Recovery Plan

for

Potato Wart Disease

Caused by

Synchytrium endobioticum (Schilberszky) Percival

January 9, 2007

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This recovery plan is one of several disease-specific documents produced as part of the National Plant Disease Recovery System (NPDRS) called for in Homeland Security Presidential Directive Number 9 (HSPD-9). The purpose of the NPDRS is to insure that the tools, infrastructure, communication networks, and capacity required to mitigate the impact of high consequence plant disease outbreaks are such that a reasonable level of crop production is maintained.

Each disease-specific plan is intended to provide a brief primer on the disease, assess the status of critical recovery components, and identify disease management research, education and extension needs. These documents are not intended to be stand-alone documents that address all of the many and varied aspects of plant disease outbreak and all of the decisions that must be made and actions taken to achieve effective response and recovery. They are, however, documents that will help USDA guide further efforts directed toward plant disease recovery.

Executive Summary

Synchytrium endobioticum, the causal agent of potato wart disease, is the most important world-wide quarantine plant pathogen infecting potato. *S. endobioticum* is on the United States Select Agent list - a list of pests capable of considerable economic damage to agricultural crops, but not resident within the United States. Potato wart disease was recently evaluated as a top tier threat to agriculture on the United States Department of Agriculture, Animal and Plant Health Inspection Service, Plant Protection and Quarantine (USDA/APHIS/PPQ) list of regulated pests. The need for intense regulatory scrutiny is due to the latent persistence of the resting spores, a lack of effective chemical control measures and few resistant varieties that are horticulturally accepted in the United States.

Potato wart is a dramatic disease characterized by development of tumor-like galls or warts on tubers and underground portions of potato stems. Occasionally, galls form on the upper stem, leaf or flower. The warts act as a sink for nutrients and increase rapidly in size at the expense of the tubers, which may be replaced entirely by warts. Because the symptoms generally occur underground, with only a slight reduction in vigor noticed above ground, the disease is insidious and may not be evident until potatoes are dug at harvest.

Spread of potato wart between countries or between farms is through infected seed potatoes and movement of contaminated soil by machinery and workers. *Synchytrium endobioticum* has a limited capacity for natural spread, making effective control possible by statutory means.

Exclusion of the pathogen from non-infested areas is the most efficient method of disease control.

More than eighteen million metric tons of fresh and seed potatoes with a market value of $2.9 billion were produced in the United States in 2005. The economic impact of potato wart disease is not from direct disease losses but from loss of international trade markets, long-term quarantines, and regulatory restrictions placed on infested areas and the buffer zones surrounding infested land.

There is little funding available for research of a pathogen that USDA/APHIS/PPQ declared eradicated from the United States in 1974. While a large body of research on potato wart exists in Europe, much of it is not applicable to the United States because different potato varieties are used on the two continents. Canada has some research projects underway due to a potato wart outbreak and containment in 2000-2004. These North American projects should be expanded by the U.S. in the areas of developing molecular methods of pathogen identification, surveillance, evaluating current potato varieties for resistance and breeding for resistance.

Potato Wart Disease

Caused by

Synchytrium endobioticum (Schilberszky) Percival

Contributors

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I. Introduction

Potatoes rank fourth in the list of world food crops, after rice, wheat and maize. The United States ranks fifth in fresh market production after China, the Russian Federation, India and the European Union.

Information in the following table ranks the states by production figures, an indication of where the economic losses would be greatest if *Synchytrium endobioticum* is identified in commercial fields. Weather conditions approximating those known to be conducive to potato wart development occur throughout the northeastern states and a large part of the Great Lakes states. Those areas comprise about 25% of the potato production dollar value in the U.S. However, there is no information available about the possibility of wart survival in arid but irrigated potato production areas of western states or hot but humid southern states.

United States Potato Production (2005)		
State	*Weight in Billions of Pounds*	*Value of Production*
Idaho*	11.8	$674 M
Washington*	9.5	$535 M
Wisconsin*	2.8	$219 M
Colorado*	2.5	$214 M
Oregon*	2.2	$129 M
North Dakota*	2.1	$139 M
Minnesota*	1.8	$114 M
Maine*	1.5	$128 M
California*	1.5	$202 M

United States Potato Production (2005)		
State	*Weight in Billions of Pounds*	*Value of Production*
Michigan*	1.4	$110 M
Nebraska*	0.8	$70 M
Florida	0.8	$114 M
Texas	0.6	$73 M
New York*	0.5	$64 M
Pennsylvania	0.3	$31 M
Montana*	0.3	$32 M
North Carolina	0.3	$22 M
Kansas	0.2	$14 M
Nevada	0.2	$13 M
Illinois	0.2	$13 M
New Mexico	0.2	$12 M
Missouri	0.2	$12 M
Arizona	0.1	$14 M
Virginia	0.1	$11 M
Maryland	0.09	$7 M
Ohio	0.09	$7 M
Delaware	0.08	$7 M
Massachusetts	0.06	$5 M
New Jersey	0.05	$4 M
Alabama	0.02	$2 M
Rhode Island	0.01	$0.9 M
United States (2005)	42.4	$2.9 Billion

**States having potato seed certification agencies.*

USDA potatoes 2005 summary, http://usda.mannlib.cornell.edu/usda/current/Pota/Pota-09-21-2006.pdf

Synchytrium endobioticum, the causal agent of potato wart disease, is the most important world-wide quarantine plant pathogen infecting potato. *S. endobioticum* is on the United States Select Agent list and was recently evaluated as a top tier threat to agriculture on the Animal and Plant Health Inspection Service (APHIS) list of Regulated Pests (Rossman et al., 2006).

