Department
for Environment
Food & Rural Affairs

Pest specific plant health response plan:

Outbreaks of *Potato spindle tuber viroid* on potato crops

Figure 1. Healthy potato tuber (left), and spindle shaped tubers (right) that have been affected by PSTVd. © Dr. J. W. Roenhorst

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1. Introduction and scope

1.1. This pest specific response plan has been prepared by the Chief Plant Health Officer Unit. It describes how the Plant Health Service for England will respond if infection by *Potato spindle tuber viroid* (PSTVd) is discovered on potato (*Solanum tuberosum*).

1.2. This document will be used in conjunction with the Defra Contingency Plan for Plant Health in England, which gives details of the teams and organisations involved in pest response in England, and their responsibilities and governance. It also describes how these teams and organisations work together in the event of an outbreak of a plant health pest.

1.3. The aim of this response plan is to facilitate the containment and eradication of PSTVd.

1.4. This document can also be used as a basis for responding to outbreaks in potato of related pospiviroids. A datasheet containing background information on PSTVd is included in the appendix.

2. Anticipate

2.1. *Potato spindle tuber viroid* (PSTVd) probably originates from Central America, but it was first identified in New Jersey, USA, in 1922 (Martin, 1922). It is now also present in South America, Europe, Africa, Asia and Oceania (EPPO PQR, 2014). Within Europe, the viroid is widespread in Belarus and is present or occasionally present in a number of other countries (EPPO PQR, 2014). The viroid causes growth reduction and other damaging symptoms in potato (*Solanum tuberosum*), tomato (*Solanum lycopersicum*) and pepper (*Capsicum annum*). Other *Solanum* spp. and some ornamental species in the family *Solanaceae* can also be infected, but the viroid is generally asymptomatic in these species. Yield losses of ~ 65% in potato have been recorded (Hunter and Rich, 1964), and potential yield losses of almost 100% may occur for tomato plants that are infected early (EFSA Panel on Plant Health, 2011). In the UK, there have been two outbreaks of PSTVd on tomato, one in 2003 and one in 2011, and the viroid was eradicated on each occasion in the same year. There have also been several interceptions of the viroid in ornamental plants which have originated within the EU.

3. Assess

3.1. In 2011, the European Commission asked the Panel on Plant Health to deliver a risk assessment on solanaceous pospiviroids (EFSA Panel on Plant Health, 2011). The objective of this assessment was twofold: to identify and evaluate risk management options for the pospiviroids and to assess the effectiveness of measures listed in Commission Decision 2007/410/EC specifically for PSTVd.

3.2. The viroid currently has a mitigated UK plant health risk register score of 30, which is reviewed as and when new information becomes available (https://secure.fera.defra.gov.uk/phiw/riskRegister/viewPestRisks.cfm?cslref=11980).

4. Prepare

4.1. *Potato spindle tuber viroid* is a IAI listed organism and therefore the introduction into, and spread within all member states, is banned (Council Directive 2000/29/EC).

Solanaceae

4.2. Plants of Solanaceae intended for planting, other than seeds, ware and seed potatoes, and other stolon- or tuber-forming plants for planting, are prohibited from third countries other than European and Mediterranean countries (Annex III, Council Directive 2000/29/EC).

4.3. Prohibited solanaceous plants can be imported and held under a plant health licence in quarantine conditions (usually for research purposes). Once work on the plants has been completed, the plants are normally destroyed. However, given adequate testing, the plants can, in some cases, be released from the terms of the licence if they are shown to be free of pests and pathogens.

4.4. Plants of Solanaceae intended for planting, other than potato tubers and tomato, that are from countries where PSTVd is known to occur, must be accompanied by an official statement that no PSTVd symptoms have been observed on the plants at the place of production since the start of the last complete cycle of the vegetation (Annex IV part A section 1, Council Directive 2000/29/EC).

4.5. Plants of stolon- or tuber-forming species of *Solanum* intended for planting (other than *Solanum tuberosum*) must also be tested and found free of harmful organisms (Annex IV part A section 2, Council Directive 2000/29/EC).

4.6. The Plant Health Service should be aware of the measures described, and trained in responding to an outbreak of PSTVd. It is important that capabilities in detection, diagnosis, and risk management are available.

Potato

4.7. The import of *Solanum tuberosum* tubers for propagation (seed potatoes), into the EU, is prohibited from third countries other than Switzerland under Annex III, Council Directive 2000/29/EC. There is a derogation to bring in tubers for trial, scientific or varietal selection purposes (Commission Directive 2008/61/EC), but they must be placed under quarantine conditions and tested for the viroid before being used for propagation purposes.

4.8. Ware potatoes and their hybrids are prohibited from third countries, with the exception of Algeria, Egypt, Israel, Libya, Morocco, Syria, Switzerland, Tunisia and Turkey, and other European third countries which are recognised as being free from *Clavibacter michiganensis* ssp. *sepedonicus*, or in which provisions recognised as equivalent to those of the EU territory for mitigating *C. michiganensis* spp. *sepedonicus* have been fulfilled (Annex III, Council Directive 2000/29/EC).

4.9. Ware potatoes, with the exception of early potatoes, that are from countries where PSTVd is known to occur must have their germination suppressed (Annex IV part A section 1, Council Directive 2000/29/EC).

4.10. Within the EU, potato tubers for planting must come from advanced selections, have been produced within the EU, and been maintained under appropriate conditions and tested, using appropriate methods, for harmful organisms (Annex IV part A section 2, Council Directive 2000/29/EC).

4.11. Seed potatoes can only be marketed in the EU if they meet the requirement of Council Directive 2002/56/EU.

4.12. Certification schemes are available for certain commodities, such as potatoes and ornamentals, which are based on the selection of healthy mother plants (through visual inspection and/or testing). This is compulsory for seed potatoes in the EU.

Tomato

4.13. Tomato seeds must be obtained by an appropriate acid extraction method or equivalent procedure, and either originate from areas where PSTVd is not known to occur, be produced by plants that have not shown symptoms of PSTVd during the complete cycle of the vegetation at the place of production, or have been tested negative for PSTVd on a representative sample using appropriate methods (Annex IV part A section 1, Council Directive 2000/29/EC).

