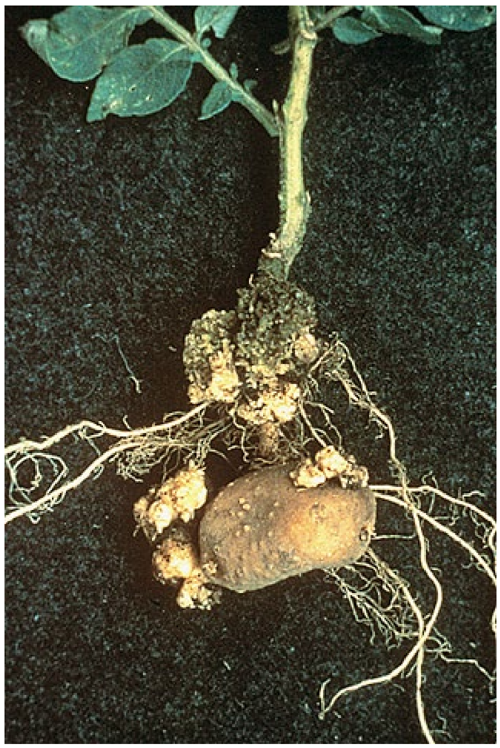
Animal and Plant Health Inspection Service
U.S. DEPARTMENT OF AGRICULTURE

Assessing pathways of introduction for potato wart (*Synchytrium endobioticum*) from Canada into the United States



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Executive Summary

This report evaluates the likelihood of introduction of the potato wart pathogen (*Synchytrium endobioticum*) from Canada into the United States via a) commercially produced propagative material (excluding true potato seed), b) commercially produced potatoes for consumption, and c) soil.

When assessing the ability of *S. endobioticum* to follow each pathway, we considered its life cycle, host range, and climatic requirements for disease development. We did not consider any mitigation measures beyond minimal brushing and washing prior to export and visual inspection at ports of entry. Our conclusions are as follows:

- The full extent of the potato wart infestation in PEI is still unknown but is likely to be larger than currently reported.
- Potatoes are commercially produced and grown in home gardens throughout the continental United States.
- About half of the potato production areas in the contiguous United States and all potato production areas in Alaska have a suitable climate for potato wart establishment.
- An estimated 37 percent of U.S. seed potato imports from PEI go to climatically suitable areas. Without additional mitigation measures, seed potatoes from PEI would introduce potato wart into U.S. potato production areas.
- Potatoes for consumption may be a pathway for the introduction of potato wart into the United States if:
    - untreated potato waste from processing plants or stores is fed to livestock and fresh manure is then applied to fields or gardens where potatoes may be grown; or
    - untreated potato waste is applied as fertilizer directly to fields or gardens where potatoes may be grown; or
    - infected potatoes are discarded into homeowner compost piles and the compost is then used to grow potatoes.
- Infested soil is a pathway for the introduction of potato wart into the United States; introduction can occur via soil contaminating tubers and via non-sanitized equipment, tools, and vehicles.
- *In vitro* plants or minitubers produced under greenhouse conditions and strict production guidelines are unlikely to be a pathway for potato wart.
- Infected potatoes for consumption that are commercially processed, discarded into landfills, composted per U.S. Composting Council guidelines, or used for fuel conversion are not pathways for introduction.

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Introduction

This report evaluates the likelihood of introduction of the potato wart pathogen (*Synchytrium endobioticum*) from Canada into the United States[1] via a) commercially produced propagative material (excluding true potato seed), b) commercially produced potatoes for consumption, and c) soil.

On October 29, 2021, the Canadian Food Inspection Agency (CFIA) notified the U.S. Department of Agriculture, Animal and Plant Health Inspection Service, Plant Protection and Quarantine (USDA APHIS PPQ) of two new detections of potato wart at two processing potato farms on Prince Edward Island (PEI) (NAPPO, 2021). In response to these new detections, Canada voluntarily halted fresh potato exports from PEI to the United States (Simpson, 2022). Their investigations found a third infested field in 2022 (CFIA, 2022b). The CFIA has placed the fields under official control and is carrying out control measures in accordance with their Potato Wart Domestic Long-Term Management Plan (CFIA, 2009).

USDA APHIS lists *Synchytrium endobioticum* as a Select Agent (USDA APHIS, 2021b). Although potato wart was previously detected in Pennsylvania and West Virginia in 1918, and in Maryland in 1920, these infestations were declared eradicated in 1994 (Baker et al., 2007; Putnam and Sindermann, 1994). In Canada, potato wart is present and under official control in Newfoundland and Labrador, and PEI. While little commercial potato production occurs in Newfoundland and Labrador, PEI ranks among the top three Canadian potato producing provinces, which includes seed potatoes and potatoes for consumption. The other top provinces for potato production include Alberta and Manitoba, which are both free of potato wart (CHC, 2018). Because Newfoundland and Labrador do not export potatoes to the United States, we focused our analysis on exports from PEI. From January to October 2020, PEI exported 5,107 metric tons of seed potatoes and 174,711 metric tons of potatoes for consumption to the United States (ARM, 2022). In 2020, the United States imported over 500,000 metric tons of potatoes from all of Canada, valued at over $285 million (FAO, 2022).

In response to a 2014 detection of potato wart on PEI, USDA APHIS PPQ implemented the 2015 Federal Order for imports of potatoes for seed and for consumption from PEI to prevent the introduction of potato wart into U.S. potato production areas (PPQ, 2015). Since the order's implementation, the CFIA has reported additional detections of potato wart in 2016, 2018, 2020, 2021, and 2022 on PEI (CFIA, 2020, 2022b; NAPPO, 2020, 2021); detections in 2014 and 2020 included seed potato farms (Appendix A). Because of these continuous detections, the U.S. potato industry remains concerned about potato exports from PEI potentially introducing potato wart to the United States.

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[1] The United States includes all 50 states, the District of Columbia, Guam, the Commonwealth of the Northern Mariana Islands, Puerto Rico, and the U.S. Virgin Islands.

USDA APHIS PPQ is reviewing the 2015 Federal Order to determine if any adjustments to the import requirements are warranted. The Plant Pest Risk Analysis unit evaluated three potential pathways of introduction for potato wart, specifically propagative material, tubers for consumption, and soil, to aid in this review.

Pest information

Synchytrium endobioticum is a soilborne fungal pathogen that requires a living host to reproduce. It forms two spore types. The resting spores, which are the overwintering stage, are formed in response to environmental stress (Franc, 2007). Resting spores form deep within the potato tubers, triggering the classic wart symptom; these spores are released into the soil when the warts rot (Curtis, 1921; Noble and Glynne, 1970). When specific climatic conditions are met, the resting spores germinate, releasing mobile spores into the soil (Bojňanský, 1960; Hartman, 1955; Weiss, 1925). These mobile spores swim through water in the soil to the potato plant, entering the eyes of the tuber (Franc, 2007).

Under ideal conditions, inoculum levels as low as 1 resting spore in 25 grams of soil can lead to new infections (Baayen et al., 2005; Hampson, 1992; Przetakiewicz, 2015). In the absence of a host, inoculum levels do not increase but resting spores can remain infectious after 40 or more years in the soil if the climate is suitable (Przetakiewicz, 2015). However, in an unsuitable climate, the resting spores became non-infectious within 7 years, with most becoming non-infectious by year 3 (Bojňanský, 1960; Steinmöller et al., 2012). Resting spores are considered viable if their cellular contents appear to be intact (Przetakiewicz, 2015) and they are considered infectious if they can germinate and infect a host (Steinmöller et al., 2012). However, a viable resting spore may not be infectious under certain conditions (Bojňanský, 1960; Steinmöller et al., 2012).