Presence of the pathogen does not affect the safety of potatoes for consumption, but causes cauliflower-like deformities to grow on potatoes making them unmarketable, and reduces yield. The pathogen affects the growing points on the potato plant, such as eyes, buds and stolon tips. At the end of the growing season, resting spores are produced that can remain viable in the field soil for 40 years or more, effectively eliminating infested fields from commercial potato production. The need for intense regulatory scrutiny is due to the latent persistence of the resting spores, a lack of effective chemical control measures and scarcity of resistant varieties that are horticulturally accepted in the United States.

Potato wart disease is believed to have coevolved with the potato in the Andes Mountains and was subsequently distributed around the world by trade in potatoes. The disease was first described in England in 1896, then reported on the European continent in Czechoslovakia (1898), subsequently spreading over the entire continent except Portugal. Potato wart has also been reported in Africa (Algeria, South Africa, Tunisia), Asia (Bhutan, India, Nepal), New Zealand, North America (Canada and the United States) and South America (Bolivia, Chile, the Falkland Islands and Peru) (De Boer, 2005).

The disease is commonly known as potato wart, but is also know by various names, including black scab, black wart, cauliflower disease, potato tumor, wart and warty disease. Potato is the principal host, but *S. endobioticum* has been experimentally transferred to tomato, and to black nightshade and climbing nightshade (*Solanum nigrum* L. and *S. dulcamara* L.). Both nightshades developed wart infections in pot experiments, though neither had been observed to be attacked in nature. Extensive testing of a number of species belonging to the Solanaceae did not produce any infections (Weiss, 1925; Hampson, 1993).

The first report of potato wart in North America was from Newfoundland in 1909, where it has been under quarantine since 1912. In 2000 and 2001, new infestations were reported in commercial potato fields on Prince Edward Island (P.E.I.), Canada.

Wart was identified in the United States in the early 1900s. Poor potato harvests in the U.S. during 1911 and 1912 resulted in the importation of millions of pounds of tubers from Europe where potato wart was spreading. In 1912, the United States adopted a strict quarantine against countries where wart disease occurred. Shipments of tubers imported prior to 1912, however, were believed to have reached diverse sections of the U.S. There is no evidence of the spread of wart from Newfoundland to continental North America.

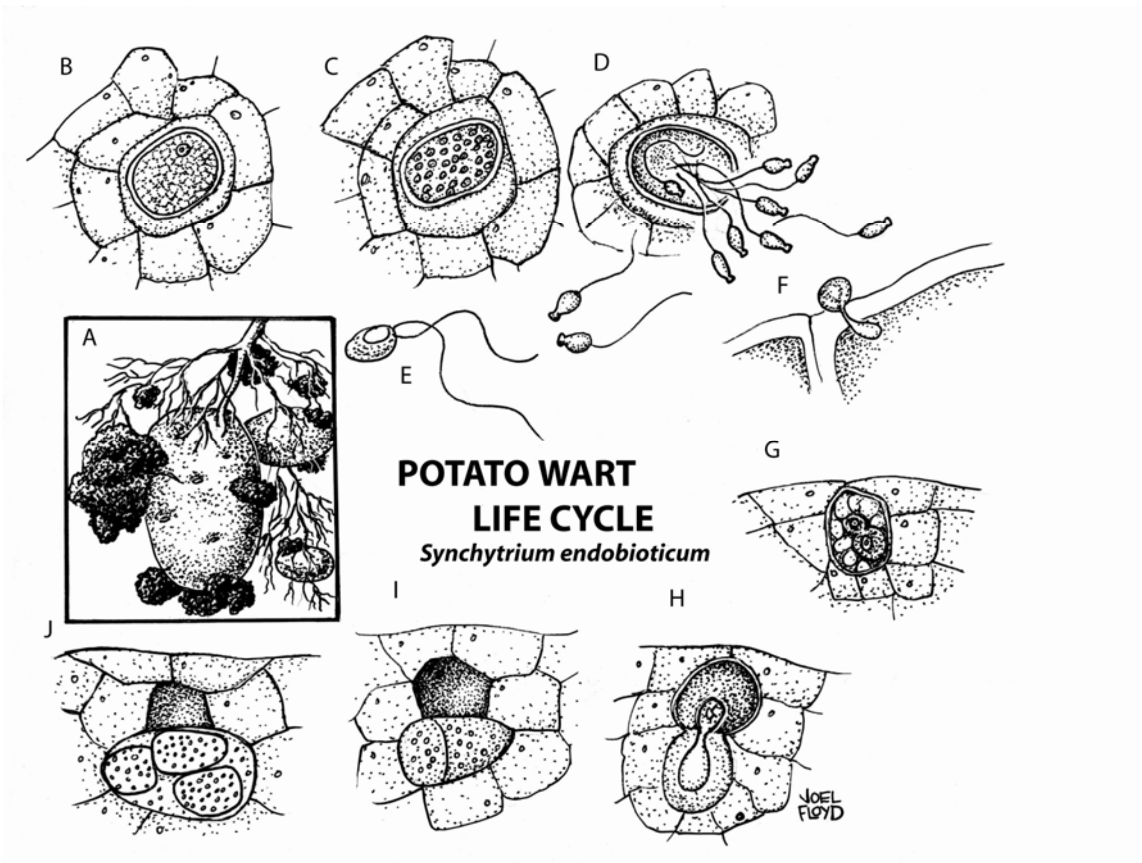
In 1918 potato wart was discovered in Pennsylvania, soon after in West Virginia and, in 1920, the disease was found in Maryland. The potato wart discoveries were confined to home gardens in coal mining areas of the states. Despite a 1919 national survey for potato wart by the Plant Disease-Survey in cooperation with the Federal Horticultural Board, no more infestations, other than those in West Virginia and Maryland, were discovered (Lyman et al., 1920).