5. Response

Official action to be taken following the suspicion or confirmation of PSTVd on imported plants, including seeds

Holding consignments at ports of entry

5.1. If PSTVd is suspected by the Plant Health and Seeds Inspectorate (PHSI) to be on a consignment moving in trade, the PHSI should hold the consignment until a diagnosis is made. Samples should be sent in by the PHSI to Fera, Sand Hutton, York, YO41 1LZ (01904 462000). If PSTVd is confirmed, the consignment should be destroyed by either incineration or deep burial.

5.2. If PSTVd is confirmed, a Europhyt notification should be made.

5.3. In the event that all or part of the consignment has not been held and has been distributed to other premises prior to diagnosis, trace forward inspections should take place upon suspicion or confirmation of PSTVd.

Official action to be taken following the suspicion of PSTVd inland

5.4. Due to the potential for spread, if PSTVd is suspected in a potato field, an amber alert status should be given by the PHSI. An amber alert status refers to a serious plant pest/disease with potential for relatively slow but extensive spread leading to host death and/or major economic or environmental impacts.

5.5. A Contingency Core Group (CCG) or Incident Management Team, chaired by the Incident Commander and including specialists from APHA, Defra and other organisations, should subsequently be set up to assess the risk and decide on a suitable response at strategic and operation levels. This may include gathering more information on the suspected outbreak, notification of ministers and senior officials, and agreeing a communications strategy.

5.6. If PSTVd is suspected (or confirmed) in an allotment or garden then this will be dealt with on a case by case basis.

Restrictions on movement of material, equipment and machinery to and from the place of production

5.7. *Potato spindle tuber viroid* can be transmitted mechanically, on gloves and hands (e.g. van Brunschot *et al.*, 2014), on machinery (e.g. Merriam and Bonde, 1954) and on tools (e.g. Verhoeven *et al.*, 2010b). The viroid can also remain infective on the outside of plants for at least 8 weeks (Mumford *et al.*, 2004b). Movement of material, equipment and machinery between infected and non-infected areas should therefore be restricted. However, if movement is necessary, the material, equipment and machinery should be thoroughly cleaned and disinfected (see 5.22).

Precautionary measures

5.8. Hygiene best practice should be followed (adapted from EFSA Panel on Plant Health, 2011). This includes:

- Training staff to identify symptoms of PSTVd, and to follow best practice procedures.
- Prohibiting the sorting/packing of tubers produced from other companies/locations. If the tuber is infected, machinery, equipment and people could become contaminated and infect other crops on the premises.
- Using clothes (including overshoes), which will either be destroyed (via incineration or deep burial) or washed following work on a particular field. This prevents spread between fields.
- Using disposable gloves that will be destroyed (via incineration or deep burial) following work on a particular crop, between different areas within a crop or between plants (reducing spread).
- Washing hands with soap before and after entering a new field (reducing spread).
- Restricting the use of equipment, particularly knives, to one location, to prevent the viroid spreading to other locations (via mechanical transmission).
- Chemical disinfection of knives and pruning instruments (between crops, areas within a crop or plants to reduce spread) (see 5.22).
- Cleaning and disinfection of machinery between crops. As with handheld equipment, machinery is another means of mechanical transmission. Disinfection and cleaning of machinery with high water pressure, steam cleaners or other methods may therefore reduce spread. Records of this should be maintained.

- Maintaining the working direction. If human-assisted spread of a pathogen occurs, it will occur in the direction that the human is working. Working in the same direction reduces the extent of the spread and allows measures to be carried out in a more concentrated way.
- Restricting access to the working area. The fewer people entering a particular field, the less chance there is that PSTVd will be introduced. Wherever possible, employees should work in the same areas each day rather than swapping around work areas.

5.9. Volunteer plants and weeds, particularly perennials, act as reservoirs for PSTVd (EFSA Panel on Plant Health, 2011). Controlling these plants reduces the chance of the crop becoming infected. Volunteer plants and weeds arising in potato cultivations can be controlled mechanically (e.g. hoeing machine), chemically (herbicides) by cultural practices (e.g. lifting of potatoes). It is important there is no ‘carry over’ into the next crop by self-sown seedlings arising from seed of squashed fruit from the previous season.

5.10. Transmission of PSTVd by aphids has occasionally been reported in potato within and between species but transmission is at a very low level. Recent research suggests that the higher levels of transmission have been observed when the viroid has been acquired from potato plants co-infected with Potato leafroll virus (PLRV) (e.g. for *Myzus persicae*, Syller *et al.*, 1997). Controlling aphids in crops, particularly those crops that are also hosts of PLRV, is therefore recommended.

Preliminary trace forward / trace backward

5.11. Information obtained on the origin of suspected plants should be used to find out locations where other potentially infected plants may be or where cross contamination may have occurred. Information should also be obtained on the location to which suspect plants have been sent. This process is particularly important for propagation or seed stock.

Confirming a new outbreak

How to survey to determine whether there is an outbreak

5.12. Information to be gathered on the suspicion of PSTVd by the PHSI, in accordance with ISPM 6; guidelines for surveillance (http://www.acfs.go.th/sps/downloads/13717_ISPM_6_E.pdf):

- The origin of the potatoes and seed lot numbers etc.
- Details of other premises or destinations where the potatoes have been grown or sent, where the viroid may be present.
- The layout of the premises and surrounding area, including a map of the cultivations/buildings, at risk growers, any other host plants, including susceptible ornamentals etc.
- Details of the host plant: the species, variety, growth stage and any other relevant information.
- Description of the surrounding habitat and climate.
- Level of infection, including a description of symptoms (could take photos).
- The date and time the sample was taken, how it was identified and by whom.

- Current controls in place e.g. chemical treatments (These cannot be used against the internal viroid infection, but may be used for insect control. Chemicals may also distort the appearance of symptoms, reducing the effectiveness of visual survey).
- Details on the movement of people, equipment, machinery etc. to and from the infected area.
- Cultural and working practices.
- History of PSTVd on the site and nearby, if any.
- The presence of aphids and PLRV.

