred different plant species, including pea (Bergua et al., 2014; Fletcher, 1993; Freeman and Aftab, 2011). On pea AMV can cause symptoms such as mosaic, malformed pods and slower growth (Esfandiari et al., 2005). AMV is non-persistently transmitted by aphids, such as *A. pisum, A. kondoi, A. craccivora, A. gossypii, A. spiraecola* and *M. persicae*, and has been shown to be seed transmitted in alfalfa plants (CABI, 2016a; Frosheiser, 1973).

Bean common mosaic virus (BCMV) is non-persistently transmitted by *A. pisum, A. fabae* and *M. persicae* (Bos, 1971). A strain of the potyvirus BCMV was shown to infect pea, but did not produce symptoms (Provvidenti, 1991).

Beet mosaic virus (BtMV) is a *Potyvirus* which causes necrotic stripes and clearing of stems and veins, and wilting of leaflets on pea (Russell, 1971; Sutic et al., 1999). BtMV is non-persistently transmitted by a number of aphids including *M. persicae* and *A. fabae* (Russell, 1971).

Beet western yellows virus (BWYV) is a *Polerovirus* which causes stunting and yellowing on pea. BYMV is persistently transmitted by aphids, a survey in Australia found that *A. craccivora, Aulacorthum solani, Brevicoryne brassicae, M. orantus, M. persicae, A. kondoi, Hyperomyzus lactucae* and *Therioaphis trifolii forma maculate (Aftab and Freeman, 2013).*

Broad bean mottle virus (BBMV) is a *Bromovirus* which has been found to naturally infect pea, and other legumes. Fortass and Diallo (1993) found that the virus could be transmitted by weevils, *S. lineatus* was able to transmit BBMV between faba bean and pea. On pea the virus causes lethal systemic wilt (Gibbs, 1972).

Broad bean stain virus (BBSV) (synonyms Pea mild mosaic virus and Pea green mottle virus) is a *Comovirus* (Clark, 1972; Harrison and Murant, 2013; Perez-Egusquiza et al., 2014). The virus causes vein clearing, necrosis and leaf rolling. BBSV has shown to be seed transmitted on faba bean (Cockbain et al., 1976) and can be transmitted by weevils *A. vorax* and *S. lineatus* (Summerfield, 2012). BBSV was shown not to be transmitted by aphids, *A. pisum* and *A. fabae*, or pollen beetles (Cockbain et al., 1975).

Broad bean wilt virus 1 (BBWV-1) and ***Broad bean wilt virus 2*** (BBWV-2) were originally thought to be one virus, they were then described as two serotypes of the virus before finally being recognised as two viruses. Both are part of the *Comovirus* genus and are both able to infect pea (Uyemoto and Provvidenti, 1974). Sutic et al. (1999) gave a general description of symptoms caused by BBWV on pea, including dwarfing, leaf roll, chlorosis on leaves and necrosis of pods preventing seed development. Both viruses are transmitted in a non-persistent manner by aphids, *M. persicae* and *A. craccivora*. BBWV1 can also be transmitted by *M. euphorbiae* and *A. fabae* was able to transmit an isolate found in nasturtium. BBWV2 has also been shown to be transmitted by *A. pisum* and one isolate of BBWV2 was found to be seed-borne on broad bean but at a low frequency (Taylor and Stubbs, 1972; Zhou, 2002).

Clover yellow vein virus (ClYVV) is a *Potyvirus* which can causes necrosis and chlorosis in peas and other legumes (Hisa et al., 2014). Experiments on coriander showed that *A. solani, A. pisum*, *M. euphorbiae* and *M. persicae* were able to non-persistently transmit ClYVV (Hollings and Stone, 1974; Singh and López-Abella, 1971).

Cucumber mosaic virus (CMV) is a *Cucumovirus* which causes chlorotic mottle and necrotic spots on pea plants (Sutic et al., 1999). CMV is non-persistently transmitted by aphids such as *A. kondoi*, *A. craccivora*, *A. glycines, A. gossypii, A. spiraecola, Aulacorthum solani, Lipaphis erysimi, M. euphorbiae, M. persicae* (CABI, 2017a; Freeman and Aftab, 2011). Fukumoto et al. (2003) found that pea plants infected with both CMV and *Watermelon mosaic virus* (WMV) may have more severe symptoms that those peas infected with CMV alone. CMV has the broadest known host range of any virus with over 1200 host species.

Lettuce mosaic virus (LMV) can infect pea, at least experimentally. LMV causes mosaic symptoms and vein clearing on pea. LMV is seed-borne in lettuce and can be non-persistently transmitted by a number of aphids including *A. pisum, M. persicae* and *M. euphorbiae* (Le Gall, 2003).

Red clover mottle virus (RCMV) is a *Comovirus* which can affect the shoot apices and cause a slight mosaic symptom (Valenta and Marcinka, 1971). The virus was mechanically transmitted on to legumes, but was not found to be transmitted by soil, seed or six aphids tested (Sinha, 1960).

Red clover vein mosaic virus (RCVMV) is a *Carlavirus* (Fletcher et al., 2015). RCVMV has been shown to cause mild chlorosis, a rosette shape of leaves, and violet steaks on the leaf petioles, stem and veins. Infection of the pods can prevent the formation of seeds and peas which show necrosis often die (Sutic et al., 1999). RCVMV has been responsible for severe crop losses on pea, chickpea and lentils in India and the USA, it was recently found to be in New Zealand though it did not seem to give visible symptoms so the losses are probably

negligible (Fletcher et al., 2015). RCVMV is non-persistently transmitted by *A. pisum, Cavariella aegopodii, C. theobaldi, M. persicae* and *Therioaphis ononidis.* RCVMV has also been reported to be transmitted by seed (Fletcher et al., 2015; Varma, 1970).

Tobacco necrosis virus (TNV) has been isolated from pea roots (Sutic et al., 1999). TNV is transmitted by the root infecting fungus *Olpidium brassicae* (Kassanis, 1970). Although the virus is occasionally found to cause superficial damage in potato tubers, little is known on the impact of this virus in other hosts.

Tobacco streak virus (TSV) is an *Ilarvirus* which can infect pea. TSV can cause a variety of symptoms on plants such as distortion, yellowing and necrosis on leaves and dwarfing. TSV is transmitted by thrips, *Frankliniella occidentalis*, *F. schultzei* and *Thrips tabaci* (CABI, 2016f).