Infestations in Pennsylvania and West Virginia were eradicated in the 1950s and 1960s, respectively. Infestations in Maryland were thought to be eradicated but non-viable cysts of the pathogen were found in one home garden during a survey in 1974. Subsequent bio-assays conducted with susceptible potato cultivars, and soil collected from the infected site did not produce any evidence of the pathogen. Potato wart was considered eradicated from Maryland in 1994 (Putnam and Hampson, 1989).

II. Biology and Symptoms

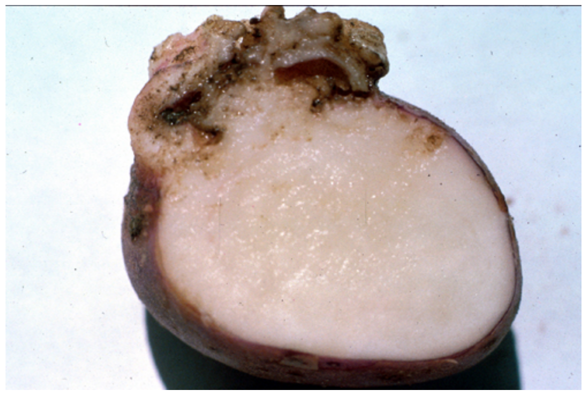
S. endobioticum is an obligate parasite – a pathogen that can only feed on the living tissues of the host plant and cannot be grown in artificial culture medium. The pathogen does not produce hyphae. When not actively growing, it can survive as resting spores in the soil for as long as 40 years.

Conditions favorable for disease development include cool summers with average temperatures of 18°C (64°F) or less, winters of approximately 160 days at or below 5°C (41°F) and annual precipitation of 70 cm (28 in.). Temperatures between 12-24°C (54-75° F) favor infection.



Life cycle diagram of **Synchytrium endobioticum**. *A, infected tubers, stem and stolons with wart symptoms; B, resting sporangium; C, resting sporangium with maturing zoospores; D, discharged motile zoospores; E, two zoospores form a (diploid) sporangium to later form a zygote; F, zoospore entering a host cell by direct penetration; G, young prosorus in host cell; H, contents of prosorus passing into host cell; I, cross section of sorus with two (haploid) sprorangia and remains of empty prosorus; and J, three mature (haploid) sporangia in sorus with zoospores beginning to be released. The haploid sporangia are summer sporangia and the diploid sporangia are resting winter sporangia* (Stevenson et al., 2001; illustrations after Walker, 1957).

A typical disease cycle of potato wart begins when cool spring temperatures, and rainy weather or irrigation cause the soil-borne thick-walled overwintering sporangia to germinate. Instead of hyphae, each germinating sporangium produces as many as two- to three-hundred motile zoospores (2-4 µm). The zoospores have a tail-like flagellum enabling them to move through soil water. Zoospores can survive for 1-2 hours, infecting susceptible potato tissue with which they come into contact. The plant cells around the penetration point swell and proliferate, producing the characteristic warty, cauliflower appearance. The internal cells entered by the zoospores also become greatly enlarged. More spores are discharged from the infected tissue, re-infect surrounding cells which, in turn, produce more spores and subsequent infections as long as conditions remain favorable (cool, wet summer growing conditions). The persistent resting spores form at the end of the growing season and are capable of surviving in the soil for decades at depths of up to 50 cm (20 inches).



Potato tuber with gall

Stem galling on potato

Photos: Michael Hampson

The warts are tumor-like galls affecting tubers and underground portions of potato stems. Occasionally, warts form on the upper stem, leaf or flower. The warts range from the size of a pea to large masses that cover the entire tuber. Warts at first appear green or white, turn brown and then black at maturity as they decay. Roots are not known to be attacked. The warts act as a sink for nutrients and increase rapidly in size at the expense of the tubers, which may entirely transform into warts. Because the symptoms generally occur underground with only a slight reduction in vigor above ground, the disease is insidious and may not be evident until potatoes are dug at harvest (Stevenson et al., 2001; EPPO Bulletin 34, 2004).

Potato wart on tomato

There is one report from 1920 that several varieties of tomato became infected with potato wart when grown in infested soil.

In 1918, L.O. Kunkle and C.R. Orton completed a survey of vegetables other than potatoes, and weeds growing in infested Pennsylvania gardens. They found no evidence of potato wart infection. However, they were aware of the range of potato varieties susceptible to potato wart, and set out to see if tomatoes, close relatives of potatoes, also showed varietal susceptibility. In 1919, they planted two plants each of fifty tomato varieties in an *S. endobioticum* infested garden in Lehigh, Pennsylvania. About half the plants died from damping-off fungus, but of the remaining plants that survived until harvest, seven varieties showed signs of potato wart on the roots and stems. The warts on the roots were the size of a pea or smaller. The warts on the stems were considerably larger than on the roots. Warts were confined to the underground portions of the stem or to portions just above the surface of the soil. Microscopic examination revealed that both root and stem warts contained large numbers of resting sporangia. The warts on the tomato were harder and less succulent than those on the potato. Kunkle and Orton felt that the large numbers of warts on the roots of a tomato plant might somewhat lessen the yield. It was not believed that the disease would cause serious damage to susceptible tomato varieties, but growing these varieties on infested soil would keep the disease alive from year to year and transplanting seedlings from infested soil might spread it to new fields. The warted stem of the Maulc’s New Imperial tomato variety is show below (Lyman et al., 1920).