5.13. Further to information gathering, samples of other symptomatic host plants should be taken to confirm the extent of infection e.g. in surrounding lots or fields. This initial survey will be used to determine if it is an isolated case or an established outbreak.

5.14. Finance for the surveys will depend on the individual circumstances of the outbreak, and will be subject to discussion.

Sampling

5.15. Following the identification of a suspect plant, symptomatic parts of the plant (e.g. leaves, fruit and stems) should be placed in a sealed bag or container, within at least two other layers of containment. Plants should be handled with gloves. Gloves should be destroyed (via incineration or deep burial) following use. The samples should be submitted to the diagnostic team at Fera, Sand Hutton, York, YO41 1LZ, in containers that are not liable to be crushed during transit. Hygiene best practice should be followed while sampling. Each sample should be labelled with full details of sample number, location, variety etc.

Diagnostic procedures

5.16. The principal means of detecting pospiviroids is through reverse transcription-polymerase chain reaction (RT-PCR) (Shamloul *et al.*, 1997; Bostan *et al.*, 2004; Verhoeven et al., 2004; Verhoeven *et al.*, 2011). At Fera, TaqMan is used. This method is generally non-specific and will not allow identification down to species level (e.g. Singh *et al.*, 1999; Verhoeven *et al.*, 2011). Real-time RT-PCR is also often run in tandem, which narrows down the viroid species to either PSTVd or TCDVd (Boonham *et al.*, 2004). Identification to species level and separation from similar viroids such as TCDVd requires sequencing of the RT-PCR products and BLAST analysis (Boonham *et al.*, 2005; Verhoeven, 2010a). This is in accordance with ISPM 8 (http://www.acfs.go.th/sps/downloads/13730_ISPM_8_E.pdf) and ISPM 27 Annex 7 (https://www.ippc.int/static/media/files/publications/en/2015/02/18/dp_07_2015_2006-022_draftdp_pstvd_2015-02-06.pdf).

Criteria for determining an outbreak

5.17. If PSTVd is detected at a location other than at a port or confined to a particular consignment with no risk of spread, then an outbreak should be declared.

Official Action to be taken following the confirmation of an outbreak

Communication

5.18. The Incident Management Team will assess the risks and communicate details to the IPPC, EU and EPPO, in accordance with ISPM 17: pest reporting (https://www.ippc.int/en/publications/606/), as well as within Government to Ministers, senior officials and other government departments and agencies (e.g., the Environment Agency) on a regular basis as appropriate; and to other relevant stakeholders. The scale of the outbreak will determine the size and nature of the management team and action.

Surveillance

5.19. All host plants in the affected field should be visually inspected, particularly potato, and symptomatic plants should be tested.

5.20. Locations to survey:

- neighbouring potato fields
- fields which staff/growers have visited or worked in
- fields where machinery used was the same as that for the infected field and
- other fields where there is a perceived risk such as those linked by a footpath

Demarcated zones

5.21. The affected field, neighbouring fields, other fields which staff/growers have visited or worked in, including those fields where machinery used was the same as that for the infected field, stores, grading lines, premises in which stock has been sent or received, and/or any other premises where there is a perceived risk, should be demarcated for surveillance.

Decontamination procedures

5.22. Thorough cleaning and application of disinfectants should be used for all non-disposable material, equipment and machinery. Virkon S (2%, containing potassium peroxymonosulfate) and sodium hypochlorite (e.g. 10% Clorox regular bleach) are recommended disinfectants (Li *et al.*, 2015). Any waste (plant or other potentially infected material) should be removed and destroyed (via deep burial, incineration or other appropriate methods prescribed in 5.32 - 5.33).

Tracing forwards / backwards

5.23. Once other sites that are potentially infected by PSTVd have been identified, these should be inspected as per surveillance highlighted in paragraphs 5.19 - 5.20. Information, which is aimed at raising awareness of the disease and its symptoms, should be sent to affected and at risk growers.

Pest Management procedures

5.24. Host plants should not be moved off site, with exception of potato tubers which may be moved off site for retail/processing if agreed by the incident management team.

5.25. There are no chemical or biological methods for controlling PSTVd. Therefore, the only effective method of eradication is destruction. If an outbreak is found within a breeding stock or in seed potatoes, there should be no further propagation from the infected stock or other stocks on the same production unit and all plants should be destroyed. Likewise, if infection is detected in ware potatoes, normally, all potatoes within the field should be destroyed. However, restricted movement of seed and ware potatoes may be allowed under particular circumstances (to be agreed by the incident management team).

5.26. Fields which are not known to be infected, but have used the same machinery as an infected field or have been exposed to PSTVd in another way, should be treated as if they are infected.

5.27. Work on known infected fields should be completed at the end of the day to avoid spreading the viroid to other areas. Machinery should be cleaned and disinfected using water and detergent to remove soil and plants and then treated with an appropriate disinfectant.

5.28. Once all susceptible crops have been harvested, the field should be inspected for known hosts of PSTVd and other solanaceous weeds, and subsequently destroyed. This would involve the removal of any weeds and volunteer plants, thereby reducing the likelihood of PSTVd carrying over into any following susceptible crops. Weeds should be removed from the field and in hedgerows around the field.

5.29. Before potatoes can be planted in the infected field again, it should have been free from host volunteer plants for a minimum of two consecutive years (EPPO, 2011). Volunteer potato plants and weed hosts found should be tested for PSTVd.

5.30. During the two years following an outbreak, several measures have been prescribed in EPPO (2011) for other fields on the same premises or those being used by the same grower, if potatoes are being grown, including:

- Potato production, handling and storage should be carried out under official supervision of the PHSI.
- Harvested seed- and ware-potato stocks should be kept separate, or cleaning and disinfection should be carried out between the handling of the stocks.
- Only certified seed potatoes should be planted.
- Official monitoring should be conducted using laboratory testing at a sampling rate established by the NPPO.

5.31. Following this period, only ware potatoes should be produced for at least one rotation cycle, with harvested tubers and leaf material inspected and tested for PSTVd (sampling rate to be determined by the incident management team). If found free of PSTVd, either seed or ware potatoes may then be produced on the field (EPPO, 2011).