Tomato black ring virus TBRV is a *Nepovirus* which has a wide host range, including *Phaseolus spp.* TBRV is spread by nematodes *Longidorus attenuates* and *L. elongates* and can be retained by the host for weeks. TBRV can also be spread in soil which contains viruliferous nematodes and seed (EPPO, 1990). Sutic *et al*. (1999) state that "Tobacco black ring virus" caused yellowing and ringspots on infected peas, however no other reference to this virus could be found. Sutic *et al.* (1999) could have meant *Tomato black ring virus* (TBRV) which Edwardson and Christie (1991) list as infecting pea, but no other reports of TBRV on pea could be found.

Tomato spotted wilt virus (TSWV) is a *Bunyaviridae* which has a wide host range (approximately 800 species), and causes wilting of flowers, necrosis spots on pods and upper leaves and brown-purple colouration of stem (Salamon et al., 2012; Sutic et al., 1999). TSWV is persistently transmitted by thrips, *F. occidentalis*, *F. fusca, F. intonsa, F. schultzei, F. bispinosa, T. palmi, T. tabaci* and *T. setosus* and transmission of seed is thought to be very rare (Kormelink, 2005). The virus is recorded as only having a limited distribution in the UK, and is largely limited to outbreaks in protected edibles and ornamentals where the conditions under glasshouse protection are more favourable for the survival of the vector.

Turnip mosaic virus (TuMV) is a *Potyvirus* causes chlorotic mottle, necrotic mottle, deformation of pods and leaves, and stunting in pea (Segundo et al., 2003). TuMV is non-persistently transmitted by a number of aphids, including *M. persicae* and *B. brassicae* (Tomlinson, 1970).

White clover mosaic virus **(**WClMV) is a *Potexvirus* which causes mosaic and mottle symptoms on legumes (Hisa et al., 2014). A strain of WClMV has been reported to be transmitted by *A. pisum*, but others have failed to repeat this. There is also a record of WClMV being transmitted by seed, though not specifically from pea (Bercks, 1971).

Viruses of peas: reports originating from Europe and the rest of the world

As part of horizon scanning activity, it was also noted that there are several viruses which are known to be present in Europe which have not been previously reported from the UK, these are presented in Table 4. Among these viruses are those with a broad distribution across Europe, which present the greatest potential for future outbreaks in the UK. Those with a distribution outside Europe, but with only a limited distribution within mainland Europe, or those limited to the South and East of the continent may be considered to present a lower risk to the UK at present. Table 5 presents those viruses which have been recorded on pea crops elsewhere in the world. Whilst these present the lowest risk for future incursions into the UK, the emergence of these viruses should be monitored and tracked in the scientific literature to ascertain any change in this level of risk.

Table 4 Viruses present in Europe but not previously reported from the UK

Virus	Acronym	Distribution	Spread	Vector	Reference
Aphid transmission: Non-persistent					
Cowpea aphid-borne mosaic virus	CABMV	Netherlands, Germany, Italy, Hungary, Africa, Asia, USA, South America and Australia	Can be seed-borne	*Aphis fabae, A. gossypii, A. medicaginis, A. craccivora, Macrosiphum euphorbiae* and *Myzus persicae*	(CABI, 2016c)
Peanut mottle virus	PeMoV	Bulgaria, East Africa, Japan, Malaysia, Australia, USA and South America.		*A. gossypii, A. craccivora, Hyperomyzus lactucae* and *Rhopalosiphum padi*	(Bock and Kuhn, 1975)
Pea streak virus	PeSV	Germany, Czech		*Acyrthosiphon pisum*	(Sarkisová et al., 2016;

		Republic, USA and Canada			Sutic et al., 1999)
Peanut stunt virus	PSV	Europe, Sudan, China, Korea, Japan and USA.	Seed-borne on peanut	*A. craccivora, A. spiraecola, M. persicae*	(Plantwise)
Aphid transmission: Persistent					
Soybean dwarf virus	SbDV	Germany, North and West Africa, East and West Asia, Australia and USA.		*Aulacorthum solani*, *Nearctaphis bakeri*	(CABI, 2016e)
Black medic leaf roll virus	BMLRV	Austria, Azerbaijan and Sweden		Unknown	(Grigoras et al., 2014)
Faba bean necrotic yellow virus	FBNYV	Spain, Western Asia and Northern Africa		*A. pisum, A craccivora* and *A. fabae*	(CABI, 2016d)
Pea yellow stunt virus	PYSV	Austria			(Grigoras et al., 2014)
Pea necrotic yellow dwarf virus	PNYDV	Germany, Netherlands		*A. pisum* (Experimental)	(Gaafar et al., 2017; Grigoras et al., 2010)
Other					

Pea false leaf-roll virus		Germany	Reported to be seed-borne and to be transmitted by oomycetes and aphids	*Pythium spp.* and *Myzus persicae*	(Smith, 2012)

Cowpea aphid-borne mosaic virus (CABMV) is a *Potyvirus* which causes different symptoms depending on the cultivar, most show a systemic mottle while Laxton is symptomless. CABMV is seed borne and non-persistently transmitted by aphids, *A. fabae, A. gossypii, A. medicaginis, A. craccivora*, *M. euphorbiae* and *M. persicae* (Bock and Conti, 1974).

Faba bean necrotic yellows virus (FBNYV) is a *Nanovirus* which causes leaf rolling, stunting, yellowing and necrosis of leaves in *Vicia faba* (CABI, 2016d; Makkouk et al., 2003) and has been known to naturally infect pea (Fauquet et al., 2005). FBNYV is also transmitted persistently by aphids, *A. pisum, A. craccivora* and *A. fabae* (CABI, 2016d; Sicard et al., 2015).

Pea false leaf-roll virus was found in Germany in 1968. The virus caused leaf roll, necrosis and discolouration of leaves. The virus was transmitted in the soil by *Pythium spp.*, by the aphid *M. persicae* and it was seed-borne on pea (Smith, 2012).

Peanut mottle virus (PeMoV) is a *Potyvirus* which causes necrosis and systemic mottle on pea, the severity differs between virus strains and cultivars. PeMoV is transmitted non-persistently by the aphids *A. gossypii, A. craccivora, H. lactucae, M. persicae* and *R. padi*. Seed transmission does occur in groundnut but does not seem to seed-borne in pea (Bock and Kuhn, 1975).

Pea necrotic yellow dwarf virus (PNYDV) is a *Nanovirus* which causes stunting, leaf rolling and yellowing of the tops of pea plants (Grigoras et al., 2010) (See Figure 5). PNYDV was first found in pea in Germany in 2009 (Grigoras et al., 2010), since then it has been found infecting faba bean, lentil and vetch in Austria and Germany where it caused significant yield loss (Gaafar et al., 2016). More recently it was found in a routine survey of peas in the Netherlands (Gaafar et al., 2017). PNYDV is transmitted by aphids in a persistent circulative, non-propagative manner (Gaafar et al., 2017). Grigoras *et al.* (2010) were able to transmit

PNYDV from peas to faba bean using *A. pisum*, at least experimentally this aphid has been shown to spread the virus.