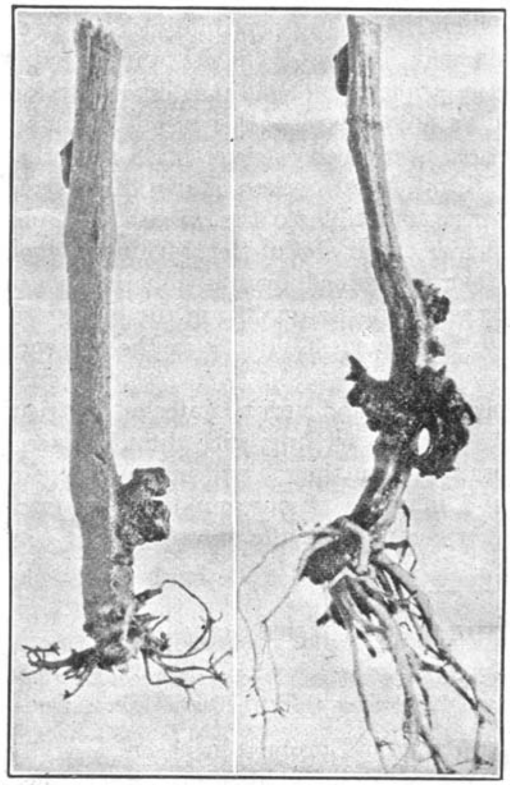


FIG. 4.—Wart on the tomato. Infected stems of plants of Maule's New Imperial variety grown in a wart-infested garden at Upper Lehigh, Pa., in the season of 1919.

III. Spread

Synchytrium endobioticum has a very limited capacity for natural spread, making it possible to control it effectively by statutory means. Spread of potato wart disease between countries or between farms is primarily through infected seed potatoes. The potato industry in the United States has excellent programs in place to safeguard the disease-free quality of seed and fresh potatoes on a state by state basis, and is in the process of establishing a nationally verifiable system. It may still be possible for infected potatoes with incipient warts to pass undetected through visual inspection. However, many programs start with tissue cultured stock that eliminates all pathogens. Wart in a seed field would be detected early because in the early seed generations the potatoes are checked individually.

Local spread may occur by the movement of fungal spores in soil, water, or in contaminated soil adhering to tubers, equipment, implements or other carriers. Manure from animals that have fed on infected tubers may also spread the disease. USDA-APHIS-PPQ's prohibition on the movement of foreign soil into the United States makes it unlikely that potato wart could enter the U.S. on imported plants or plant parts (EPPO bulletin 34, 2004; Stevenson et al., 2001).

IV. Monitoring and Detection

Synchytrium endobioticum has been subject to quarantine and domestic legislation to prevent its spread worldwide for more that 65 years. Crop protection chemicals have not proven effective in controlling potato wart. Exclusion of the pathogen from non-infested areas is the most efficient method of disease control.

Potato wart is not a disease that is regularly surveyed by the APHIS Cooperative Agricultural Pest Survey (CAPS) program. Some limited survey work was conducted in parts of Idaho, Washington, Massachusetts, Oregon, Vermont and Nevada between 2000 and 2005. All results were negative. The state of Montana will complete a CAPS survey for potato wart in 2006 but results are not yet available (NAPIS website; Personal communication with Montana Department of Agriculture).

Potato wart falls under both state and federal regulations within the United States. Monitoring for potato diseases is built into the U.S. potato industry at several levels. There is a formal program of inspection and certification of seed potatoes to ensure that the tubers sold for seed meet the quality standards mandated by state law. The standards ensure that only high quality seed is marketed to growers of fresh market and processing potatoes. Authority for certifying seed potatoes at the state level resides with the agency granted authority by state law. The agency is usually a land grant university, state department of agriculture, crop improvement association or a combination of all three.

There are formal and informal inspections of tablestock potatoes during and after harvest, when potatoes travel by conveyor belt into cold storage and again, on the conveyer moving potatoes from cold storage to be washed and sold. Seed potatoes are subject to inspection by state regulatory officials when crossing state lines.

Each state land grant university diagnostic laboratory, as part of the National Plant Diagnostic Network (NPDN), has a protocol for preliminary identification of *S. endobioticum* and instructions for sending suspicious samples to the USDA national lab for confirmation and species identification.

Because *S. endobioticum* is on the federal Select Agent list (42 C.F.R. Part 73, 7 C.F.R. Part 331, and 9 C.F.R. Part 121), any suspected incidences of the pathogen in the United States must be sent for confirmation to the Plant Protection and Quarantine (PPQ) division of APHIS. Morphological identification of *S. endobioticum* will be performed by the National Mycologist at the USDA-APHIS-PPQ Plant Safeguarding and Pest Identification National Identification Services in Beltsville, MD. Confirmatory molecular testing and validation of primers for PCR or serological tests for the pathogens is performed at the USDA-APHIS-PPQ National Plant Germplasm and Biotechnology Laboratory (NPGBL) in Beltsville, Maryland. This laboratory also has all the necessary permits, registrations, and containment approvals to handle select agents.

In the future, other laboratories may obtain certification and registrations for making presumptive determinations but must abide by guidelines set under various permits and authorizations maintained by APHIS Plant Protection and Quarantine.

V. USDA Pathogen Permits

The possession, use and transfer of select agents as well as plant pests or infected plant material, regardless of quarantine status, is specifically regulated.

PPQ permit and registration requirements for plant diseases and laboratories fall under two authorities, the Plant Protection Act (7 CFR Part 330) and the Agricultural Bioterrorism Protection Act of 2002 (7 CFR Part 331). Laboratories receiving suspect infected plant material or cultures are required to have PPQ permits. Laboratories possessing, using, or transferring select agents are required to be registered as a select agent laboratory. However, diagnostic laboratories that identify select agents are exempt from this requirement as long as they complete an APHIS/CDC Form 4 and destroy or transfer infected material to a laboratory registered with the APHIS Select Agent Program within seven calendar days of learning of a positive confirmation.