Disposal plan

5.32. The primary means of destruction of potato plants in a field is through herbicide application. Actives that can be used include diquat (Reglone), carfentrazone-ethyl (Spotlight plus) and glufosinate ammonium (Harvest), but the Defra Chief Plant Health Officer Unit should be consulted for appropriate treatments.

5.33. Tubers that remain in herbicide treated fields/areas should be harvested and destroyed by incineration (licensed) or deep burial. These destruction methods may also be preferred for small batches of infected plants outside of fields. Deep burial may be done at an approved landfill site, or on the site or nearby farm, if practical and in agreement with the local Environment Agency. Incineration must comply with appropriate waste management regulations, Environment Agency in England, Scottish Environment Protection Agency and Natural Resources Wales. If the material has to be moved off the premises, it should be contained within at least two sealed layers, if possible.

5.34. Aside from herbicide application, incineration and deep burial, other viable methods of destruction, at least for potato tubers, include heat sterilization, industrial processing (subject to adequate disposal of waste water), fermentation and composting, steaming and feeding to animals, and anaerobic digestion. Alternatively, tubers can be fed directly to cattle in a contained area. This is on the basis that manure and debris is collected and composted for at least 2 months in a contained area and is not returned to arable land likely to be used for host crops. Fermentation of contaminated potatoes during silage production provides a pre-treatment to direct feeding.

Review measures in the case of prolonged official action

5.35. Following an outbreak in potatoes, the infected field should be surveyed for the presence of volunteer potato plants and weed hosts of PSTVd. No potato crop should be grown in the infected field until there have been 2 years during which no volunteers have been found. Monitoring should involve visual inspection and testing of volunteer plants and/or weeds. Other demarcated fields should also be visually surveyed. In addition, it is advised that potatoes from these fields are inspected following harvest.

5.36. The EPPO protocol states that if continuing official action is required within the demarcated area over a prolonged period, a review of eradication and containment measures should be undertaken regularly to determine the success and cost-effectiveness of measures in the longer term. This review will involve consultation with stakeholders and should include:

- Evaluation of the effectiveness of current measures
- Evaluation of the economic impact and cost-effectiveness of continuing existing measures
- Consideration of further measures to strengthen containment and eradication actions
- Consideration of statutory obligations and impact on import and export procedures
- Consideration of alternative approaches, including pursuing measures to contain the pest rather than eradication or even the cessation of statutory action.

In circumstances where it is considered that the pest cannot be eradicated or contained and official action is no longer considered appropriate, stakeholders should be consulted and a timetable and mechanism for the removal of official measures, and for the dissemination of pest management information, should be agreed with the EU commission.

6. Criteria for declaring eradication / change of policy

6.1. *Potato spindle tuber viroid* can be declared eradicated (by the Chief Plant Health Officer Unit) in potato after at least two years during which no volunteers have been identified in the field due to the persistence of volunteer plants and no weeds have been found to be infected with PSTVd (EPPO, 2011).

7. Evaluation and review of the contingency plan

7.1. The Defra Contingency Plan for Plant Health in England requires that the pest specific plan is reviewed following an outbreak. This pest specific contingency plan should also be reviewed annually to take into account of changes in legislation, control procedures, sampling and diagnosis methods, and any other relevant amendments.

7.2. Lessons should be identified during and after any PSTVd or non-PSTVd outbreak, including what went well and what did not. These should be included in any review of the contingency plan leading to continuous improvement of the plan and response to outbreaks.

8. Appendix

Data sheet for *Potato spindle tuber viroid*

Identity

PREFERRED SCIENTIFIC NAME	AUTHOR (taxonomic authority)
Potato spindle tuber viroid	Diener (1971)

SUPERKINGDOM: Viroids
FAMILY: Pospiviroidae
GENUS: Pospiviroid

NON- PREFERRED SCIENTIFIC NAME (EPPO PQR)	AUTHOR (taxonomic authority)
Potato gothic virus	-
Potato spindle tuber pospiviroid	-
Potato spindle tuber virus	-
Tomato bunchy top viroid	-

INTERNATIONALLY USED COMMON NAME(S) AND INTERNATIONAL LANGUAGE (EPPO PQR):

Spindelknollenkrnakheit (German)
Bunchy top of tomato (English)
Spindle tuber of potato (English)

Notes on taxonomy and nomenclature

There are two viroid families; Avsunviroidae and Pospiviroidae. They are distinguished based on the presence or absence of a Central Conserved Region (CCR) and hammerhead ribozymes. The family Pospiviroidae has a CCR and does not form hammerhead ribozymes. This family is composed of five genera, including the genus Pospiviroid. *Potato spindle tuber viroid* (PSTVd) is the type species of the Pospiviroid genus (CABI, 2015; Flores *et al.*, 2009).

Species are discriminated from one another based on their level of sequence similarity across the whole genome; if their sequences differ by more than 10%, they are classified as separate species (Flores *et al.*, 2005). However, some genetically similar viroids are also separated because of differences in host range and symptoms. This is the case for PSTVd and *Tomato chlorotic dwarf viroid*.

Biology and ecology

Once the viroid has been transmitted into a host plant cell, it replicates within the nuclei via a rolling circle mechanism (Flores *et al.*, 2009).