Figure 5. Pea plant infected by *Pea necrotic yellow dwarf virus* (right) showing chlorosis and dwarfing with a healthy pea plant (left) for comparison. Picture by kind permission of H. Ziebell, JKI-Braunschweig, Germany.

Pea streak virus (PeSV) is a *Carlavirus*, late season infection can cause purple or brown streaks on stems, brown lesions on pods and necrotic spots on leaves and early infection kills most pea cultivars. PeSV is non-persistently transmitted by *A. pisum* (Hampton and Weber, 1983). Biddle and Cattlin (2007) record PeSV as common in the USA where the virus and aphid overwinter on alfalfa, and that the virus is occasionally found in Europe, and potentially the UK. No formal report could be found of the presence of PeSV in the UK, hence the inclusion herewith the formal reports of the distribution of PeSV.

Peanut stunt virus (PSV) is a *Cucumovirus* which Echandi and Hebert (1971) found could cause systemic mottle and stunting in the pea variety Alaska (Plantwise). PSV is non-persistently transmitted by aphids, *A. craccivora, A. spiraecola* and *M. persicae*, and is seed borne on peanut (Mink, 1972).

Soybean dwarf virus (SbDV) is a *Luteovirus* which can be symptomless or cause mild yellowing in pea. SbDV has been found to be transmitted by *Nearctaphis bakeri* and persistently transmitted by *A. solani* (Harrison et al., 2005; Tamada and Kojima).

In 2014 Grigorias *et al.* conducted a survey of legumes in Europe to look for nanoviruses. In this study they discovered two new viruses ***Pea yellow stunt virus*** in pea in Austria and ***Black medic leaf roll virus*** in pea and black medic (*Medicago lupulina*) in Austria, Azerbaijan and Sweden. Due to the recent discovery of these viruses little is known about their broader characterisation.

Table 5. Pea viruses reported from outside of Europe.

Virus	Acronym	Distribution	Spread	Vector	Reference
Broad bean mild mosaic virus		Unknown	Unknown	Unknown	(Sutic et al., 1999)
Broad bean necrosis virus	BBNV	Japan	Thought to be transmitted by fungi in soil	Unknown	(Inouye and Nakasone, 1980)
Cowpea severe mosaic virus	CPSMV	USA and South America	Transmitted by beetle, seed transmission reported in cowpea and aspagus bean.	Beetles from the *Chrysomelidae* family	(de Jager, 1979; Edwardson and Christie, 1991)
Milk vetch dwarf virus	MDV	Japan	Persistent aphid transmission	*A. craccivora*	(Sano et al., 1998)
Pea stem necrosis virus	PSNV	Japan	Transmitted by fungus	Fungi from *Olpidium* genus	(Osaki et al., 1988)
Peanut mild chlorosis virus		China	Unknown	Unknown	(Abraham et al., 2006)
Plantago mottle virus	PlMV	USA (New York)	Like to be transmitted by beetles	Unknown	(Prowidenti and

					Granett, 1976)
Subterranean clover mosaic virus	SCMoV	Australia	Mechanical transmission and low level of seed transmission	Mechanical transmission by animals and vehicles	(Jones et al., 2001)
Subterranean clover stunt virus	SCSV	Japan	Persistent aphid transmission	*A. craccivora*, *A. gossypii, M. euphorbiae* and *M. persicae*	(Chu and Vetten, 2003)
White lupin mosaic virus	WLMV	Idaho	Likely to be non-persistently transmitted by aphids	Unknown	(Provvidenti and Hampton, 1993)

Broad bean mild mosaic virus causes pea plants to grow slowly, shortened internodes and small curled leaves. Seed from the plants infected with this virus are misshapen and discoloured (Sutic et al., 1999).

Broad bean necrosis virus (BBNV) is a *Pomovirus* which can experimentally infect pea, causing necrotic streaks and flecks, mottling and stunting of the plant (Inouye and Nakasone, 1980).

Cowpea severe mosaic virus (CPSMV) is a *Comovirus* which is transmitted by beetles from the *Chrysomelidae* family and transmission by seed has been seen in cowpea and asparagus bean. Edwardson and Christie, 1991 record pea as a host but no other report of CPSMV on *Pisum* could be found. CPSMV is only found naturally in legumes, though has been found to experimentally infect a wider range of legumes and a small number of plants from different families. CPSMV infected plants often develop chlorotic or necrotic lesions in inoculated leaves, the virus can also cause distortion of leaves and systemic chlorosis and blistering (de Jager, 1979).

Milk vetch dwarf virus (MDV) is another nanovirus that can infect pea. It is persistently transmitted by *A. craccivora* and causes dwarfing and yellowing in pea and other hosts (Sano et al., 1998).

Pea stem necrosis virus (PSNV) is a *Carmovirus* which causes necrosis of stems, yellowing, wilting and vein necrosis. PSNV is transmitted though the soil by fungi belonging to the genus *Olpidium* (Osaki et al., 1988; Suzuki et al., 2002).

Pea mild chlorosis virus is a proposed member of *Polerovirus* genus, it was found in pea and faba bean. Sequencing showed it to be closely related to an isolate of a poleorvirus found in Ethiopia, which has the proposed name Chickpea chlorotic stunt virus (Abraham et al., 2006; Zhou et al., 2012).

Plantago mottle virus (PlMV) is a *Tymovirus* which causes necrosis, mottle and chlorosis on pea plants (Prowidenti and Granett, 1976). The transmission of PlMV has not been confirmed, but other tymoviruses are transmitted by beetles, possibly though mechanical transmission or by an association between beetle and virus. There are two cases where tymoviruses have been transmitted by aphids or seed (Koenig and Lesemann, 1979).

Subterranean clover mottle virus (SCMoV) is a *Sobemovirus* which can experimentally infect pea (cv. Greenfeast) and causes necrotic lesions. SCMoV is transmitted by seed at a low level and is mechanically transmitted e.g. animal and vehicles (Jones et al., 2001).

Subterranean clover stunt virus (SCSV) are SCSV infects clover in the wild but can experimentally infect pea, causing stunting, leaf rolling and chlorosis. SCSV can be persistently transmitted by *A. craccivora, A. gossypii, M. euphorbiae* and *M. persicae* (Chu and Vetten, 2003).