- The Plant Protection Act permit requirements apply to all plant pests and infected plant material, including diagnostic samples, regardless of their quarantine status. If any material is shipped interstate, it is a requirement that the receiving laboratory has a permit. For further guidance on permitting of plant pest material, consult the PPQ permit website at: http://www.aphis.usda.gov/ppq/permits/ or contact PPQ Permit Services at (301) 734-8758.

- Federal regulation by the Agricultural Bioterrorism Protection Act of 2002 (7 CFR Part 331) specifies requirements for possession, use, and transfer of organisms listed as select agents and toxins. Once a diagnostic laboratory identifies a select agent, it must immediately notify the APHIS Agriculture Select Agent Program, complete an APHIS/CDC Form 4 and submit within 24 hours, and either destroy or transfer the agent to a registered entity within 7 calendar days. In compliance with this Act, if a diagnostic laboratory held back part of a screened sample for voucher purposes and the sample that was forwarded to the USDA Beltsville Laboratory came back as positive for a select agent, the diagnostic laboratory is required to notify the APHIS Select Agent Program immediately. If the determination of the laboratory is to destroy the sample, this must take place within seven (7) calendar days of results notification and a PPQ Officer must witness the destruction of the sample on or before the 7-day period expires. Clarification of this and other information related to adherence to the select agent regulations is available on the following APHIS website: http://www.aphis.usda.gov/programs/ag_selectagent/index.html, or call (301) 734-5960.

VI. Response

While this plan is focused primarily on recovery, certain facets of the response to a new detection involve aspects of recovery with a continuum of activities from response to recovery. The response is under USDA-APHIS-Plant Protection and Quarantine's authority delegated from the Secretary of Agriculture under the Plant Protection Act of 2000.

After a detection of *S. endobioticum* has been confirmed by a USDA-APHIS-PPQ recognized authority, APHIS, in cooperation with the appropriate state department of agriculture, is in charge of the response. Race or pathotype determination is not necessary to initiate the response as all races are under quarantine. The response is immediate in the form of advance assessment teams of state and federal experts and survey personnel. They are sent to the site of initial detection to prevent the movement of regulated articles, conduct investigations, and initiate delimiting surveys using trace back and trace forward information, crop, tuber, and soil samples, shipping point inspections, post-harvest field sampling and/or bioassay of crops. Actions that may be taken include regulatory measures to quarantine infested or potentially infested production areas, stop movement of infected or potentially infected articles in commerce, and other control measures which may include host removal and destruction, and/or insuring adherence to required sanitary practices. APHIS imposes quarantines and regulatory requirements to control and prevent the interstate movement of quarantine-significant diseases or regulated articles, and works in conjunction with states to impose these actions parallel to state regulatory actions which restrict intrastate movement.

The field(s) known to be positive (index sites), all adjacent fields, and fields within a ½ mile (0.8 km) core (regulated) area around the index site will be placed under quarantine. All fields with previous linkages to index field(s) by shared harvesting equipment, vehicles, or machinery are called contact fields and will also be placed under quarantine. Regulated articles include host plants and plant parts (potato and tomato), soil and crops contaminated with soil, machinery, equipment and vehicles from the regulated area. Also included are bags, tools, seed houses, and storage sheds with links or associations to infested fields or tuber lots. Host material and soil are prohibited movement outside the regulated area and any regulated equipment, tools, vehicles, machinery, or storage areas must be disinfested with prescribed formulations of quaternary ammonium.

Fields that are positive for *S. endobioticum,* and all host crops in the regulated area must have the current crop destroyed with an approved herbicide. The dead plant material is subsequently destroyed by burning, incineration, or removed and sent to an approved landfill. Harvested potatoes from regulated fields are also destroyed by approved methods. Prohibition of host crops in the regulated area remains in effect until the disease is considered eradicated. An exception to this is allowed if the race is determined to be one with which immune varieties of potato are available, and they can be planted. Potatoes from these plantings can only be used for processing under compliance agreement, and are not allowed for use as seed or tablestock. In a minimum of ten years the fields are resurveyed requiring planting with a susceptible variety for three consecutive years with conducive environmental conditions for the disease. If no evidence of potato wart is detected in those three years, the fields can be released from quarantine.

VII. Infrastructure and Experts

Much of the infrastructure, outside the regulatory community, for detecting and diagnosing a pest of national concern such as potato wart, has been organized and developed in the past four years. The National Plant Diagnostic Network (NPDN) was established by USDA-CSREES in 2002 to enhance national crop security by quickly detecting and diagnosing introduced plant pests and pathogens. To date, more than 12,000 growers, crop consultants and extension educators have received NPDN training to be aware of unusual or suspicious plant symptoms for many different pathogens and pests, to collect and package suspicious plant samples properly, and quickly submit them to the nearest state land grant university diagnostic lab. More information about NPDN First Detector training and training materials can be found at http://www.npdn.org/, Click on First Detector Information under NPDN portal.

The NPDN has also updated lab equipment and linked all land grant university diagnostic laboratories electronically, giving labs the ability to visually compare samples over a secure network. Standard Operating Procedures are being developed for the identification of many plant pathogens, including potato wart. National training sessions are regularly provided for diagnosticians to upgrade diagnostic techniques.

Standardized protocol for handling specimens, securing identification and facilitating communications has been developed jointly between NPDN and APHIS-PPQ. This protocol has been practiced in 43 of 50 states, using simulated diagnostic events of high risk pests. The diagnostic exercises have involved extension educators, extension specialists, land grant university diagnostic labs, and both state and federal regulatory officials.

Each region of the U.S. where potatoes are grown has at least one land grand university plant pathologist specializing in potato diseases. U.S. plant pathologists that specialize in potato diseases can be queried from the American Phytopathological Society website (http://www.apsnet.org/) under membership directory, advanced search.