Synchytrium endobioticum mobile spores disperse in water in the soil for a distance of 50 mm or less (Franc, 2007; Weiss, 1925). Potato wart can also be spread by the movement of infested soil, which may be attached to tubers, on farm tools and machinery, in irrigation water runoff, or be windblown from wart-infested fields (CABI, 2022; Hampson, 1981, 1993, 1996; Hilli, 1932; Jösting, 1909; Langerfeld, 1984; Stachewicz and Langerfeld, 1998). One study also suggested that earthworms feeding in the vicinity of infested tubers may move resting spores up to 25 centimeters as they pass through the soil (Hampson and Coombes, 1989).

Likelihood of introduction

The likelihood of introduction is based on both the entry and the establishment potential of a pest. For introduction of potato wart to occur, the pathogen must be present in or on the imported commodity, survive shipping and storage, enter the United States undetected, escape into an area with hosts and a suitable climate, infect a host, and reproduce. In our assessment we did not consider any mitigations beyond minimal washing and brushing[2] of tubers in Canada prior to export and visual inspection at U.S. ports of entry. Appropriate mitigation measures will be determined based on this assessment and addressed in a separate document.

Since 2000, potato wart has been detected on PEI in three seed potato fields and 31 fields of tubers grown for consumption (CFIA, 2002, 2020, 2022b). The most recent detections in seed potato fields occurred in 2020 when the CFIA detected potato wart in 2 of 63 surveyed fields intended for export. Within each field, viable resting spores were detected in a single soil sample; we do not know how many samples were collected in each field (CFIA, 2020). In a survey of an infested processing potato field initially reported in 2000, resting spores were detected in 15 of 400 soil samples tested (CFIA, 2002). In neither report did the CFIA provide the number of viable resting spores detected in each sample.

We have incomplete information about the 2021 and 2022 detections of potato wart in PEI potatoes for consumption because traceforward and traceback investigations are not finished (CFIA, 2022c). However, there appears to be a trend toward increasing frequency of detection within PEI potato fields. Since the first detection in 2000, potato wart has been detected in 2004, 2007, 2012, 2013, 2014, 2016, 2018, 2020, 2021, and 2022 (CFIA, 2020, 2022b). This trend is consistent with previous observations that it may take multiple potato growing cycles for inoculum to reach detectable levels (Sanders, 1919; Stefan et al., 1999). Crop rotations, which Canada practices (CFIA, 2022a), can delay inoculum buildup and symptom detection (Bojňanský, 1960); this may help explain what is being observed in PEI potato fields.

Areas suitable for potato wart establishment

Areas where hosts are present

Potato (*Solanum tuberosum*) is the only known cultivated host of *S. endobioticum.* In addition, the pathogen infects some species of wild potatoes under natural conditions (IPPC, 2021; Niederhauser, 1953): *So. vallis-mexici*, which is not present in the United States (USDA NRCS, 2022), *So. stoloniferum*, which is present in Arizona, New Mexico, and Texas with an unverified report from Colorado (Kartesz, 2015), and an unidentified wild potato species. Other solanaceous species (see Appendix B) can reportedly become infected after artificial inoculation in a greenhouse. In two experiments, researchers obtained conflicting results after planting tomato (*So. lycopersicum*) plants into potato wart-infested gardens. In the first, no symptoms were observed on the tomato plants (Sanders, 1919). In the second, a few plants developed symptoms consistent with potato wart, however the researcher did not show *S. endobioticum* was able to produce infectious resting spores (Lyman et al., 1920). There have been no other reports of potato wart naturally infecting tomato in over 100 years.

[2] Minimal washing and brushing means that the imported tubers for consumption will meet U.S. grading standards prior to entry; currently, the grading standards only require 90 percent of the tubers be completely free of soil (USDA AMS, 2011, 2022).

The most important host for *S. endobioticum*, potato, is grown throughout the United States, either commercially (Figure 1) (USDA NASS, 2020a, 2020b), or in home gardens (USDA NRCS, 2022). Therefore, host plants are readily available for potato wart throughout the country. This leaves climate as the key factor that determines the suitability of an area for potato wart establishment.

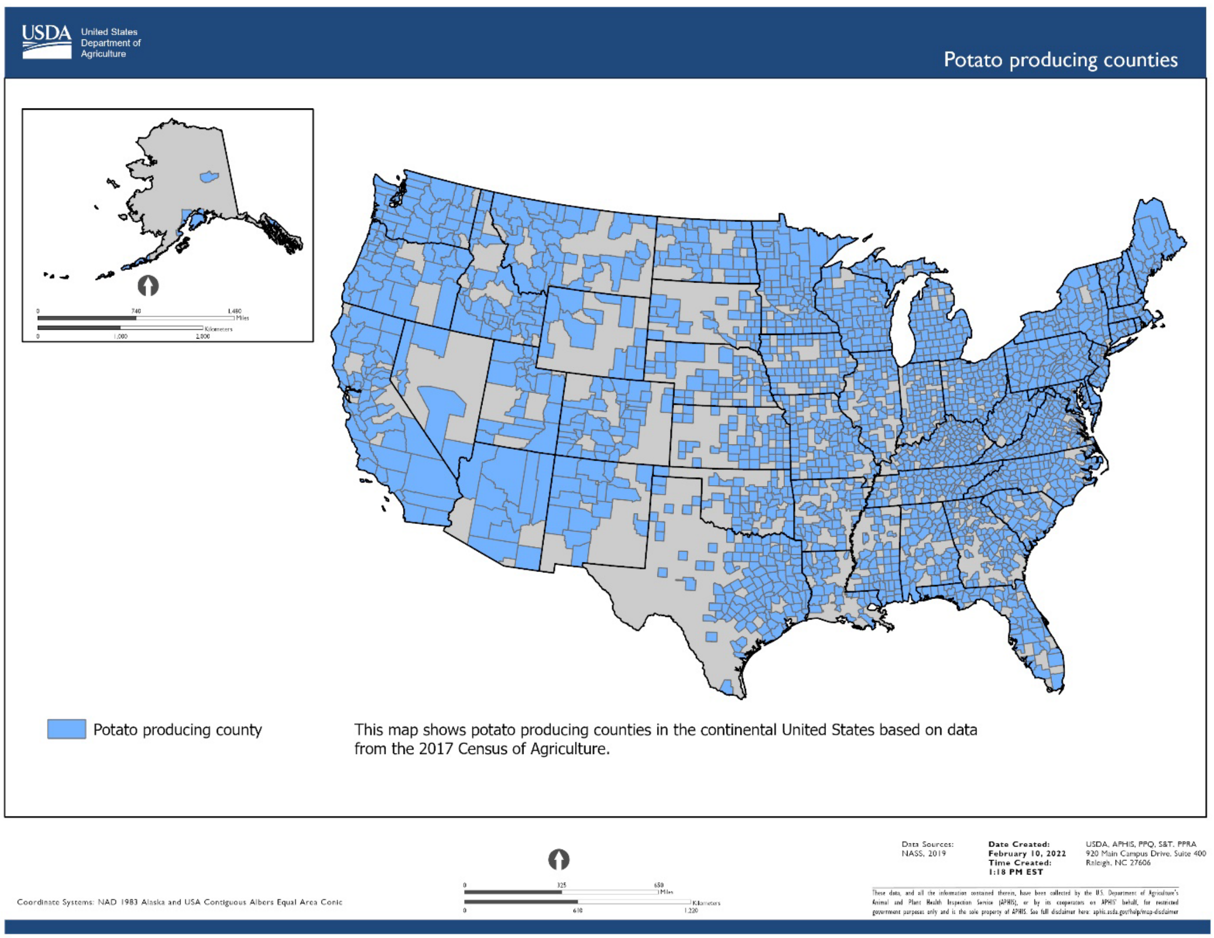

Figure 1. *Counties in the continental United States where potatoes are commercially produced (USDA NASS, 2020b).*

Areas where climate is suitable

The most important climatic parameters for potato wart establishment are[3]:

- Annual precipitation greater than 700 mm (Bojňanský, 1960),
- At least 160 days with a minimum temperature of 41°F or below (Bojňanský, 1960),
- Average air temperatures between 50.2 and 75.6°F during the growing season for one month or more (Bojňanský, 1960; Weiss, 1925).