Hosts/crops affected

The main host of PSTVd is considered to be potato (*Solanum tuberosum*), primarily because of the severity of symptoms that are seen on the plant following infection. Other hosts which suffer symptoms are tomato (*Solanum lycopersicum*), pepper (*Capsicum annuum*) and Cape gooseberry (*Physalis peruviana*) (Mackie *et al.*, 2002; Lebas *et al.*, 2005; Ward *et al.*, 2010). Symptomless infections have also been reported from avocado (*Persea americana*), *Brugmansia* spp., *Chrysanthemum* sp., *Calibrachoa* sp., *Cestrum* spp., *Dahlia* sp., *Datura* sp. *Lycianthes rantonnei*, *Petunia* sp., *Solanum pseudocapsicum*, *Streptosolen jamesonii*, *Solanum jasminoides*, *Solanum muricatum*, sweet potato (*Ipomoea batatas*) and wild *Solanum* spp. (Salazar, 1989; Owens *et al.*, 1992; Querci *et al.*, 1995; Behjatnia *et al.*, 1996; Di Serio, 2007; Verhoeven *et al.*, 2008a, b, 2009, 2010; Lemmetty *et al.*, 2011; Luigi *et al.*, 2011; Mertelik *et al.*, 2010; Verhoeven, 2010b; Tsushima *et al.*, 2011). The experimental host range of the viroid is even wider, numbering over 130 species, including several solanaceous plants (e.g. *Solanum melongena*) and species from

Amaranthaceae, Asteraceae, Boraginaceae, Campanulacaeae, Caryophyllaceae, Compositae, Convolvulaceae, Dipsaceae, Orobanchaceae, Sapindaceae, Scrophulariaceae and Valerianaceae (Singh, 1973; Matoušek *et al.*, 2007; Vachev *et al.*, 2010; Matsushita and Tsuda, 2015).

Plant stages affected

Potato spindle tuber viroid affects the flowering stage, fruiting stage and the vegetative growing stage.

Plant parts affected

Potato spindle tuber viroid affects the leaves, roots, fruits and tubers, as well as the size of the plant.

Symptoms/signs – description

Potato

Growth is often reduced, but impacts range from very mild (barely noticeable) to severe (CABI, 2015). There is an accumulation of pigment at the top of stems, which is generally associated with the rolling of terminal leaflets. If viewed from above, an infected potato plant is considered to exhibit clockwise phyllotaxy (= arrangement of leaves on the plant stem) (EPPO data sheet). Vines may be smaller, more spindly and upright. Leaves may also be smaller, as well as darker and more crinkled (CABI, 2015). Axillary buds sometimes proliferate to give the impression of Witches' Broom (EPPO data sheet). Further down the plant, tubers lose their shape, some becoming thinner and smaller, while others become bigger ('giant hill') (Gilbert, 1925; CABI, 2015; EPPO data sheet). The tubers also exhibit a cracked appearance (CABI, 2015). The eyes of the tubers are sometimes more pronounced and increase in number, and may be borne on 'knob-like protuberances' (Martin, 1922, 1924; CABI, 2015). Sprouting might also be slower than normal (EPPO data sheet).

The type and severity of symptoms vary depending on the strain of PSTVd and the cultivar of potato (Singh *et al.*, 1971; Pfannenstiel and Slack, 1980; Kowalska-Noordam *et al.*, 1987; Nakahara *et al.*, 1997). For example, Macleod (1927) found symptoms to be more obvious on Irish Cobbler than on Oreen Mountain Potatoes. Environmental conditions have also been shown to impact on symptoms, with higher soil moisture and temperature resulting in more serious damage of tubers (Goss, 1930).

Tomato

The first signs of PSTVd are growth reduction, epinasty (drooping of the leaf, caused by greater growth on the upper surface), chlorosis and crinkling at the top of the plant (Fig. 2; CABI, 2015; EPPO data sheet). This is followed by more severe chlorosis lower down the plant, which eventually results in reddening and purpling, and/or necrosis, and the leaves becoming brittle (Fig. 3; CABI, 2015). The growth reduction at the top of the plant may also lead to stunting of the whole plant (CABI, 2015). This is coupled with the cessation of flower and fruit initiation (CABI, 2015). In the worst case, stunting is followed by the death of the plant.

Figure 2. Epinasty, chlorosis and leaf crinkling of tomato plant.
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Figure 3. Purpling of tomato leaves.
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Pepper

Outside of the laboratory, the only symptoms observed on pepper have been the distortion of the leaf margins at the top of the plant (Lebas *et al.*, 2005). Artificial inoculation of the viroid has also resulted in a reduction of fruit size (Verhoeven *et al.*, 2009a).

Other fruit and vegetable crops, and ornamentals

Infection outside of potato, tomato and pepper is generally asymptomatic, though there is a record of symptom expression in Cape gooseberry plants (Ward *et al.*, 2010). Symptoms have also been displayed in aubergine and *Petunia* × *hybrida* following experimental inoculation (Matsushita and Tsuda, 2015).

Morphology

Potato spindle tuber viroid is a small, circular, single stranded RNA (Gross *et al.*, 1978). Depending on the strain, the number of nucleotides can total between 356 and 363 (Puchta *et al.*, 1990; Lakshman and Tavantzis, 1993; Behjatnia *et al.*, 1996; Verhoeven *et al.*, 2010a).

Similarities to other species/diseases/plant damages

The host range and symptom expression of other pospiviroids is similar to PSTVd (CABI, 2015). At least seven pospiviroids outside of PSTVd have been recorded naturally infecting tomato, and *Pepper chat fruit viroid* (PCFVd) has been recorded naturally infecting pepper (EFSA Panel on Plant Health, 2011). However, only PSTVd has been confirmed to infect potato in nature. All other pospiviroid infections of potato have been the result of experimental transmission (EFSA Panel on Plant Health, 2011).

Detection and inspection methods

Visual inspection of potato and tomato allows for the detection of pospiviroids if symptoms are present. However, because symptoms are similar between pospiviroids, it is difficult to distinguish PSTVd from other species. Depending on the severity of the strain, the environmental conditions and the host, symptoms may also not be evident. Laboratory tests are therefore required.

The principal means of detecting pospiviroids is through reverse transcription-polymerase chain reaction (RT-PCR) (Shamloul *et al.*, 1997; Bostan *et al.*, 2004; Verhoeven *et al.*, 2011). This method is generally non-specific and will not allow identification down to species level (e.g. Singh *et al.*, 1999; Verhoeven *et al.*, 2011). Identification to species level requires sequencing of the RT-PCR products and BLAST analysis (Boonham *et al.*, 2005; Verhoeven, 2010a).