North American scientists with expertise in potato wart include:

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Steven B. Johnson - University of Maine Cooperative Extension, PO Box 727, 57 Houlton Road, Presque Isle, ME 04769-0727, (207) 764-3361, sjohnson@umext.maine.edu

Jim Stack – National Plant Diagnostic Network (Director), experts in diagnosis and detection. Kansas State University, 4024 Throckmorton Hall, Manhattan, KS 66506-5502, 785-532-1388, jstack@ksu.edu .

The Canadian Food Inspection Agency (CFIA) maintains the following centers involved with potato wart research for Canada:

- CFIA Laboratory - Charlottetown, Prince Edward Island, Center of Expertise for Potato Diseases.
  The Center provides testing, and reference services for CFIA's Seed Potato Certification program. Activities include research to improve tests for potato diseases of quarantine and trade significance. The Center also provides audit and technical support for the accreditation of non-federal labs to test seed potatoes for import, export and disease control programs.

- CFIA Laboratory – St. John's, Newfoundland.
  Provides testing for potato wart disease and cyst nematodes; collaborates with Agriculture and Agi-food Canada and the Newfoundland government in the development of potato cultivars resistant to potato wart and potato cyst nematodes.

The European and Mediterranean Plant Protection Organization (EPPO) is an intergovernmental organization responsible for European cooperation in plant health. Founded in 1951 by 15 European countries, EPPO now has 48 members, covering almost all countries of the European and Mediterranean region. Its objectives are to protect plants, to develop international strategies against the introduction and spread of dangerous pests and to promote safe and effective control methods.

VIII. Economic Impact and Compensation

Member nations of the World Trade Organization are entitled to ban imports of plant material that may introduce exotic diseases into their territories. Thus, importing countries that are themselves free of a particular highly contagious plant disease will routinely impose sanitary or phytosanitary restrictions on trade with countries in which that disease occurs. This can result in billions of dollars of lost trade.

In 1987, a senior policy advisor (D. Karamchandani) with Agriculture and Agrifood Canada, did an analysis of the putative economic losses of a potato wart discovery to Atlantic Canada and the far-reaching consequences for the rest of the country. At that time there had not been an incidence of potato wart in a commercial Canadian field. The analysis proved prophetic when the economic impact from the 2000-2001 discoveries of potato wart on P.E.I. closely followed her assumptions. Karamchandani assumed new outbreaks would be small and sporadic and would be detected before they caused major crop damage. She concluded that the impact would not be caused directly by the pathogen but would result from the imposition of various measures such as embargoes, quarantines, long crop rotations, increased research activity and incentives to grow only resistant cultivars. In Atlantic Canada's major potato growing region, farm revenues would fall, potatoes would be consumed locally at lower cost to the consumer, and supplies to central and western Canada would fall, causing increased costs in potato-deficit areas. Governments would be under pressure to bear most of the adverse economic consequences, and there would be repercussions on world trade as other countries would most likely cease to import Canadian potatoes (Hampson, 1993).

Federal Crop Insurance

Federal crop insurance compensation is provided for potato losses due to plant disease but only if good farming practices are followed that include disposing of any infected crop from previous years, use of appropriate crop protection chemicals, and using recommended rotation practices for the specific disease. The various policies for potatoes can be accessed by policy number from the website listed below.

POTATO

Policy Name	Policy #	Ref #
Northern Potato	98-184	3
Northern Potato Quality Endorsement	98-84A	3
Northern Potato Processing Quality Endorsement	98-84B	3
Northern Potato Certified Seed Endorsement	2001-84C	3
Northern Potato Storage Coverage Endorsement	98-84D	3
Central & Southern Potato	99-284	3

http://www.rma.usda.gov/policies/2001policy.html

IX. Mitigation and Disease Management

Modeling

The North Carolina State University/APHIS Plant Pest Forecast (NAPPFAST) (www.nappfast.org) System is an internet tool for plant pest modeling using georeferenced climatological weather data. NAPPFAST has developed risk maps representing the influence of weather and climate on potato wart development. The probability risk maps are estimated from 30 years of daily climatic data using two simple models. The first model represents the influence of climatic conditions upon overwintering and the second represents epidemic development of the disease during the growing season (Magarey et al., 2004).

Chemical control options

It the past, infested soils were chemically treated to eradicate surviving soil inoculum of potato wart. This approach is no longer suitable. The drastic ecological impact of the type and high rates of chemical treatments (mercury, sulfur, copper, chlorine-based chemicals and formaldehyde) that were used left the soil barren. This is unacceptable because the intention of soil treatment is to resume potato cultivation (Reigner, 2006; De Boer, 2005).

There is zero tolerance for potato wart. For any crop protection chemical to be considered effective, it must be eradicative, not just suppressive. More than 400 compounds have been tested for controlling potato wart. To date, no chemicals are recommended for managing the disease (Hampson, 1993).

Biological control

Several biological control theories and non-chemical treatments, such as the use of chitin, urea, organic fertilizers and crab shell meal have been proposed and investigated in areas of known infestation of the wart pathogen. None have been widely adopted in field use, and efficacy information is limited.

Disease management

To date, the best method of managing an initial outbreak of potato wart disease is quarantine and movement restriction on fields that are within a buffer area and associated with the index field.

Prince Edward Island (P.E.I.) Potato Wart Disease Case Study

Potato wart was first discovered on P.E.I. on October 24, 2000. Originally, one field of potatoes was found to be infested in New Annan, P.E.I. in 2000, and in 2002 five additional infested fields were discovered. The Canadian Food Inspection Agency (CFIA) and the United States Department of Agriculture (USDA) developed a three-year working plan including restricted movement of host material and equipment within the quarantine area, surveillance activities, and a certification process for potatoes produced on P.E.I. Potato wart was detected in one P.E.I. field during 2003, indicating that the conditions were favorable for the disease in that location. One indication that the 2003 potato growing season on P.E.I. was conducive for potato wart was that there were symptomatic volunteer plants in an index field near the New Glasgow area.