White lupin mosaic virus (WLMV) is a *Potyvirus* which can cause a range of symptoms depending on the pea cultivar, some produce a mild mottle whereas in other cultivars it caused severe necrosis (Provvidenti and Hampton, 1993).

Incidence and Impact

Yield losses due to viruses can vary due to the variety of plant, strain of virus, when the plant was infected with virus and the environmental conditions (Bos, 1982). Generally, the earlier in a season a plant is infected, the more severe the symptoms and greater the yield loss (Irwin et al., 2000). Losses can also be affected by the number of viruses infecting a plant, the infection of a plant with multiple viruses is common (Bos, 1982). During a survey in 1999, (Latham and Jones, 2001) found it common that pea crops would have two, or even three, viruses. Fletcher (1993) found that over half of pea crops had multiple infections. The effect on yield due to the presence of viruses varies. In many cases these yield loss data available for pea infecting viruses only covers alternate hosts, for example in cowpea cv. California Blackeye the yield of seed was reduced by 2.5% by *Blackeye cowpea mosaic virus* and 14% by CMV, separately. When the host was infected with both viruses the yield of seed was

reduced by 86%. Whereas, infection of red clover plants with *Red clover necrotic mosaic virus* reduced yield by 57% and infection with WClMV reduced yield by 22%. When red clover was infected with both viruses the yield was reduced by 57% (Bos, 1982). As previously mentioned, pea plants infected with both CMV and WMV had more severe symptoms than those with a single infection (Fukumoto et al., 2003).

Yield loss by viruses can either be from the infection reducing the growth of the plant, which could affect the pods, or, as in the case of PSbMV, reduction of seed quality. Pea plants infected with PSbMV may produce seed which have split seed coats, discolourations and reduction in seed weight (Coutts et al., 2009). These symptoms can cause either downgrading or rejection of the seed (Coutts et al., 2008).

In Western Australia, Latham and Jones (2001) found that of pea crops sampled, 15% were infected with AMV and 10% were infected with BYMV. Crops also tested negative for BWYV and PSbMV. While in 1999 of crops sampled, 56% were infected with BWYV, 18% were infected with BYMV, 6% were infected with CMV and 42% were infected with PSbMV. Crops tested negative for AMV. The use of clean input seed and exploiting varietal resistance is important in the control of PSbMV, which is highlighted by Coutts et al. (2008) who reported that the susceptibility and resistance of pea to PSbMV varied greatly between genotypes. In one experiment they found the incidence of PSbMV to be 1% for a highly tolerant genotype (WAPEA2128) through to 95% for the cultivar Snowpeak. In the same experiment, four commercial cultivars of pea had incidences of PSbMV ranging from 67-87% and were all recorded as being highly susceptible. (Coutts et al., 2009) recorded a yield loss of 25% in plants grown from 6.5% infected seed in a year when conditions favoured aphids. The following year, conditions were less favourable to aphids and yield loss from 8% infected seed was 13%.

Fletcher (1993) surveyed pea crops around Canterbury and Malborough in New Zealand in 1987 and 1989. The survey included processing crops, processing seed crops and field pea crops. Across the two regions, years and crop type percentage of crops infected with virus was between 11-80% for AMV, 11-100% for PSbMV, 0-100% SDV and 22-100% BWYV. Furthermore, 50 and 60% of process seed and field pea, respectively, were found to be infected with CMV in Canterbury in 1989 and 6.5% of field pea in Canterbury in 1987 were found to be infected with BYMV.

The *Nanoviruses* are rapidly emerging as important group of viruses in Europe. PNYDV caused high yield losses on pea and faba bean in the Austria (Gaafar et al., 2016) and FBNYV has caused the complete failure of faba bean crop in Egypt between 1992 and 1998 (Makkouk and Kumari, 2009).

Control

Aphids can cause losses on plants indirectly by spreading viruses and directly by feeding. Feeding damage of *A. pisum* on peas can cause a reduced number of pods and seed and reduced seed weight (McVean et al., 1999). Many of the viruses listed in this review are transmitted by aphids, in either a persistent or non-persistent manner. Non-persistently transmitted viruses are stylet-borne, they are quickly acquired by an aphid and can remain viable for a few hours, and they can also be lost after probing on a healthy plant. Non-persistent viruses can be acquired by a wide range of aphids, and due to the short viability time are spread over short distances. Conversely, persistently transmitted viruses can only be transmitted by a small number of aphids and are retained by the aphid for the rest of its life. Persistently transmitted viruses have a longer acquisition time, between minutes and several hours, and then undergo a latency period. As the aphid does not lose the virus, the virus can be spread over great distances (Hooks and Fereres, 2006; Makkouk and Kumari, 2009). It is also important to understand the epidemiology of each of the viruses as some viruses survive on weeds between cropping seasons which would mean control of the virus should involve removal of nearby weeds (Freeman and Aftab, 2011; Makkouk and Kumari, 2009).

Use of cultivars which are tolerant or resistant to prevalent viruses can help control yield loss. For some viruses, such as PSbMV, using varieties which are highly tolerant to the virus are important in disease management strategies. Latham and Jones (2001) discuss the importance of testing the susceptibility of cultivars, genotypes or species of plants to viruses which are important in that area. Planting a cultivar which is susceptible to viruses found in that area could lead to yield losses. This susceptible crop could then act as a primary inoculum, which could then cause infection in nearby crops. In New Zealand, peas with resistance to viruses have been bred due to previous outbreaks (Fletcher, 1993). For example, in New Zealand plants were bred which had a tolerance to SbDV. Fletcher (1993) proposes that a high incidence of SbDV in 1989 was due to the use of cultivars from USA and Europe which will have been bred to be resistant to BLRV, rather than SbDV.

The principal of ‘start clean, stay clean’ is one of the cornerstones of virus management. The use of input seed which has a low percentage of infection can also reduce the yield loss, and this can be ensured through the use of seed obtained from certification programmes. It has been shown in PSbMV on pea, and CMV on lupin, that using seed with low levels of infection resulted in lower incidences of virus, compared to when seeds were used with a higher level of infection (Congdon et al., 2017c; Thackray et al., 2004). This is because the plants grown from infected seed provide a primary source inoculum, aphids then acquire and spread the virus to neighbouring plants. However, this may not be true for all pathosystems.