We assessed climatic suitability using 1-kilometer Daymet climate data from 2000 to 2019 (ORNL, 2020; SAFARIS, 2022; Thornton et al., 2018). Our methodology is described in detail in Appendix C. Climatic suitability was calculated based on the occurrence of all three environmental parameters in the same area over that 20-year period. If one or more parameters did not meet the climatic requirements, then the likelihood for that area became zero and the area was considered unsuitable. In other words, we defined "unsuitable" as meaning that over the past 20 years, there was no year when all three parameters were met in that area.

Our results indicated that the Pacific Northwest, upper Midwest, Northeast, and parts of California are the most climatically suitable areas for potato wart establishment in the United States (Figure 2). Other suitable areas include parts of Colorado, Montana, Wyoming, Utah, the Great Plains, and the eastern United States down to northern Georgia, but only at higher elevations. In Alaska, the southern coastal areas are most suitable for potato wart establishment, with areas further inland less suitable due to suboptimal precipitation (see Appendix C). Our maps are based on natural precipitation only and do not include irrigation; this is because irrigation is too variable and crop-dependent for us to reliably assess its effect in naturally unsuitable areas.

There are no climatically suitable areas for potato wart establishment in Puerto Rico and the U.S. Virgin Islands (see Appendix C). However, limited areas with a suitable climate occur on Maui and the Big Island of Hawaii (see Appendix C).

About 48 percent of the contiguous United States has a suitable climate for potato wart establishment. This area encompasses all the top seed and table stock potato-producing states (USDA NASS, 2020a). About 36 percent of Alaska is climatically suitable. All of Alaska's potato producing counties fall within this suitable area. While 5 percent of the area in the state of Hawaii is climatically suitable, only off-season growing of seed lots in the highly controlled certification process occurs in that state (Bohl and Johnson, 2010).

[3] There is some evidence to suggest that certain soil types are more suitable than others for potato wart establishment (Hampson, 1985; Mel'nik and Malakhanova, 1998; Weiss, 1925); however, we did not incorporate this into our calculations.

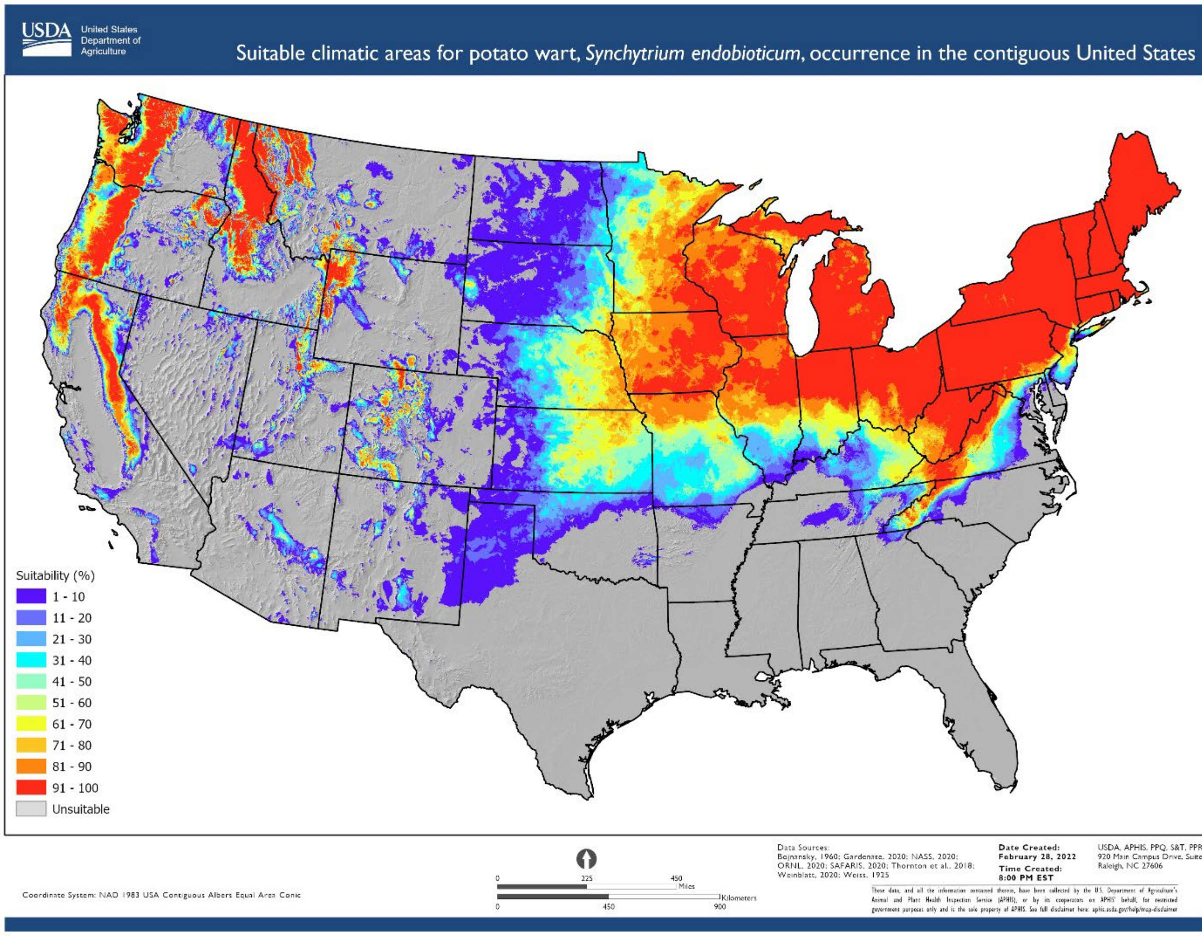

Figure 2. *Climate suitability for potato wart establishment in the contiguous United States. The map shows the likelihood that all three parameters (average temperatures between 50.2 and 75.6°F for ≥ 1 month during the potato growing season; ≥ 160 days during the year with minimum temperatures ≤ 41°F; and average annual precipitation ≥ 700 mm) will be met within a given area in any given year. Unsuitable means that from 2000 to 2019, there was no year when all three parameters were met in that area.*

Pathways

Potatoes are usually stored and shipped at 37 to 40°F (Bohl and Johnson, 2010; Welby and McGregor, 2004), and *S. endobioticum* will survive those conditions. While latent infections may develop symptoms during storage (Franc, 2007; Noble and Glynne, 1970), the infection will not spread into neighboring tubers (Bojňanský, 1960; Hampson, 1993; Hartman, 1955). Therefore, we expect the number of infected tubers to neither increase nor decrease during storage and transport.