Following is a narrative of how the disease outbreak was handled by the Canadian government, and the regulatory requirements imposed by USDA before potatoes could again be imported into the United States from the island.

In October 2000, the United States closed its border to shipments of potatoes from P.E.I., Canada because potato wart had been identified in a field on the island. Harvesting was stopped as soon as the first infected potato was seen, and harvesting equipment was sanitized. Canadian regulatory actions to delimit the infestation included immediate quarantine of the area where the pathogen was found, a prohibition on the movement of potatoes and machinery from the index field as well as surrounding fields, collecting and analyzing thousands of soil samples in the index field and surrounding area, conducting trace-backs and trace forwards on the seed potatoes, and investigating past farming practices in the index field. The field where the infected potatoes were found was enclosed with a chain-link fence and security guards were posted 24 hours a day. By mid-November 2000, the delimiting survey determined that the initial detection was restricted to the section of the original index field.

The U.S. border remained closed to P.E.I. potatoes for six months, until April 2001, while a scientific risk analysis was completed (Brown, 2006). The objective of the assessment was to recommend a general surveillance survey to reduce the risk of *S. endobioticum* moving from P.E.I. into the United States. The risk in need of surveillance was the independent existence of undetected infestations (cryptic fields) occurring on P.E.I.

The U.S. border reopening came with strict USDA-APHIS provisions for Canadian inspection and handling of the 2000 potato crop. A 3-year plan was put in place whereby Canadian inspectors must inspect every P.E.I. potato field after harvest to determine if there was a detectable level of potato wart disease. Officials also had to inspect random samples of potatoes heading into and out of storage (Herglotz and Jones, 2001).

In September 2002, two more incidences of potato wart were detected from two different fields (independent of the original infestation) approximately six and 15 miles from the original find in 2000. Both infections were discovered during a Canadian Food Inspection Agency post-harvest field inspection required under the 3-year Canada/US working plan. The new finds did not negatively affect trade. The CFIA regulations put into place for P.E.I. after the initial detection, mitigated this expanded risk. The inspection was instrumental to safeguarding U.S. trade with Canada.

In the four years immediately following the disease outbreak, 126,000 hectares were surveyed for evidence of the disease and 26,000 soil samples were processed for pathogen extraction. The overall cost of the P.E.I. outbreak was estimated at over $83 million. It is estimated that the loss to the island's economy and its 600 potato growers was between $30 and $50 million (Canadian Phytopathological Society website: http://www.cps-scp.ca/pathologynews/potatowart.htm).

X. Research, Extension, and Education Priorities

Research Priorities

<u>Evaluation of U.S. potato varieties for resistance/susceptibility to potato wart</u>

North American potato varieties differ from those used in Europe and have not been included in the virulence testing there, so very little is known about the resistance/susceptibility of North American varieties. There is no program in the United States for evaluating the resistance of potato varieties to *S. endobioticum*. However, there is a program at the CFIA Laboratory in Newfoundland that could be a useful model, a starting point, or a resource for beginning a new or cooperative program of resistance evaluation for U.S. potato varieties.

In countries with known infestations of potato wart, cultivation of resistant (immune) potato varieties has been the prime measure for managing the disease. The European Union (EU) member states are obliged annually to send the EU commission a list of potato cultivars which have been officially tested and found to be resistant to *S. endobioticum*. The EU directive does not specify the methodology to be used for testing, only describes the phytosanitary goal that is to be reached in terms of risk. Complete resistance to *S. endobioticum* is not required. Rather, resistance should be such that secondary infection within the crop, or of a subsequent crop of the same cultivar, need not be feared (Baayen et al., 2005).

The Canadian Food Inspection Agency (CFIA) maintains a website listing descriptions of all commercial potato varieties used in Canada (http://www.inspection.gc.ca/english/plaveg/potpom/var/indexe.shtml). The list can be queried by specific disease. Fifty potato varieties are included that range from immune to highly resistant to potato wart, with pathotype resistance listed where known. Only three varieties on this list are grown in the United States.

Over 20 different pathotypes of potato wart have been described, mainly from Europe where resistance testing has been on-going since 1920. Each pathotype is characterized by its pattern of infectiousness on different potato varieties. Because the pathotypes work in subtly different ways within potatoes, genetic resistance must be specific to each pathovar. To date, there is no international harmonization of pathotype codes (Baayen et al., 2006).

Pathotyping is a time-consuming and difficult procedure. One of the *S. endobioticum* isolates from the 2000/2001 P.E.I. potato wart outbreak has been identified as the strain consistent with German pathotype 6, and typing of two other isolates has not been successful thus far. Newfoundland, Canada is known to harbor pathotypes 1, 2, 6 or 7, and 8 (Stachewicz and De Boer, 2002).

The United States would benefit from the development of cooperative projects with Canada and European countries for the purpose of including U.S. potato varieties in potato wart resistance screening programs. While the U.S. does not have a national public database for potato varieties and pest resistance, there are regional websites such as the Potato Information & Exchange (http://potatoes.wsu.edu/) at Washington State University that could benefit from the inclusion of disease resistance/susceptibility information in their varietal lists.

Breeding for Resistance

Potato resistance breeding programs are crucial in the control of potato wart disease. Potato wart resistance/susceptibility is not a consideration in U.S. potato breeding as there is no program available to test against North American pathotypes and it is an uncommon practice to breed for resistance to pests that do not occur in the country.