Other methods that allow for the detection of pospiviroids include the use of indicator plants (Raymer *et al.*, 1964; Fernow *et al.*, 1969; Singh, 1984; Grasmick and Slack, 1987), gel electrophoresis (Morris and Wright, 1975; Schumann *et al.*, 1978; Schumacher *et al.*, 1986), nucleic acid hybridization (Owens and Diener 1981; Salazar *et al.*, 1983, 1988a, Lakshman *et al.*, 1986; Roy *et al.*, 1989; Candresse *et al.*, 1990; Podleckis *et al.*, 1993; Singh *et al.*, 1994; Khan *et al.*, 2009; Monger and Jeffries, 2015), real-time RT-PCR (Boonham *et al.*, 2004; Roenhorst *et al.*, 2005), reverse transcription loop-mediated isothermal amplification (RT-LAMP) (Tsutsumi *et al.*, 2010), real-time RT-LAMP (Lenarcic *et al.*, 2012) and macro/microarrays (Agindotan and Perry, 2008; Tiberini and Barba, 2012).

Distribution

(P) present, (W) widespread, (L) localized, (O) occasionally present, (D) reported in the past, no longer present, (E) eradicated, (I) absent, intercepted only (T) transient, actionable, under eradication		
COUNTRY/REGION	**DISTRIBUTION** (see codes above)	**REFERENCES**: please write (name, date) citation here and include full bibliographic details in reference list
ASIA		
AFGHANISTAN, AZERBAIJAN, BANGLADESH, GEORGIA	P	CABI/EPPO (2012); EPPO (2014)
CHINA	L	CABI/EPPO (2012); EPPO (2014)
Hebei, Jiangsu	P	CABI/EPPO (2012); EPPO (2014)
Heilongjiang	P	Singh *et al.* (1993b); Tien (1985); CABI/EPPO (2012); EPPO (2014)
Qinghai	P	Tien (1985); CABI/EPPO (2012); EPPO (2014)
INDIA	O	He *et al.* (1987); Owens *et al.* (1992); CABI/EPPO (2012); EPPO (2014)

Himachal Pradesh	P	Owens *et al.* (1992); CABI/EPPO (2012); EPPO (2014)
Maharashtra	P	CABI/EPPO (2012); EPPO (2014)
IRAN	O	Arezou *et al.* (2008); CABI/EPPO (2012); EPPO (2014);
ISRAEL	P	EPPO (2014)
JAPAN	O	Takahashi (1987); CABI/EPPO (2012); EPPO (2014)
Honshu	O	EPPO (2012); EPPO (2014)
TURKEY	O	Bostan *et al.* (2010); CABI/EPPO (2012); EPPO (2014)
AFRICA		
EGYPT	P	CABI/EPPO (2012); EPPO (2014)
NIGERIA	P	CABI/EPPO (2012); EPPO (2014)
NORTH AMERICA		
CANADA	E	CABI/EPPO (2012); EPPO (2014)
Alberta, British Columbia	D	CABI/EPPO (2012); EPPO (2014)
New Brunswick, Prince Edward Island	E	CABI/EPPO (2012); EPPO (2014)
MEXICO	P	CABI/EPPO (2012); EPPO (2014)
USA	E	EPPO (2014)
Alaska, Colorado, Idaho, Maine, Michigan, Minnesota, Mississippi, Montana, Nebraska, New Hampshire, New York, North Dakota, Ohio, Oregon, Washington, Wyoming	E	CABI/EPPO (2012); EPPO (2014)
California, Wisconsin	E	Ling and Sfetcu (2010); CABI/EPPO (2012); EPPO (2014)
North Carolina	E	EPPO (2014)
CENTRAL AMERICA & THE		
COSTA RICA	P	CABI/EPPO (2012); EPPO (2014)
DOMINICAN REPUBLIC	P	Ling *et al.* (2014)
SOUTH AMERICA		
ARGENTINA	E	Fernandez-Valiela and Calderoni (1965); CABI/EPPO (2012); EPPO (2014)
PERU	P	Singh (1983); Querci *et al.* (1995); CABI/EPPO (2012); EPPO (2014)
VENEZUELA	P	Singh (1983); CABI/EPPO (2012); EPPO (2014)
EUROPE ***Not normally present in food crops**		
AUSTRIA, BELGIUM, CROATIA, GERMANY	O	CABI/EPPO (2012); EPPO (2014)
BELARUS	W	CABI/EPPO (2012); EPPO (2014)
BULGARIA, IRELAND, SWITZERLAND	D	CABI/EPPO (2012); EPPO (2014)
CZECH REPUBLIC	O	Mertelik *et al.* (2010); Cervená *et al.* (2011); CABI/EPPO (2012); EPPO
FINLAND, FRANCE	E	CABI/EPPO (2012); EPPO (2014)
GREECE	T	CABI/EPPO (2012); EPPO (2014)
Crete	T	CABI/EPPO (2012); EPPO (2014)
HUNGARY	T	CABI/EPPO (2012); EPPO (2014)
ITALY	O	EPPO (2011); CABI/EPPO (2012); EPPO (2014)
NETHERLANDS	T	Verhoeven *et al.* (2008a); CABI/EPPO (2012); EPPO (2014); IPPC (2014a, b)
POLAND	T	EPPO (2011); CABI/EPPO (2012); EPPO (2014)
RUSSIAN FEDERATION	P	CABI/EPPO (2012); EPPO (2014)
Central Russia, Northern Russia, Russian Far East, Southern Russia	P	CABI/EPPO (2012); EPPO (2014)
SLOVAKIA	I	EPPO (2014)

SLOVENIA	O	IPPC (2007); Marn and Plesko (2012); CABI/EPPO (2012); EPPO (2014)
SPAIN	P	CABI/EPPO (2012); EPPO (2014)
UK	T	EPPO (2011); IPPC (2011); CABI/EPPO (2012); EPPO (2014)
England and Wales	T	CABI/EPPO (2012); EPPO (2014)
Scotland	I	EPPO (2014)
UKRAINE	P	CABI/EPPO (2012); EPPO (2014)
OCEANIA		
AUSTRALIA	O	CABI/EPPO (2012); EPPO (2014)
Australian Northern Territory	E	Behjatnia *et al.* (1996); CABI/EPPO (2012); EPPO (2014)
New South Wales	E	Cartwright (1984); CABI/EPPO (2012); EPPO (2014)
Queensland	O	EPPO (2014)
South Australia	E	Schwinghamer *et al.* (1983); Cartwright (1984); CABI/EPPO (2012); EPPO (2014)
Victoria, Western, Australia	E	CABI/EPPO (2012); EPPO (2014)
NEW ZEALAND	O	Ward *et al.* (2010); CABI/EPPO (2012); EPPO (2014)