Potato wart is difficult to detect visually in the field because aboveground portions of the plant are usually asymptomatic (Franc, 2007; Przetakiewicz, 2015; van de Vossenberg et al., 2022). Infected plants produce symptoms only on below-ground portions (Rowles-van Rijswijk et al., 2017). Therefore, infections are not likely to be noticed until symptomatic tubers are harvested.

Even after harvest, visual detection may be difficult if infections are latent (Franc, 2007; Hampson, 1993).

Pathway 1: Propagative plant material

Laboratory-produced *in vitro* plants and greenhouse-produced minitubers derived from *in vitro* plants serve as nuclear or elite (i.e., foundation) source material for production of certified seed potato lots in the field. In Canada, these lots will be multiplied and increased for up to seven generations in the field until commercial quantities have been produced; there may be a 2 to 3 year crop rotation within these fields (CFIA, 2022a). During the increase process, the seed lots are visually inspected for varietal purity and presence of viral, bacterial, and fungal pathogens; inspectors examine both plants in the field and tubers at harvest (BC CSPGA, 2017; DeHaan, 1994). For seed potatoes, soil from the fields must be tested for potato wart resting spores within one year of harvest before they can be exported; the CFIA may also test soil from other fields as part of traceforward and traceback surveys should potato wart be detected (CFIA, 2009; PPQ, 2015).

In vitro *plants and minitubers*

In vitro plants and minitubers are unlikely to introduce *S. endobioticum* into the United States as long as they meet the CFIA seed certification requirements (BC CSPGA, 2017; CFIA, 2018). *In vitro* plants are produced under aseptic conditions, in soil-less media, and in a protected environment (CFIA, 2018; Frost et al., 2013; Johnson, 2008). They are sourced from mother plants that are tested for diseases, including potato wart (CFIA, 2018; Frost et al., 2013; USDA APHIS, 2021a). Any plantlet showing symptoms or signs of pathogen contamination are removed from production immediately and destroyed, and the contaminated containers are immediately sanitized (CFIA, 2018; Frost et al., 2013; Johnson, 2008; USDA APHIS, 2021a). The *in vitro* plants are then transplanted to a greenhouse where they produce minitubers. The minitubers do not touch soil up to this point. These minitubers are then used as foundation seed in the field, where they are multiplied to commercial quantities for eventual sale as certified seed potatoes (BC CSPGA, 2017; UCIA, 2015). All seed potato certification requirements are enforced by the CFIA or their authorized entity (BC CSPGA, 2017; CFIA, 2018); we found no data on their enforcement activities.

Because of the way the information is collected at U.S. ports of entry, we were unable to distinguish import volumes of minitubers produced in greenhouses from seed potatoes produced in the field (USITC, 2022). However, foundation seed potatoes typically stay within the province or state in which they are being grown (Shepard and Claflin, 1975).

Certified seed potatoes

Healthy foundation seed potatoes can become infected when planted into infested soil (e.g., Franc, 2007; Hampson, 1993), even if the infested field has been out of potato production for several decades (CFIA, 2002). Seed potato fields can become infested by planting infected seed potatoes into previously uninfested soil, even if the seed potatoes are asymptomatic (Weiss and Brierley, 1928).

Potato wart outbreaks have been reported in three PEI seed potato fields (CFIA, 2020; NAPPO, 2014), but it is likely that the infestation is more extensive than reported. The CFIA conducts soil testing of known infested fields as part of their long-term management plan (CFIA, 2009). For the 2021 and 2022 detections, the CFIA has yet to complete their traceback and traceforward investigations: 1) while some soil samples from the 2021 detection have been tested, several thousand remain to be collected, and 2) the soil sample collection and testing for the 2022 detection has just begun (CFIA, 2022c). In addition to the soil sampling described above, the CFIA also inspects seed potatoes for export for potato wart symptoms (CFIA, 2009). However, there may be no observable symptoms on the harvested tubers for the first two growing cycles after infestation; disease incidence will increase after three or more growing cycles (Sanders, 1919; Stefan et al., 1999). Crop rotation will also delay inoculum buildup and symptom detection (Bojňanský, 1960).

In 2020, all U.S. seed potato imports came from Canada (USDA FAS, 2022), with 5,107 metric tons imported from PEI (ARM, 2022). Import data from 2018 to 2019 showed approximately 37 percent of the PEI seed potatoes were shipped to states with a suitable climate for potato wart establishment (CFIA, 2021). Because they would be directly introduced into agricultural production systems, even a single infected tuber will result in pathogen establishment if the climate is suitable (Baayen et al., 2005; Hampson, 1992; Przetakiewicz, 2015). This is how potato wart was introduced into the United States over 100 years ago (Putnam and Sindermann, 1994; Sanders, 1919).

Currently, Canadian potatoes at U.S. ports of entry are visually inspected (USDA APHIS, 2022a, 2022b). However, asymptomatic infections or tubers with desiccated galls would not be readily detectable (Franc, 2007; Hampson, 1993). Therefore, these inspections are unlikely to prevent entry of potato wart-infected seed potatoes.

Pathway 2: Potatoes for consumption

In 2020, the United States imported 153,746 metric tons of table stock and 20,965 metric tons of processing potatoes from PEI (ARM, 2022). Using 2018-2019 shipment data provided by the CFIA, we estimated about 57 percent (87,635 metric tons) of PEI table stock potatoes went to climatically suitable areas including Connecticut, Maine, Massachusetts, New Jersey, New York, Pennsylvania, and Rhode Island (CFIA, 2021). Approximately 17 percent of the U.S. population lives in those areas (Brinkhoff, 2022). We also estimated about 20 percent (4,193 metric tons) of PEI processing potatoes went to climatically suitable areas including Massachusetts, New Jersey, North Carolina, Pennsylvania, and Rhode Island (CFIA, 2021).

Table stock tubers are intended for the fresh market (e.g., grocery stores and restaurants). Most fresh potatoes are purchased by consumers, although in 2011-2012, 8 percent of fresh potatoes became non-marketable after delivery to supermarkets (Buzby et al., 2016). The Environmental Protection Agency (EPA) has developed a Food Recovery Hierarchy (EPA, 2022) to help grocery stores manage their waste. Recommended options are to dispose of edible food waste first as animal feed, second for industrial uses (e.g., fuel conversion), third for commercial composting, and as a last resort to a municipal solid waste landfill (MSWLF). Large U.S. grocery store chains have set goals to meet EPA's recommendations (Albertsons, 2015; Costco, 2021; PCC, 2018; Wal-Mart, 2017), however few have consistently applied these strategies (Kroger, 2021; Molidor, 2018). Kroger (2021), for example, reported that 16 percent of their food waste went to anaerobic digestion, 13 percent to animal feed, 17 percent to composting, and 54 percent to MSWLFs.

Most industrial uses would destroy the infected tubers and the resting spores (Girotto et al., 2015). One exception would be unsterilized digestate from anaerobic digestion (Schleusner et al., 2019); this material would be a similar pathway to fresh animal manure which we discuss below.