Observations of *Soybean mosaic virus* (SMV) on soybean suggested that plants grown from infected seed did not have much effect on secondary spread of SMV because the plants grown from infected seed were stunted and overshadowed by surrounding healthy plants (Irwin et al., 2000). In order to reduce infection by PSbMV, it has been suggested to plant seeds at a greater depth to reduce survival of seedlings from infected seed (Congdon et al., 2017c). Additionally, in a system where a high level of seed-borne PSbMV is expected, the fractionation of seed into different size classes may also be helpful to minimise seed-borne transmission risk (Congdon et al., 2017a).

Sowing date may be adjusted according to when aphids are least active. It has been recognised that the early planting of faba beans in Syria and Egypt, leads to higher incidence of infection with FBNYV than when the crops are planted later. This is because there are fewer aphid vectors carrying FBYNV from nearby sources (Makkouk and Kumari, 2009). Whereas, for PSbMV a later sowing date is advised in some locations to avoid early aphid populations (Congdon et al., 2017c). Mature plants are generally more resistant to viruses than younger plants. Crops could be planted so that they will be mature when the aphid is most active, this could include using cultivars which mature early (Makkouk and Kumari, 2009).

Approaches to manage viral infections utilised in other crop systems should also be considered and explored for their potential. Though, no record could be found of the use of viral cross protection in pea crops, this emerging area should not be discounted as a possible management approach. Plants can be purposefully infected with a mild strain of a virus which then excludes infection by closely related isolates which could cause a more severe infection. Cross protection has been used successfully to control *Potyviruses* on a range of plants, for example it has been used to reduce yield losses in citrus orchards from *Citrus tristeza virus* and C*auliflower mosaic virus* on brussels sprouts (Irwin et al., 2000). This approach is also currently being used widely in Europe to minimize the impact of *Pepino mosaic virus* in tomato crops (Hanssen et al., 2010; Schenk et al., 2010). However, to use cross protection the mild strain of the virus must be monitored to ensure that it does not cause unwanted side effects. Cross protection may only provide protection to closely related viruses therefore protection against all viruses using this method would be impractical (Hooks and Fereres, 2006).

Other approaches can be taken in season to reduce the levels of virus inoculum, such as rogueing, i.e. the practice of removing visibly infected plants, thereby removing a source of virus inoculum, and this approach is commonly practiced in other crops such as potatoes. However, this is unsuitable where symptoms are unclear, and to be effective it needs to be done prior to vectors have started visiting the plants. Neither is it feasible in large-scale farming (Makkouk and Kumari, 2009).

Removal of weeds adjacent to crops can reduce virus incidence. Some weeds are hosts to viruses, these weeds can then act as a primary source of inoculum (Freeman and Aftab, 2011). Fletcher, 1993 proposes that the difference in incidence of CMV and BYMV between seasons in New Zealand may be due to the incidence of disease on nearby weeds. Weeds are also thought to be involved in the survival of viruses and aphids between cropping seasons (Freeman and Aftab, 2011). However, it should also be noted that weeds could give improved groundcover which has been linked to a reduction in aphid numbers (A'Brook, 1968) which could be taken as proxy for lowering risk from virus transmission.

These approaches all focus on reducing virus pressure by minimising (or eliminating) virus inoculum in the crop by planting clean seed and growing in the absence of sources of virus. The other key aspect of effective virus management is to reduce or eliminate the exposure of healthy plants to the vectors of viruses. In virtually all cases the work here focusses on aphid control. Chemical control of aphid vectors is more successful in controlling the spread of persistent viruses than non-persistent viruses (Bos, 1982). This is because aphids carrying non-persistent viruses are able to infect a plant before they are killed by the insecticide (Makkouk and Kumari, 2009). The application of insecticides may also cause an increase in aphid activity, which would then increase transmission of virus, this is thought to be due to aphids secreting an alarm pheromone and the insecticide also killing aphid predators and parasitoids (Hooks and Fereres, 2006; Irwin et al., 2000). There is also the problem of aphids becoming resistant to insecticides (Hooks and Fereres, 2006) and the effect of insecticides on the environment (Makkouk and Kumari, 2009).

Mineral oils may interfere with the ability of the aphid to retain virus, which in turn reduces transmission efficiency. Dawson et al. (2015) working on potatoes, found that in some years the use of mineral oils could reduce infection levels of virus. However this varied between seasons and varieties used. The authors speculate that environmental conditions led to these differences. Problems associated with mineral oils include the potential for their degradation in UV light, that they could be washed off by rain and that they have been reported to reduce yield or quality of crops through possible phytotoxicity (Bos, 1982; Hooks and Fereres, 2006; Irwin et al., 2000). In their investigation, (Dawson et al., 2015) were unable to determine if mineral oils affected yield due to the variability between seasons, though they did find that mixtures of mineral oils and fungicides could improve control of foliar blight. Two of the fungicides used in tank mixtures caused more severe phytotoxic effects, suggesting that tank mixtures should be tested prior to use.

Barrier plants may also be used in controlling viruses. Barrier plants are a secondary plant surrounding the crop and are generally non-hosts of the virus. Some studies on members of the Fabaceae family found that using barrier plants led to a reduction in number of infected

plants, percentage of infected seed or transmission of the virus (Hooks and Fereres, 2006). Although it is currently unclear how barrier plants protect the crop, current theories are that they might act as a 'virus-sink', they are a physical impediment to the aphid or are more attractive to the aphid than the crop is or it is a combination of multiple factors (Hooks and Fereres, 2006; Irwin et al., 2000). The virus-sink hypothesis is that a migrating aphid which is carrying the virus may land on the secondary plant rather than the crop, the aphid then probes the secondary plant to determine whether it can feed. Non-persistent viruses are lost quickly and often when feeding, so during probing of the secondary plant the aphid loses the virus. The aphid may then move on to the crop but will not transmit the virus (Hooks and Fereres, 2006). Alternatively, the secondary plant may act as a physical barrier and interrupt aphid movement (Bos, 1982; Hooks and Fereres, 2006). It has also been argued that by diversifying the plants present, could increase the number of natural predators present. Natural predators are unlikely to have an effect of the spread of a virus in crop, but they may reduce the numbers of colonising aphids (Hooks and Fereres, 2006). Planting a mixture of susceptible and resistant plants means that aphids are more likely to land on the resistant plants. By probing on the resistant plants, the aphid loses the virus but the plant is not infected. Then if the aphid moves on to a susceptible plant it will not transmit virus (Irwin et al., 2000). However, barrier plants do not work well in all situations and are thought to work best when there is limited secondary spread and while they may reduce the impact of one pest they may have no effect on another. There is also the issue of competition between the crop and barrier plant and whether barrier plants increase yield enough to make them economically viable (Hooks and Fereres, 2006).