Resistant germplasm is available for use in breeding. Researchers in Germany at the Max-Planck Institute for Plant Breeding Research have developed potato lines that harbor multiple resistance genes by marker assisted selection. Knowledge of the genetic position of the desirable traits and of closely linked DNA-based markers allows the targeting of specific genes for introgression, and provides a fast track to increase genetic gain in crop breeding. The plant lines generated are resistant to four important potato pathogens, Potato Virus Y, *Synchytrium endobioticum*, and the root cyst nematodes *Globodera rostochiensis* and *Globodera pallida*. The selected plants can be used as sources of multiple resistances and are available from the Institut für Pflanzengenetik und Kulturpflanzenforschung (IPK) potato germplasm bank in Germany. Selection of *Synchytrium*-resistant potato cultivars may be facilitated by using markers closely linked with a resistance gene or by transferring a cloned gene for resistance into susceptible cultivars. A single, dominant gene for resistance to *Synchytrium endobioticum* has been located on potato linkage *group XI* (Gebhardt et al., 2005).

Developing improved molecular diagnostic tools for detection of *S. endobioticum* in both plants and soil

A discovery of potato wart infection is soon followed by intensive testing of soil and tissue for evidence of the pathogen. Time is of the essence in order to determine the extent of the infestation and delineate the quarantine area. The best qualitative and quantitative testing procedures must be continually scrutinized and updated to the standards of new molecular technology.

A technique developed in Canada during the 2000-2001 outbreak, used the DNA of several potato wart-diseased potatoes including one specimen from the original outbreak in Newfoundland in 1903. The DNA extraction and subsequent development of probes for detection made possible the creation of a highly sensitive test for detecting as few as one to three pathogen spores per gram of soil (Levesque, 2001).

Recent work in Germany demonstrated the utility of 18S rDNA sequence of *S. endobioticum* in microarrays for the simultaneous detection of fungal and viral pathogens of potato. The study suggests that oligonucleotide-based microarray has great potential, providing a very convenient option for multiple pathogen detection, especially in quarantine laboratories where plant materials are routinely screened for both characterized and uncharacterized disease-causing organisms (Abdullahi et al., 2005).

Delimiting surveys and the potato wart surveillance model

The North Carolina State University (NCSU)/APHIS Plant Pest Forecast (NAPPFAST) System, a web-based interface used for mapping the distribution of invasive pests, recently completed a project on potato wart (described in the Disease Management and Mitigation section under *Modeling*). The project was a general assessment for the United States, as a whole. The next step would be to refine the model for the important potato production states. It is essential to determine the likelihood of conditions being conducive for survival of *S. endobioticum* – as an individual state may have some areas that are less likely to support the disease than other areas in the same state. The information would be of assistance when planning detection and delimiting surveys for potato wart. NAPPFAST allows a wide range of users to rapidly create weather-based development/incidence models to support predictive pest mapping needs, and to assist in pest prediction and occurrence (Magarey et al., 2004).

Ranking research priorities

Priority ranking for research projects could change depending on the current situation with *S. endobioticum*. Included here are three scenarios that would affect the priority of the ranking.

Condition A: *Potato wart is not known to exist in the United States*

Priority of research projects:

1. Developing improved molecular diagnostic tools for detection of *S. endobioticum* in both plants and soil
2. Delimiting surveys and the potato wart surveillance model
3. Evaluation of U.S. potato varieties for resistance/susceptibility to potato wart
4. Breeding for resistance

Condition B: *Potato wart is discovered in the United State*s

Priority of research projects:

1. Delimiting surveys and the potato wart surveillance model
2. Developing improved molecular diagnostic tools for detection of *S. endobioticum* in both plants and soil
3. Evaluation of U.S. potato varieties for resistance/susceptibility to potato wart
4. Breeding for resistance

Condition C: *Potato wart becomes established in the United States*

Priority of research projects:

1. Breeding for resistance

2. Evaluation of U.S. potato varieties for resistance/susceptibility to potato wart
3. Delimiting surveys and the potato wart surveillance model
4. Developing improved molecular diagnostic tools for detection of *S. endobioticum* in both plants and soil

Extension and Educational Priorities

Extension specialists and educators must continue to build awareness of potato wart disease among their professional and nonprofessional clientele through written and web-based learning materials, educational programming and continued participation in the National Plant Diagnostic Network's (NPDN) First Detector training program. It is also important to promote awareness among home gardeners as part of the Master Gardener curriculum.

Extension specialists and educators are an integral part of the NPDN diagnostic exercise program. The exercises are providing practice in the chain of custody and communication protocol involved with identifying and diagnosing a high risk pest. Their input into the format and function of the exercises is critical to the continued expansion and awareness-building of the program among growers, extension personnel, land grant diagnostic facilities as well as state and federal regulatory officials.

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Web resources

APHIS Pest List website: http://www.aphis.usda.gov/ppq/pestlist/

Canadian Food Inspection Agency (CFIA)-Plant Health Division-Potato Section http://www.inspection.gc.ca/english/plaveg/potpom/var/indexe.shtml . The list of potato varieties used commercially in Canada can be queried by specific disease.

Canadian Phytopathological Society website: http://www.cps-scp.ca/pathologynews/potatowart.htm

EPPO Workshop on *Synchytrium endobioticum*, Paris, France. December 2005: http://archives.eppo.org/MEETINGS/2005_meetings/synchytrium_presentations/synchytrium_workshop#pres

Maine Department of Agriculture, Seed Potato Certification: http://www.maine.gov/agriculture/pi/potato/index.htm

National Agricultural Pest Information System (NAPIS): http://ceris.purdue.edu/napis/maps/pstsurvey.html#pwart

USDA National Agricultural Statistics Service 2005 potato 2005 summary: http://usda.mannlib.cornell.edu/usda/current/Pota/Pota-09-21-2006.pdf

Wisconsin Seed Certification Program: http://www.plantpath.wisc.edu/wspcp/