MSWLFs are unlikely to allow the pathogen to escape into the environment. In active landfills, waste is periodically covered with a liner and layers of soil (EPA, 2021; Hughes et al., 2013). When landfills are closed, they must be covered with a cap that includes a 46-centimeter layer of clay to impede water infiltration and at least 15 centimeters of vegetated soil to prevent erosion; the cap may also include a gas venting layer and stone or synthetic material to keep out burrowing animals (Harnik et al., 2006). The closed landfills must then be monitored and maintained for the next 30 years (EPA, 2021; Harnik et al., 2006). Resting spores can remain viable at soil depths of up to 50 centimeters for 40 to 50 years, and potato roots — which are not infected by potato wart — may reach that soil depth (Bohl and Johnson, 2010; Franc, 2007); however, potato tubers typically form in the top 20 centimeters of the soil (Zheng et al., 2016). Therefore, even if closed landfills are converted to agricultural land, it is unlikely that potato tubers would become infected.

Commercial composting, if done according to U.S. Composting Council guidelines (131 to 149°F for 3 to 14 days), renders the resting spores non-infectious (Glynne, 1926; Kerins et al., 2018; Noble and Roberts, 2004; Steinmöller et al., 2012). However, composting at lower temperatures, even for longer periods of time, may allow resting spores to remain infectious (Steinmöller et al., 2012). If the guidelines are not followed and the compost is then used in garden beds or fields where potatoes are grown, potato wart could establish.

Processing of potatoes (canning, freezing, frying, and drying) will eliminate the pathogen (Furrer et al., 2018; Granda et al., 2004). However, untreated waste streams from potato processing facilities directly applied to agricultural land or fed to livestock, as well as table stock discarded from grocery stores used for animal feed may be pathways (Charmley et al., 2006; Gebrechristos and Chen, 2018; Hinman and Sauter, 1978; Hung et al., 2006; Kroger, 2021; Marschman, 2022; UNL, 2022). For discarded table stock, we estimated 2,033 metric tons of tubers may go to animal feed or anaerobic digestion. Approximately 50 percent of the potatoes imported for processing (2,097 metric tons) may end up being discarded as waste (Charmley et al., 2006; Steinmöller et al., 2012), and an unknown portion of this could be fed to livestock. Resting spores may survive passage through animal digestive systems and be dispersed in contaminated, uncomposted (fresh) manure used for fertilizer (Doidge, 1922; Franc, 2007). If fresh manure is applied as fertilizer in potato production areas with a suitable climate, there is a high chance that potato wart may establish—introduction into new areas via contaminated manure has been reported (Doidge, 1922; Hampson and Coombes, 1989). About 5 percent of all U.S. cropland (mainly corn) is fertilized with livestock manure (MacDonald et al., 2009). While we do not know what percentage of this is potato fields, locally sourced manure is recommended as a fertilizer for potato growers, including those with fields in areas that are climatically suitable for potato wart establishment (Bohl and Johnson, 2010; Robinson, 2021). Based on this information, potato wart could be introduced into U.S. potato production areas via fresh manure from livestock fed infested potato waste. Untreated waste streams directly applied to agricultural fields would have a similar potential to lead to potato wart establishment (Charmley et al., 2006).

Ninety-two percent of table stock potatoes will be purchased by consumers. Household consumers reportedly throw out about 24 percent of fresh vegetables (Buzby et al., 2014). Most of the waste goes to MSWLFs or to commercial compost facilities, but up to 25 percent may end up in backyard compost piles (Griffin et al., 2009; Reynolds et al., 2014). Based on the Canadian export data (CFIA, 2021), we estimated about 4,838 metric tons may be discarded in this manner in climatically suitable areas. Usually, backyard compost piles do not achieve the temperature and time requirements to render *S. endobioticum* resting spores non-infectious (Smith and Jasim, 2009), and volunteer plants may grow out of the eyes of composted tubers (Gardening Jones, 2013). Researchers have suggested infected potatoes or peels in backyard compost piles may serve as infection foci (Hampson, 1996; Jösting, 1909). Potato wart establishment in these situations would depend on the backyard compost being used for personal potato production (Bojňanský, 1960; Weiss, 1925) (Figure 2 and Appendix C).

Prior introductions to U.S. gardens were traced to the planting of infected potatoes (Sanders, 1919); it is not clear if these tubers were originally seed potatoes or table stock potatoes misused as planting stock. We found no peer reviewed data describing how frequently people may use table stock potatoes for planting, which prevented us from being able to fully assess this pathway. However, if gardeners misused infected table stock in such a manner, we anticipate the likelihood of potato wart introduction would be the same as if the gardeners were planting infected seed potatoes.

Pathway 3: Soil

Soil as a contaminant

Infested soil could be introduced as contamination of plants, tubers, equipment, tools, or vehicles (Hampson and Wood, 1997). Soil-contaminated equipment, tools, and vehicles have been implicated in local spread in multiple instances; for example, new potato wart infestations in

Newfoundland were traced to vehicle movement from backyard gardens to potato production areas (e.g., Fiers et al., 2012; Hampson and Proudfoot, 1974; Hannukkala, 2011). Therefore, allowing entry of dirty equipment, tools, or vehicles from PEI could introduce potato wart into climatically suitable areas.

Imported tubers for consumption are required to meet U.S. grading standards prior to entry. Currently, tubers are allowed to have residual soil on them as grading standards only require 90 percent of the tubers be completely free of soil (USDA AMS, 2011, 2022); soil contaminating the shipping container is not a part of these inspections. Potato wart was equally likely to develop from healthy tubers lightly contaminated with infested soil as it was from infected tubers (Weiss and Brierley, 1928). Storage conditions for both potatoes for consumption and seed potatoes would not eliminate the resting spores in soil attached to the tubers.

Research has shown that small amounts of soil, including soil contamination on healthy tubers, can move enough resting spores to cause an infestation in a new field (Franc, 2007; Stevenson et al., 2001; Weiss and Brierley, 1928). Of the 1,890 metric tons of PEI seed potatoes shipped to climatically suitable U.S. production areas, we estimated 189 metric tons will be contaminated with soil after minimal brushing and washing to meet grading standards (USDA AMS, 1987). Soil-contaminated seed potatoes harvested from potato wart-infested fields and planted into U.S. potato production areas with a suitable climate will introduce potato wart into the United States (Weiss and Brierley, 1928).

Consumers may rinse or wash their potatoes prior to peeling or cooking, which should remove any remaining soil. This rinse water would likely go into municipal water systems or septic tanks, ultimately closing this pathway. However, if the rinse water were to be used in home potato gardens, the risk would be similar to backyard compost as described above.

Although the possibility is mentioned in the 2015 Federal Order (PPQ, 2015), we found no evidence of unwashed potatoes for processing or repacking being imported by the United States from PEI (Beltz et al., 2022). Unwashed tubers, whether for consumption or planting, would be contaminated with soil because they have not gone through the minimal washing and brushing previously described. Such washing and brushing would take place in the United States. Depending on the disposal method used, any residual soil or contaminated water may be a pathway for potato wart entry.

Non-host crops grown in fields infested with potato wart may have soil attached to them after harvest. If the non-host crop is a commodity such as seeds, grain, or fruit, potato wart would not follow this pathway since contaminating soil should not be present on the harvested commodity. If the non-host crop is a root vegetable or nursery stock intended for propagation, potato wart may follow the pathway via infested soil (CFIA, 2019). Most root vegetable crops will be destined for grocery stores or restaurants and would follow the same pathways as table stock potatoes. On the other hand, a non-host commodity for propagation may be imported from PEI with soil attached; soil is prohibited entry from Newfoundland and Labrador (7 CFR § 330, 2021; USDA APHIS, 2022b). Based on Canadian export data from 2019, less than 1 percent of all nursery stock exported came from PEI and none came from Newfoundland and Labrador (Government of Canada, 2020). We were unable to determine the portion of these PEI exports that came to the United States and the portion that included nursery stock with soil attached. However, if such plants were produced in a potato wart infested field, exported with soil attached, and planted near a U.S. potato production field in a suitable climate, this could theoretically be a pathway.