Figure 2. *Distribution of PSTVd (green dots).*

History of introduction and spread

It has been suggested that PSTVd, along with *Mexican papita viroid* and *Tomato plancho macho viroid*, descends from a common ancestor originating in Mexico, on a wild *Solanum cardiophyllum* plant (Hoop *et al.*, 2008). However, spindle tuber disease was first identified in New Jersey, USA, in 1922 (Martin, 1922), and soon after in Maine (Martin 1922; Schulz and Folsom 1923). The viroid has since spread to a number of countries across various continents (Fig. 2). Reports of the viroid in potato fields have come from the USA, Canada, China, Russia and Turkey (Singh *et al.*, 1970, 1991, 1993b; Tien, 1985; He *et al.*, 1987; Güner *et al.*, 2012). The USA and Canada have since eradicated PSTVd (Sun *et al.*, 2004; De Boer *et al.*, 2005). The viroid has also been recorded in potato collections and breeding material in the UK, Australia, Argentina, Peru, the Netherlands, Venezuela and Brazil (Cammack and Richardson, 1963; Scottish Plant Breeding Station, 1976; Schwinghamer *et al.*, 1983; Cartwright, 1984; Fernandez-Valiela, 1965; Singh, 1983; Netherlands NPPO, 2014), but has been eradicated in the UK and Argentina. In tomato, reports of PSTVd have come from Australia, Belgium, Italy, Japan, New Zealand, the Netherlands, UK and the USA (Puchta *et al.*, 1990; Elliott *et al.*, 2001; Mackie *et al.*, 2002; Hailstones *et al.*, 2003; Mumford *et al.*, 2004a; Verhoeven *et al.*, 2004, 2007; Matshushita *et al.*, 2008; Navarro *et al.*, 2009; Ling and Sfetcu, 2010). Further, there have been a number of reports of PSTVd in other crops, such as ornamentals and peppers, in other countries (e.g. EFSA Panel on Plant Health, 2011; Lebas *et al.*, 2005).

Means of movement and dispersal

There is a high transmission rate of PSTVd from mother plants to their vegetatively propagated progeny (Owens and Verhoeven, 2009). This vegetative propagation material can be moved over long distances in trade, and is thought to be a major source of spread in potato and ornamental plants, especially in the absence of symptoms (Singh *et al.*, 1993b; Di Serio, 2007; Owens *et al.*, 2009).

A further form of human assisted transmission is mechanical spread. The spread of PSTVd has been shown between plants of the same and different species, via foliage and tuber contact (Bonde and Merriam, 1951; Merriam and Bonde, 1954), gloves and hands (Siegner *et al.*, 2008; Verhoeven *et al.*, 2010b; Fujiwara *et al.*, 2013; van Brunschot *et al.*, 2014 [fruit sap]), machinery (Merrian and Bonde, 1954; Manzer and Merriam, 1961), and tools (Verhoeven *et al.*, 2010b; Fujiwara *et al.*, 2013). PSTVd remains infective for hours outside of plants, as is shown on hands and gloves (Verhoeven *et al.*, 2010b; van Brunschot *et al.*, 2014). In addition, transmission efficiency varies depending on the recipient host and the source of inoculum (Verhoeven *et al.*, 2010b). For example, PSTVd was more readily transmitted to tomato and potato from *Solanum jasminoides* than from *Brugmansia suaveolens*. Verhoeven *et al.* (2010b) has also shown that temperature is a factor, with 25°C favouring transmission of PSTVd and 15°C being inhibitory.

Transmission by seed and pollen results in spread within a species. This method of transmission for PSTVd has been reported for potato (Hunter *et al.*, 1969; Singh, 1970; Singh *et al.*, 1992), tomato (Benson and Singh, 1964; Singh, 1970; Kryczynski *et al.*, 1988; van Brunschot *et al.*, 2014), and *Scopolia sinensis*, a wild solanaceous plant (Singh and Finnie, 1973), as well as experimentally by Kryczynski *et al.* (1992) and van Brunschot *et al.* (2014). The rates of transmission in potato vary between collections (Fernow *et al.*, 1970; Singh *et al.*, 1993b). EUPHRESCO (2011) have also shown that the viroid accumulates within the tissues of tomato seeds, which might leave it protected (either fully or partially) from disinfection techniques.

Transmission by insect vectors also allows for spread within and between species. Early experiments by Kennedy *et al.* (1962) and Smith (1972) showed that the aphids *Macrosiphum euphorbiae* and *Myzus persicae* transmitted PSTVd in potato. However, a later study by Schumann *et al.* (1980) did not corroborate these findings. Further, in a study by De Bokx and Piron (1981), PSTVd was not transmitted by *M. persicae* or *A. solani*, and was only transmitted by *M. euphorbiae* to tomato with very low efficiency. More recent research has shown that PSTVd is readily transmitted by *M. persicae* in the presence of *Potato leafroll virus* (PLRV) in potato (Salazar *et al.*, 1995). The presence of the virus might even be a necessity for *M. persicae*, with PSTVd failing to be transmitted in the absence of the virus in both potato and tomato (Querci *et al.*, 1997;

Singh and Kurz, 1997; Syller *et al.*, 1997 [from *P. floridana*]). Syller *et al.* (1997) also showed that PSTVd was encapsidated by (enclosed within the protein shell of) *PLRV*, rather than simply being adsorbed onto the outside, and that this might explain the successful aphid transmission.

Although bumblebees have shown transmission of *Tomato apical stunt viroid* (TASVd) and *Tomato chlorotic dwarf viroid* (TCDVd) (Antignus *et al.*, 2007; Matsuura *et al.*, 2010), a study by Nielsen *et al.* (2012) did not demonstrate transmission of PSTVd in this way. Nielsen *et al.* (2012) also did not show transmission of the viroid in adult thrips, though encapsidation was not explored, and nor was feeding by nymphs.