Making the plants less attractive to the aphid vectors can also reduce infection. Generally aphids are attracted to plants surrounded by bare earth e.g. (A'Brook, 1968), using high planting density and narrow row spacing can generate the formation of a canopy earlier. This reduces the amount of bare earth showing and this can also 'shade-out' seedlings from infected seed (Congdon et al., 2017c; Makkouk and Kumari, 2009). Bare earth can also be covered using reflective mulches or using a variety which has bushy or dwarf characteristics (Irwin et al., 2000). However, this effect is not universal and may not be applicable in all cases, such as the effect observed for with *Soybean mosaic virus* in *Glycine max* (Halbert and Irwin, 1981).

Use of biological control agents is thought to be unsuitable for crop legumes (Makkouk and Kumari, 2009) and difficult for viruses non-persistently transmitted by aphids. Predators of aphids can reduce numbers of aphids but is unlikely predators would be able to kill the aphid before it infects a plant (Hooks and Fereres, 2006).

Additionally, limited experiments have been performed which have generated transgenic peas which show resistance to a virus. Peas which contained the AMV coat protein showed partial resistance to AMV in field and conditions (Timmerman-Vaughan et al., 2001). In another study, transgenic peas carrying the Nlb replicase gene from PSbMV were generated. The peas were then challenged with PSbMV, and after initial infection became resistant (Jones et al., 1998). Transgenic peas which contained the coat protein of PEMV showed milder symptom than controls (Chowrira et al., 1998) and there is some evidence of transgenic peas with the AMV coat protein showing at least partial resistance to AMV (Timmerman-Vaughan et al., 2001).

Diagnostics

The detection methods used, within the publications covered by this review, highlight that pea virus diagnostics are an area in need of attention, both in terms of the methods used to investigate the presence of pea viruses from affected plants, but also the methods applied to support pea seed health and trade compliance. Whilst the methods applied have moved forward from simple symptom recognition (Hagedorn, 1958) or screening using mechanical inoculations to test plants (Fletcher, 1993) the range of techniques used are limited. In many cases the choice of diagnostic method is a trade-off between cost, availability, throughput, sensitivity and accuracy. Throughout there is limited evidence of validation testing being carried out and whilst some reports have confirmed virus findings using a secondary method, there is limited evidence of subsequent molecular level or sequence confirmation, although this is largely due to the age of many of the reports.

Due to the risk of seed-borne virus diseases, the detection of PSbMV and PEBV in the trade as a method to ensure crop quality is one of the few areas where the International Seed Testing Association has adopted a standardised and internationally validated method into the International Rules for Seed Testing for virus detection (ISTA, 2014; Koenraadt and Remeeus, 2007). This method, as with many of those applied in the records reported in this review, use the Enzyme Linked Immunosorbent Assay (ELISA) method as described by Clark and Adams (1977), an antibody based method, which utilises commercially available antisera which have been developed for a wide range of well-characterised viruses. Other antibody based methods have been used such as the tissue blot immunobinding (TBIA) (Bekele et al., 2005; Freeman and Aftab, 2011). Antisera based blotting methods tend to be cost effective, but can sacrifice sensitivity and accuracy. In some cases a lack of true specificity of the antisera may be advantageous, such as in the detection of a nanovirus in Germany (Grigoras et al., 2010) where weak positive reactions with a polyclonal antisera led to the discovery of the novel nanovirus *Pea necrotic yellow dwarf virus* (PNYDV). However, as a consequence of such cross reactions further confirmation testing should always be conducted following an

ELISA screen to ensure the accuracy of reported results such as those carried out by Grigoras et al. (2010) or Freeman and Aftab (2011).

There are a limited number of pea virus specific molecular assays, such as Polymerase Chain Reaction (PCR) or real-time PCR. Assays such as that designed for the detection PEMV by Larsen and Porter (2010) have not been routinely adopted, possibly due to the availability and relative low cost of antibody based methods. However, molecular methods can be designed in hours and days in contrast to antisera based methods where it may take many months or even years to obtain reliable antisera. Therefore in the field of emerging viruses, such as in the case of PNYDV mentioned above, a specific molecular method has been designed and is being applied in ongoing virus surveillance (Gaafar et al., 2016). Thus far there is no evidence that advanced diagnostic techniques, such as Next Generation Sequencing have been applied to surveillance of pea viruses.

Prediction

There are many factors which affect the incidence of disease in plants. Knowing which factors are likely to cause high incidence of virus could help inform decisions on which disease management strategies to use to help to reduce yield loses (Thackray et al., 2004).

Studies on predictive models have been carried out in Australia on CMV, PSbMV and BYMV on legumes. South-west Australia has a climate very similar to the Mediterranean, with little rainfall in the summer and early autumn (Thackray et al., 2004). In this Mediterranean-type environment factors which can affect yield loss and epidemics are the level of primary inoculum within the crop or in neighbouring plants, the arrival date of the first aphids, the aphid species present, the number and activity of the aphids, climatic factors such as rainfall and temperature and cultural factors such as plant density, ground cover and the time when the canopy closes (Maling et al., 2008; Thackray et al., 2004).

Recent work by Congdon *et al.* (2017c) found that that rainfall in autumn and the initial infection of seed sown influenced the spread of PSbMV in south-west Australia. High rainfall in the autumn (March and April) can promote the growth of vegetation, such as weeds and pasture plants, which can support aphid populations. Whereas, when there is less rainfall there are fewer plants and there is a smaller aphid population. When there is high rainfall and more vegetation the first arrival of aphids also tends to be earlier than when there is lower rainfall and less vegetation (Congdon et al., 2017c; Thackray et al., 2004). Therefore in the Mediterranean-type climate rainfall is a key predictor of disease, whereas in the temperate climate of Northwest Europe temperature, rather than rainfall, is generally the key determinant in disease predictive models. This is because survival of aphids decreases in cold weather, such as in the models developed for predicting *Barley yellow dwarf virus* (BYDV) on wheat

and Sugar beet yellows disease (SBYD) on sugar beet as highlighted by Jones et al. (2010). However, the effects of climate change may lead to milder winters, increased aphid survival and consequently a change in aphid flight phenology. This phenomenon was observed with *M. persicae* in the spread of *Potato leaf roll virus* in Scotland where milder winters led to an increased survival of over-wintering vectors, and warmer temperatures in late spring led to earlier flights of the aphid vector in Eastern Scotland (Robert *et al*., 2000).

Discussion

The aim of this literature review was to try to ascertain the current risk to the UK pea crop posed by virus infections in terms of the viruses currently present and those that pose a potential future threat. As part of this literature review an attempt was also made to collect information on the incidence and potential impact of pea viruses as well as highlighting any work carried out on prediction and management (control) of pea viruses that may be applicable by the UK industry.