Loose soil

Consistent with our regulations, we considered loose soil to mean soil of 3 pounds or less imported for research or personal use and soil imported for other purposes such as for growing media (7 CFR § 330, 2021). We found no evidence of commercial imports of soil from Canada to the United States (USITC, 2022). USDA APHIS prohibits the importation of soil from most foreign countries, including from the Canadian provinces Alberta, British Columbia, Newfoundland and Labrador, and Quebec (7 CFR § 330, 2021; USDA APHIS, 2010); soil from PEI and the remaining Canadian provinces can be imported with only inspection and verification of origin. Potentially contaminated soil from PEI could be imported with no phytosanitary restrictions should such imports occur in the future. Meanwhile, soil imported for testing where the sample is destroyed and soil imported for research purposes are unlikely to be pathways as any remaining soil is required to be sterilized prior to final disposal (7 CFR § 330, 2021).

Conclusions

- The full extent of the potato wart infestation in PEI is currently unknown.
- About half of potato production areas in the contiguous United States and all potato production areas in Alaska have a suitable climate for potato wart establishment.
- Without mitigation measures, potato wart is almost certain to be introduced to U.S. potato production areas via seed potatoes imported from PEI. An estimated 37 percent of all PEI seed potato imports will go to climatically suitable areas.
- Introduction to U.S. production areas via potatoes for consumption may occur if fresh manure from animals fed infested potato waste is applied to potato fields. Direct application of infested potato waste to potato fields has a similar likelihood of introduction.
- Backyard potato gardens may become infested if infected table stock potatoes are used in backyard compost.
- Tools, equipment, or vehicles contaminated with infested soil are another pathway of introduction.

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Appendix A: Potato wart detections in Prince Edward Island

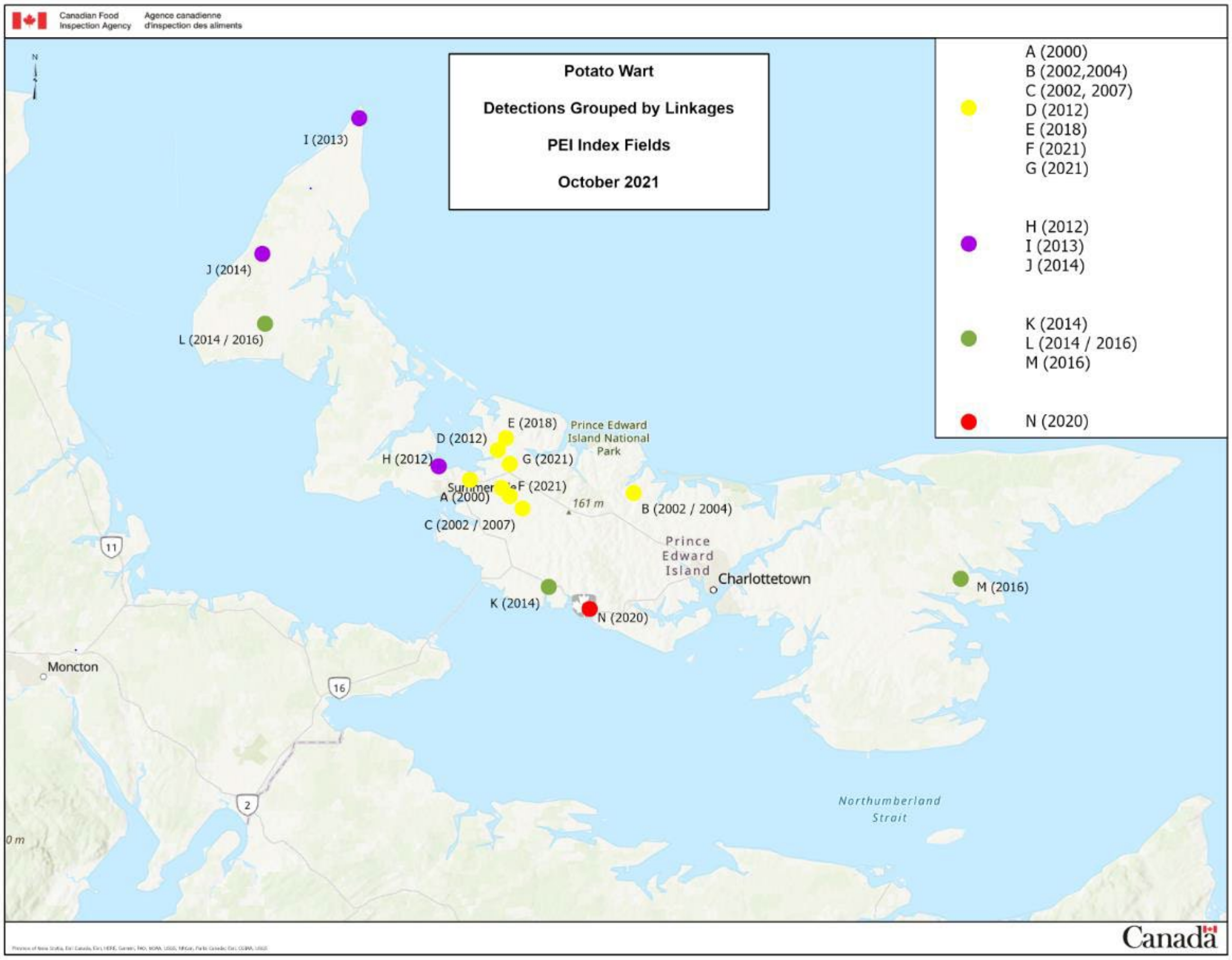

__Figure 3__. Potato wart detections in Prince Edward Island as of October 2021.

Appendix B: Experimental hosts

Some solanaceous species can become infected with potato wart but only under experimental conditions (Table 1) (Cotton, 1916; Hampson, 1976, 1981; Weiss, 1925). No infections under natural conditions have ever been reported, therefore we do not consider these species hosts (IPPC, 2021).

Table 1: *Plants that became infected with potato wart under experimental conditions*

Scientific name	**Common name**
Datura metel L. var. *fastuosa*	Angel's trumpet
Nicandra physalodes (L.) Scop.	Apple-of-Peru
Physalis alkekengi L. var. *franchetii* (Mast.) Makino syn. *Physalis franchetii* Mast.	Chinese lantern
Solanum chacoense Bitter	Wild potato
Solanum commersonii Dunal ex Poir.	Commerson's nightshade
Solanum dulcamara L.	Bittersweet nightshade
Solanum jamesii Torr.	Wild potato
Solanum lycopersicum L.[4]	Tomato
Solanum nigrum L.	Black nightshade
Solanum americanum Mill. syn. *Solanum nodiflorum* Jacq.	American nightshade
Solanum pseudocapsicum L.	Jerusalem cherry
Solanum villosum (L) Mill.	Hairy nightshade

[4] Inoculation under artificial conditions suggests that *Synchytrium endobioticum* can produce resting spores on tomato (Hampson and Haard, 1980), however we do not know if the resting spores were infectious.