Mehle *et al.* (2014) has recently shown that PSTVd can remain infective within water for up to 7 weeks, and that infected water can lead to the infection of tomato roots and later the infection of the green parts of the plant. Potato tubers developed from plants grown in PSTVd infected water were also shown to be sources of the viroid. In hydroponic systems, where water is recycled, tomato and pepper plants are grown for several months, and sometimes a year. There is therefore time for the viroid to accumulate in or on roots. Although, it should be noted that infection efficiency was low, and that if infection did occur, movement into the rest of the plant was delayed and unevenly distributed.

Control

Chemical and biological control

There are currently no effective chemical or biological control options for PSTVd itself (CABI, 2015). However, its aphid vectors can be controlled through traditional means (EFSA Panel on Plant Health, 2011).

Resistant crop cultivars

There are currently no naturally occurring plant cultivars that offer full resistance to PSTVd. *Solanum acaule* offers partial resistance and is impervious to mechanical inoculation by PSTVd, but is vulnerable to infection when cDNAs containing the viroid are used in agroinfection (Salazar *et al.*, 1988b). Partial resistance has also been reported for other plants, including *Solanum guerreroens* and *Solanum berthaultii* (Harris *et al.*, 1979; Pfannenstiel and Slack, 1980; Singh, 1985; Palukaitis, 2012). Experimentally, resistance to PSTVd has been shown by Yang *et al.* (1997), Sano *et al.* (1997) and Schwind *et al.* (2009).

Cultural controls and sanitary methods during cultivation

Hygiene best practice

Principles of hygiene best practice for pospiviroids, including PSTVd, are outlined in the EFSA Panel on Plant Health (2011) and are briefly described in the contingency plan (Precautionary measures section).

Cleaning and disinfectants

Thorough cleaning of a glasshouse using a steam cleaner, and a scrub brush for less easily accessible structures, together with detergent is advised. An acid treatment for watering tubes and drippers has also been suggested by Owens and Verhoeven (2009).

Both Virkon and Virkon S (Li *et al.*, 2015; Olivier *et al.*, 2015), and sodium hypochlorite (e.g. Clorox regular bleach, Singh *et al.*, 1989; Roenhorst *et al.*, 2005; Li *et al.*, 2015) have been shown to be particularly effective as disinfectants of PSTVd. Nonfat dry milk, Lysol all-purpose cleaner, Virocid, Hyprelva SL and Jet S have also been shown to have a marked effect on PSTVd (Li *et al.*, 2015; Olivier *et al.*, 2015). Although Menno Florades and MENNO clean are mentioned in EPPO (2011) as suitable disinfectants for PSTVd, they were not demonstrated to be that effective by Li *et al.* (2015) or Olivier *et al.* (2015), respectively. It should be noted that disinfectants were less effective when applied to dried sap droplets infected with PSTVd (Olivier *et al.*, 2015). This was attributed to thick halos of sap forming at the periphery of the droplets, allowing the viroid to avoid the disinfectants. It is therefore important that appropriate contact is made between the viroid and the disinfectant if there is to be an effect.

Monitoring and testing

Regular monitoring of a crop allows for the early identification of symptoms. Testing also provides a means of detecting PSTVd in symptomatic, but also asymptomatic, plants, such as ornamentals.

Recovery

Potato spindle tuber viroid-free plants can be recovered from the infected plants by first exposing them to low temperatures (5-8°C) and then producing a meristem culture from these plants. This resulted in a recovery rate of 18.5-80% (Lizarraga *et al.* 1980; Paduch-Cichal and Kryczyński, 1987). Treatment of plants at high temperature (33-36°C) and producing a culture from the axillary buds also resulted in PSTVd-free plants, though this only produced a recovery rate of 2.4-6% (Stace-Smith and Mellor, 1970).

Phytosanitary measures

Import control measures

At ports, general surveillance is carried out, involving visual inspection for PSTVd symptoms, and subsequent testing if symptoms are found. If PSTVd is confirmed, the consignment is generally destroyed by either incineration or deep burial. Specific surveys are also instigated if there is considered to be sufficient risk of PSTVd spread.

Impacts

Economic impact

Reported yield losses for potato vary between 10 and 74% (Singh *et al.*, 1971; Cui *et al.*, 1992; Leontyeva, 1963; Cammack and Richardson, 1963; Folsom and Schultz, 1924; Bonde *et al.*, 1943; Murphy *et al.*, 1966; Hunter and Rich, 1964; Martin, 1924, 1928; Wedgworth, 1928; McKay and Dykstra, 1932; Burger, 1927; Balashev, 1941). The level of loss is dependent on the cultivar of potato, the strain of PSTVd and the length of time the crop has been infected with the viroid. For example, in the Saco cultivar, tuber yield was reduced by 24% when infected with the mild strain, but by 64% when infected with the severe strain (Singh *et al.*, 1971).

Tomato also suffers from variable yield losses (Verhoeven *et al.*, 2004, 2007). As well as the factors mentioned for potato, the growth stage at which the plant is infected is also important. Because fruit stops developing once stunting sets in, if tomato plants are infected prior to fruit production, yield losses could be as much as 100%, whereas if they are infected post fruit production, the fruit may still develop to a marketable size. Further, high infection rates in the past have been caused by a delay in identifying PSTVd in the crop and instigating measures. It has recently been found that elevated ozone concentration can reduce the impact of PSTVd in tomato (Abraitiene and Girgždiene, 2013).

Soliman (2012) calculated the economic losses of PSTVd in Europe if left unchecked to be 4.4 million euros in potato and 5.7 million euros in tomato, with the bulk of the costs borne by consumers having to pay a higher price for the same product, due to decreases in supply. Owens and Verhoeven (2009) have also calculated yield losses in North America over the period 1922-2009 to be 1% even after attempting to control the viroid.

In peppers, ornamentals, and other plants, no yield losses have been recorded, with only mild symptoms in pepper to date (Lebas *et al.*, 2005).

Environmental impact

No impact has been recorded.

Social impact

No impact has been recorded.

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