Given the lack of publications in the subject area, it is evident that comprehensive surveys of pea viruses have not previously been carried out in the UK to any significant extent. Where surveys have been carried out, such as the report by Hagedorn (1958), they are both historic and limited in there use due to the lack of effective diagnostic support. For this reason records on the presence of pea viruses in the UK are drawn from a number of sources including general texts such as Biddle and Cattlin (2007) or Smith (2012). Reports were also cross-checked against the diagnostic records held at Fera Science Ltd. To further highlight the lack of recent work in this area, a recent review by Fox and Mumford (2017) which focussed on novel findings and first records of plant viruses in the UK did not highlight any first records of viruses in pea over the last 35 years. This could be due to under reporting and/or limited work being carried out in the area which also means that there is a lack of directly relevant information on incidence and impact of viruses in the UK. However, there is a general lack of evidence regarding the current or emerging viral threats to the UK pea crop.

It has been repeatedly demonstrated that visual examination is not as accurate as diagnostic testing because symptoms may be latent, may be confused with nutritional deficiencies or, in the case of PSbMV, may hard to identify in the field (Bekele et al., 2005; Bos, 1982; Coutts et al., 2008; Jain et al., 2013; Robert et al., 2000).

One consequence of having such limited information on the presence of viruses is that most investigative work focusses on the ‘usual suspects’ and may inadvertently exclude work on pathogens of greater significance. Diagnostic testing concentrated on those pathogens known to be present, and only giving further information on the incidence and impact of well characterised and easily detected pathogens may, in effect, become a self-fulfilling prophecy.

This may mask underlying issues from pathogens which are either not readily recognised or not known to be present. A similar situation was observed in UK carrots by Adams et al. (2014), where diagnostic based investigations have historically been focussed on a limited number of well characterised pathogens. The application of a novel diagnostic technique, Next Generation Sequencing, which has been increasingly applied as a generic method to cover both characterised and previously unknown plant viruses (Adams et al., 2009), combined with a robust statistical analysis allowed the disease of unknown aetiology to be correlated with a virus which had been thought to be of little importance. Other molecular diagnostic techniques, such as PCR and real-time PCR, offer advantages of sensitivity, accuracy, throughput and ease of development. Development of molecular assays would also allow further studies to be carried out which are not currently possible due to limited diagnostic sensitivity, such as combined aphid monitoring programmes which include virus testing of trapped aphids.

Without knowledge of the current baseline of what viruses are present, their incidence and their impact, the management of viral infections poses a major challenge. Survey studies are required to understand the natural occurrence of viruses, and their relative importance. If appropriately designed and conducted, such surveys can also be used to understand the impact of yield and quality losses. These data can then be applied to develop management and preventative strategies and inform future breeding programmes to address resistance to major diseases (Fletcher, 1993; Latham and Jones, 2001; Makkouk and Kumari, 2009). Subsequent periodic surveys can then be used to monitor these management strategies and their efficacy (Fletcher, 1993).

If broad based, these data could also help identify potential problems and allow early control of newly emerging disease problems (Fletcher, 1993). A good example of a potentially high-risk pathogen is *Pea necrotic yellow dwarf virus*. PNYDV was first described from pea in in Germany in 2009, and subsequently from Austria and The Netherlands causing significant damage to pea crops. Despite only being described in 2009, by 2016 the virus had been recorded from all pea growing regions of Germany (Gaafar et al., 2017). A rapid pest risk analysis (PRA) conducted by the German plant health authorities concluded that although the pathogen was damaging it had already spread to a point that it could not be considered a quarantine pathogen (Steinmöller et al., 2016). The virus can also affect faba bean, lentil and vetch (Gaafar et al., 2016; Gaafar et al., 2017). Host range studies with a range pea and faba bean cultivars were unable to find resistant accessions in Austria or Germany (Gaafar et al., 2016). PNYDV along with other members of the *nanoviridae* (the nanoviruses) that have been found on pea are persistently transmitted by aphids such as *A. fabae* and *A. pisum* in a persistent manner. Although these viruses have not been previously reported from the UK it

is possible, given their rapid spread and presence in neighbouring countries, that they may already be present but unreported. This would be consistent with the findings of Hagedorn (1958) where the viruses seen in West Germany and the Netherlands were also seen in England, therefore viruses which are seen in Europe could also be present and spread in the UK, especially where diseases have vectors such as aphids which can be highly mobile and have the ability to rapidly disseminate viruses over a landscape scale.

Based upon these data presented, there are two broad transmission pathways for the viruses which are thought to be the main viral causes of losses in UK crops: Seed-borne transmission (PSbMV and PEBV) and Aphid mediated transmission (PSbMV, PEMV and PeSV). Management of viruses and use of control measures can therefore be applied on the basis broad 'principles':

- Plant clean seed
- Grow in absence of virus reservoirs (alternative hosts)
- Grow in absence of vectors
- Isolate from similar crops
- Use resistant (or tolerant?) varieties

Although these principles were formulated for virus management in seed potato crops, the key points are transferable to any crop.

Based on the diagnostic records from Fera Science Ltd, some of the PSbMV epidemic scenarios reported by Congdon et al. (2017c) such as relatively high inoculum levels in input seed stocks, do not appear to be major factors in UK epidemics of pea viruses. Findings of PSbMV in input seed appear to be relatively uncommon and when the virus is detected it is not at high incidence (Fera Science Ltd, data not presented). However, the influence of virus spread through wind-mediated plant to plant contact allowing small localised foci of infection to spread prior to the arrival of aphids for onward transmission (Congdon et al., 2016b) has thus far not been investigated in the UK PSbMV pathosystem. The aphid transmitted viruses known to be present in the UK are both persistently transmitted (PEMV, BLRV) and non-persistently transmitted (PSbMV, PeSV, BYMV). Conventional virus management approaches through chemical control should give greater control of the circulative persistent viruses than stylet borne non-persistently transmitted viruses due to the associated long acquisition, lag, and transmission times giving greater scope for chemical knock down of the aphid vectors prior to transmission of the virus. However, recent experience from other UK crops suggests that current aphid control measures may not be effective against persistently

transmitted viruses in all cases, such as that observed in UK carrot crops with high incidence of the persistently transmitted virus, *Carrot red leaf virus* (Fox et al., 2015). Control measures for non-persistently transmitted viruses of peas require further investigation and investigations should look to other regions or crops where novel approaches have been used and these should be assessed for their efficacy and practicality of application. Use of resistant varieties can be an important tool in minimising the risk of viruses, however, this should not be a management measure used in isolation. Resistance will not offer broad based resistance but instead will only minimise the risk from a specific virus and without other associated control measures it is likely that another virus may increase in importance. Altering planting dates to avoid early season transmission may be a useful tool in some crops, however, in practice this will not be feasible in some crops where a harvest period is critical or in seasons where adverse weather may have an influence planting dates. Use of other approaches such as mineral oils, straw mulches and other novel practices would need to be investigated under UK conditions for both positive effects on virus levels as well as any potential negative impacts such as plant phytotoxicity, reduced yield or production cost implications.