Appendix C: Climatically suitable areas for potato wart establishment other than the contiguous United States

We assessed potato wart climatic suitability using 1-kilometer Daymet climate data from 2000 to 2019 (ORNL, 2020; SAFARIS, 2022; Thornton et al., 2018). We chose historic data because it is considered the most predictive of the climate over the next two to three years (Brown and Caldeira, 2020). For comparison, we also ran our calculations with a limited set of climate change forecast data (SAFARIS, 2022); the results showed a downward trend in the suitable area from 2041 to 2060. Climatic suitability was calculated based on the occurrence of three environmental parameters in the same area from 2000 to 2019. The three conditions' frequencies were divided by 20 to obtain the associated likelihoods, and these were then multiplied to obtain the likelihood of all three conditions happening concurrently. We checked the three parameters with Pearson's Correlation Test to make sure that they were independent and that there was no relationship between them that could affect the outcome; we found only weak correlation between the parameters (Table 2), which suggests they have little effect on each other. Specifically, the occurrence of suitable temperatures during the growing season, suitable annual precipitation, and suitable winter temperatures were multiplied to give the likelihood of all three parameters occurring in the same area in the same year. This likelihood was converted to percentage climatic suitability, which equals the likelihood that all three climate parameters will be met in any given year in that area. If one or more parameters did not meet the climatic requirements, then the overall likelihood for that area became zero and the area was considered unsuitable. In this context, unsuitable means that over the past 20 years, there was no year when all three parameters were met in that area.

$$\text{Overall likelihood} = P(A \cap B \cap C) = P(A) * P(B) * P(C)$$

Where P(A) is frequency of annual precipitation greater than 700 mm divided by 20; P(B) is frequency of at least 160 days with a minimum temperature of 41°F or below divided by 20; P(C) is frequency of average air temperatures between 50.2 and 75.6°F during the growing season for one month or more divided by 20.

We determined the climatically suitable area in Alaska (Figure 4), Puerto Rico and U.S. Virgin Islands (Figure 5), and Hawaii (Figure 6). About 36 percent of Alaska is climatically suitable and all of its potato producing counties fall within this suitable area. About 5 percent of the area in the state of Hawaii is climatically suitable; those areas are located on Maui and the Big Island. No areas within Puerto Rico or the U.S. Virgin Islands are climatically suitable for potato wart establishment.

Table 2. Pearson's Correlation matrix with P-values for the climate parameters; results suggest there may be a weak correlation, however the effect is very small

Correlation coefficient by parameter	**Annual precipitation greater than 700 mm**	**At least 160 days with a minimum temperature of 41°F or below**	**Average air temperatures between 50.2 and 75.6°F during the growing season for one month or more**
Annual precipitation greater than 700 mm	1	0.198 (P<2.2e-16)	-0.265 (P<2.2e-16)
At least 160 days with a minimum temperature of 41°F or below	0.198 (P<2.2e-16)	1	-0.137 (P<2.2e-16)
Average air temperatures between 50.2 and 75.6°F during the growing season for one month or more	-0.265 (P<2.2e-16)	-0.137 (P<2.2e-16)	1

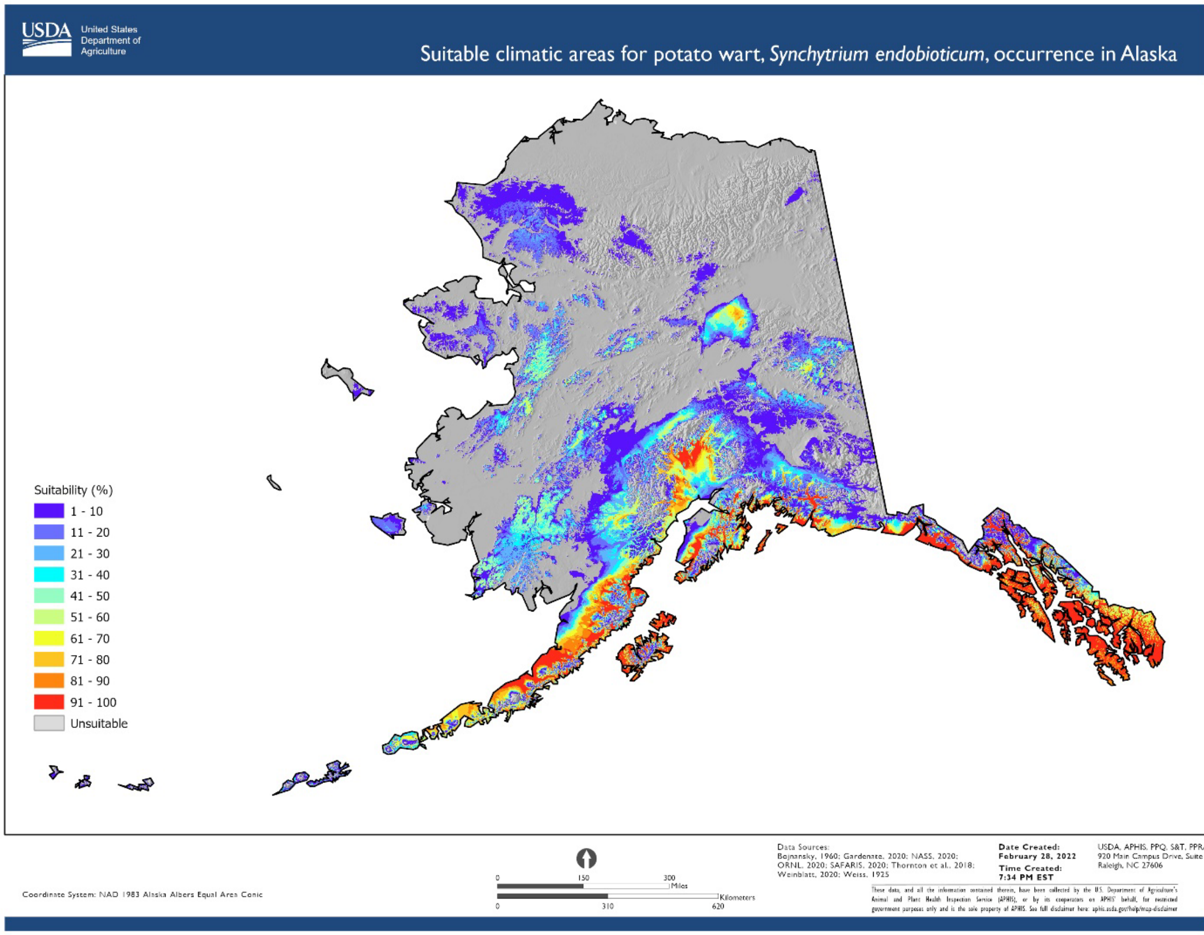

Figure 4. *Climatically suitable areas for potato wart establishment in Alaska. The map shows the likelihood that all three parameters (average temperatures between 50.2 and 75.6°F for ≥ 1 month during the potato growing season; ≥ 160 days during the year with minimum temperatures ≤ 41°F; and average annual precipitation ≥ 700 mm) will be met within a given area in any given year. Unsuitable means that from 2000 to 2019, there was no year when all three parameters were met in that area.*

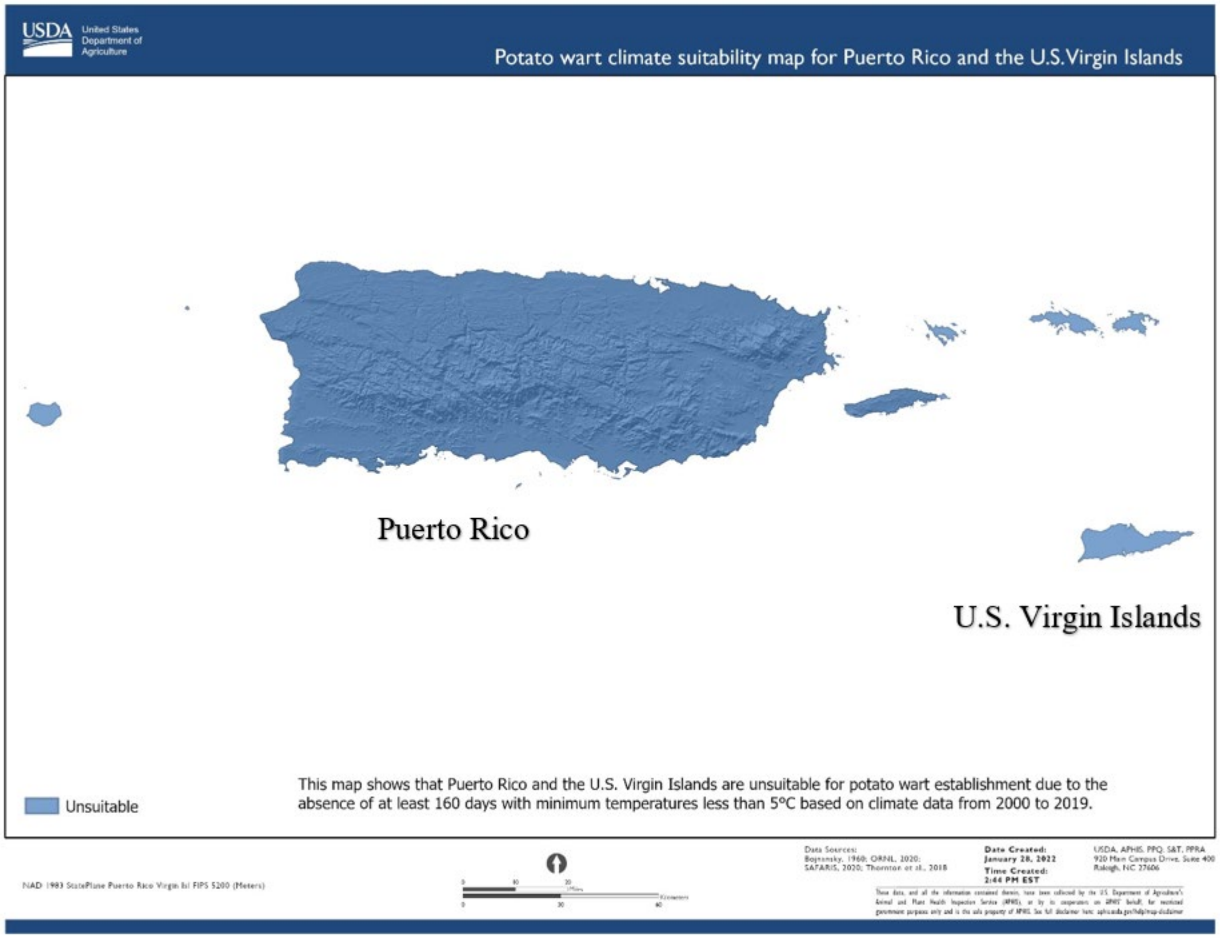

Figure 5. *Climatically suitable areas for potato wart occurrence in Puerto Rico and the U.S. Virgin Islands. The map shows the likelihood that all three parameters (average temperatures between 50.2 and 75.6°F for ≥ 1 month during the potato growing season; ≥ 160 days during the year with minimum temperatures ≤ 41°F; and average annual precipitation ≥ 700 mm) will be met within a given area in any given year. Unsuitable means that from 2000 to 2019, there was no year when all three parameters were met in that area.*

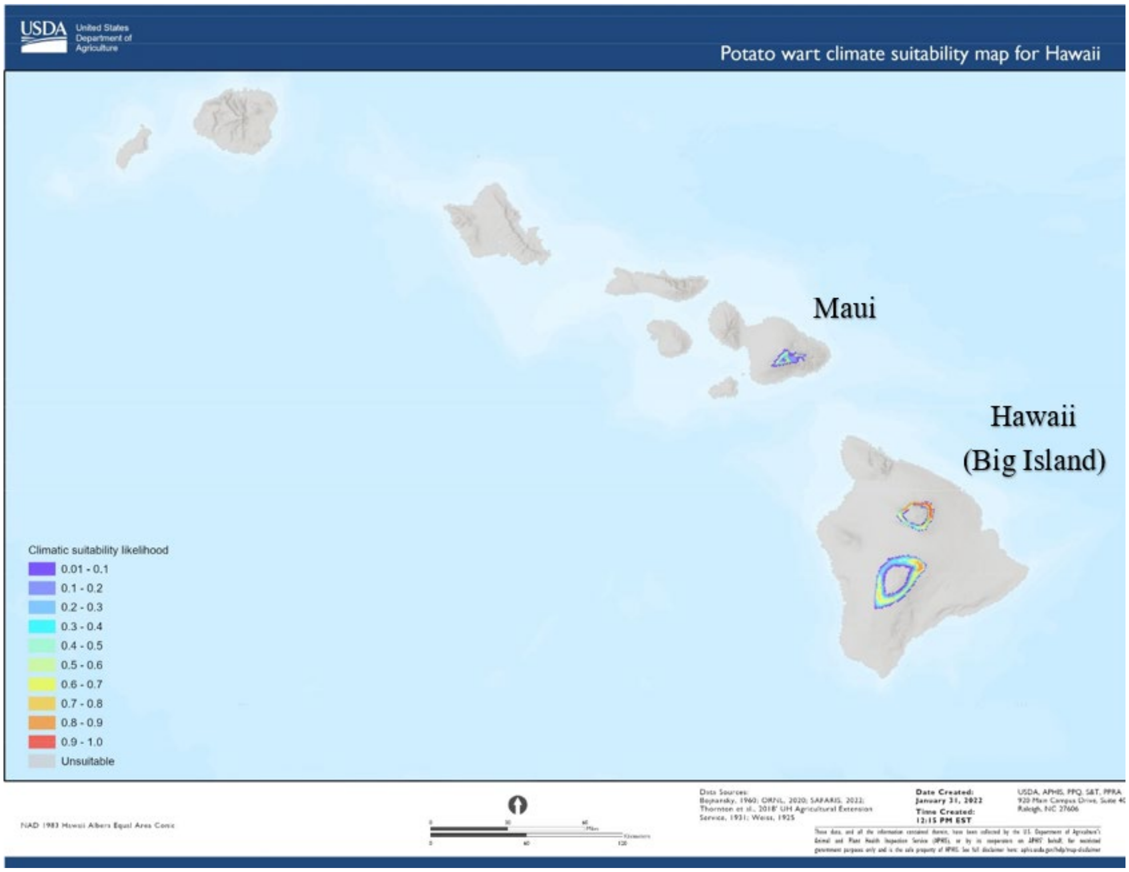

Figure 6. *Climatically suitable areas for potato wart establishment in Hawaii. The map shows the likelihood that all three parameters (average temperatures between 50.2 and 75.6°F for ≥ 1 month during the potato growing season; ≥ 160 days during the year with minimum temperatures ≤ 41°F; and average annual precipitation ≥ 700 mm) will be met within a given area in any given year. Unsuitable means that from 2000 to 2019, there was no year when all three parameters were met in that area.*