In the absence of any epidemiological models covering UK growing conditions, it would be of interest to investigate the models produced in Australia covering virus of leguminous crops. Models such as those of Thackray et al. (2004) and Maling et al. (2008) on lupin; but more specifically that of Congdon et al. (2017b) on PSbMV in peas could act as useful predictive tools and in turn feed into possible decision support systems for virus management. Whilst the UK conditions appear to be different in terms of input seed health and the different influences of temperature and rainfall on aphid flights, such models may still provide useful insights into epidemics of viruses in UK pea crops. Current AHDB resources, such as the aphid monitoring programme run by AHDB-potatoes (http://aphmon.fera.defra.gov.uk/) could be extended into pea crops and data gathered from this monitoring could be used to enhance modelling of virus outbreaks.

It is also key to remember that there may be marked changes in UK climate may occur over the medium to long term with a general warming and exposure to more extreme weather events. Such environmental changes will inevitably influence the vectors of viruses and consequently impact on the occurrence and incidence of viruses in crops. Climate change may improve survival of aphids over winter due to shorter cold spells and fewer frost days, for instance models for predicting SBYD included number of frost days that may reduce incidence of aphids and weed hosts (Jones, 2009; Jones et al., 2010). Increases in average annual temperature may lead to earlier activity of aphids, increased generations per year, and increase geographical spread. Gaafar et al. (2017) predicted that changes such as these will lead to further spread of pea-infecting nanoviruses across Europe. Jones, (2009) also

noted that a change in climate may also effect other vectors of viruses, increased rain could increase spread of fungal zoospores and rising temperatures may allow nematodes to survive in areas which were previously too cold (Jones, 2009) which in turn will influence the composition of the virome in which crops are produced.

Conclusions and further work

The primary conclusion of this study is that investigations should be carried out to ascertain the current state of the UK pea crop with respect to virus infections. To ensure outputs are of use to growers any future work should be considered under a programme which addresses the fundamental principles of plant virus management:

- **Plant clean seed**: As part of any future research programme input seed stocks should be surveyed to ensure the assumed high virus health status of input seeds is reflected in the seed being planted. This work should focus on the known seed borne viruses *Pea seed-borne mosaic virus* (PSbMV) and *Pea early-browning virus* (PEBV).

- **Grow in absence of virus reservoirs**: With limited information available on the presence and incidence of pea viruses it should be a priority to baseline current virus populations affecting pea crops. Such work should focus on those viruses known to occur in UK crops such as *Bean yellow mosaic virus* (BYMV), *Bean leaf-roll virus* (BLRV), *Pea enation mosaic virus* (PEMV), *Pea early browning virus* (PEBV), *Pea seed borne mosaic virus* (PSbMV), *Broad bean true mosaic virus* (BBTMV) and *Pea streak virus* (PeSV), but should also include testing to ensure that emerging viruses from Europe, such as the nanoviruses, are not establishing in the UK.

- **Grow in absence of vectors**: Any future survey programme should include an aphid monitoring programme and diagnostics should be developed to allow for aphids to be tested for the presence of viruses.

- **Isolate from similar crops**: If surveillance is carried out into the viruses present in crops, this should be initially carried out on a regional basis and near neighbour crops could be compared for relative virus presence and incidence.

- **Use resistant (or tolerant?) varieties**: Field survey should include a review of resistance status of any cultivars surveyed and this information can be used to assess the relative virus health of crops.

Ultimately a decision support system for the industry would be required to allow the prediction of virus outbreaks and assess the risk of virus in individual crops. Assessing the applicability

of existing models may facilitate the development of such a system but at present the knowledge gaps regarding the UK pea crop pathosytem may be too great for such models to be of immediate use.

Knowledge and Technology Transfer

A short report has been written for the AHDB Horticulture News.

Glossary

Glossary Term	Definition
Aetiology	The study of the cause of a disease symptom
Chlorosis	(Chlorotic) A symptom of infection with some viruses. Applied to any yellowing or pallid colouration
ELISA	Enzyme Linked Immunosorbent Assay - A biochemical diagnostic method based on specific antibodies designed to detected proteins, in this case the virus specific proteins on the capsid of the virus.
Enation	A symptom of infection with some viruses. The symptom is characterised by an outgrowth from the leaf surface or from another plant part.
Experimental host	A host of a pathogen that has not been recorded in nature but only through experimental inoculation.
Genus	A taxonomic level higher than species. Members of the same genus may share similar characteristics.
Latent	A non-symptomatic infection. This may be in the season of infection, with symptoms developing in subsequent generations; or latency may be species or cultivar specific.
Molecular Diagnostics	Diagnostic methods utilising the genetic code of DNA or RNA of the pathogen for its detection. The main method used is Polymerase Chain Reaction (PCR) and/or genetic sequence analysis.
Mosaic	A symptom of infection with some viruses. A mosaic is a characterised by small yellow spots through to larger irregular yellow patches on foliage.
Mottle	A symptom of infection with some viruses. A mottle is characterised by an irregular yellowing of a leaf giving a dappled appearance
Natural host	A host of a pathogen that is found in nature
Necrosis	(Necrotic) A symptom of infection with some viruses. Cellular death leading to brown colouration or patches.
Pathosystem	The system of infection, this includes the crop host, the disease vector and the pathogen, however, it should also include alternate hosts and factors influencing the epidemiology of the disease such as climate.
Resistant	A plant that will not become infected by the pathogen.

Seed-borne	An infection that is introduced into a crop via the input seed. There may be a secondary method of transmission, such as vector or contact transmission to spread infection from any initial inoculum source.
Stylet	The piercing and sucking mouthparts of an aphid
Tolerant	A plant that will become infected but not show any signs of infection and/or infection will not affect yield or quality.
Vector	The method or organism that transmits a virus from an infected host to an uninfected host.
Virus	Infectious sub-microscopic particle consisting of nucleic acid (DNA or RNA) surrounded by a protein coat (Capsid).

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