History of the balsam woolly adelgid, *Adelges piceae* (Ratzeburg), in British Columbia, with notes on a recent range expansion

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ABSTRACT

The balsam woolly adelgid, *Adelges piceae* (Hemiptera: Adelgidae), was introduced from Europe into eastern North America around 1900 and independently into western North America sometime before 1928. It was first detected causing damage in North Vancouver, British Columbia, in 1958. Since then, it has slowly spread to adjacent areas of southwestern B.C. Surveys from 2011 to 2013 confirmed the presence of *A. piceae* in the Cascades Forest District and in the town of Rossland, B.C., which are outside the pre-2014 quarantine area. Until these recent detections, provincial quarantine regulations have been the principle tool employed to prevent anthropogenic spread of the adelgid through the restriction of movement of potentially infested seedlings and nursery stock from infested coastal regions of British Columbia into the highly susceptible high-elevation *Abies lasiocarpa* stands in the Interior forests. We provide a historical overview of the quarantine regulations enacted since 1966, review the distribution of *Adelges piceae* since the first confirmed records of establishment as documented by historical survey records, and document the extent of recent survey efforts and new detections in interior subalpine fir forests.

INTRODUCTION

The balsam woolly adelgid, *Adelges piceae* (Ratzeburg) (Hemiptera: Adelgidae), occurs on both coasts of North America (NA) and can cause extensive tree damage and mortality to native *Abies* species. It was introduced into eastern NA from Europe before 1900 (Foottit and Mackauer 1980) and independently into western North America (Hain 1988), where it was first reported near San Francisco in 1928 (Annand 1928). *Adelges piceae* was first reported from British Columbia (B.C.) by E. P. Venables and R. Hopping (Anon. 1938). Those reports noted its detection, along with *Adelges nüsslini* (Börner), on *Abies procera* Rehder (=*A. nobilis* (Douglas ex D. Don) Lindley) in Vancouver. In 1958, *A. piceae* was discovered damaging a Pacific silver fir, *Abies amabilis* (Douglas *ex* Loud.) Dougl. *ex* J. Forbes, planted as an ornamental in North Vancouver, B.C. (Silver 1959). Surveys to delimit the range of this introduced pest in the province documented in the Canadian Forest Invasive Alien Species (CanFIAS)[6] database (1958–1998; Nealis *et al.* 2015) quickly demonstrated its presence on native and ornamental firs in drainages near Vancouver, as well as on southern Vancouver Island. In 1959, it was found attacking grand fir (*Abies grandis* (Douglas *ex* D. Don) Lindl.) at Thetis Lake, near Victoria, and

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the following year, it was detected at a commercial nursery near Victoria on white fir (*Abies concolor* (Gord. & Glend.)) imported from Holland five years prior to the detection.

The degree of susceptibility to damage and mortality varies amongst the three native *Abies* species in B.C.: damage is generally moderate in grand fir, while that in both Pacific silver fir and subalpine fir (*A. lasiocarpa* (Hook.) Nutt.) is more severe. Subalpine fir is the most susceptible of the true firs in the Pacific Northwest (Mitchell 1966; Hain 1988).

In North America, *A. piceae* is anholocyclic on the ancestral secondary host, *Abies* (Havill and Foottit 2007). There are two or more generations per year (Mitchell *et al.* 1961). The life stages consist of eggs, three nymphal instars, and the adults. Eggs hatch into crawlers, which are the only stage capable of independent movement and dispersal (Balch 1952). Crawlers select feeding sites, settling either on the bark of the main stem and larger branches or at the base of vegetative or reproductive buds, then insert their stylets into the cortical parenchyma. Once the stylets are inserted, the insect remains sessile for its life. As the adelgids develop, they molt and secrete waxy threads that appear as dense white, woolly, or 'cottony' masses. Adult females lay their eggs within the woolly masses—each of which may contain more than 200 amber-coloured eggs (Balch 1952).

Feeding by *A. piceae* on twigs produces gouting at nodes and inhibits new growth, reducing tree vigor. Stem infestations are a more severe form of attack by *A. piceae*. The tree responds to adelgid feeding by producing a type of compression wood in the sapwood called "rotholz". This abnormal growth of the sapwood tissue inhibits water flow within the tree and eventually leads to tree death (Balch 1952; Livingston *et al.* 2000). The presence of rotholz in the annual rings of attacked trees in North Vancouver suggested that *A. piceae* had been present in southwestern B.C. for 8–11 years before its discovery (Silver 1959).

In British Columbia, *A. piceae* has historically been restricted primarily to southwestern B.C., with the Coast and Cascade Mountains acting as natural barriers to eastward range expansion into Interior stands of *Abies lasiocarpa* growing at high elevations. To protect the susceptible subalpine fir stands in the interior of the province, the Province of British Columbia has maintained regulatory restrictions on the production and movement of all living *Abies* spp., as well as logs and cut Christmas trees since 1966. Coulson and Witter (1984) observed that the initial quarantine restrictions implemented against *A. piceae* in the mid-1960s were effective in stabilizing the infestation boundary after 1967. In contrast, in the absence of any regulatory restrictions in the western United States, *A. piceae* has expanded its range extensively through Washington, Idaho and Montana. It is now present in all U.S. counties bordering B.C. (Hayes 2015; Liebhold *et al*. 2015) and has caused extensive mortality of *A. lasiocarpa* in the Sawtooth National Forest in southern Idaho (Livingston *et al.* 2000; Livingston and Pederson 2010).

In 2008, a single branch sample was submitted from a 60-year-old *Abies lasiocarpa* planted as an ornamental at low elevation near Rossland, B.C. The condition of the sample precluded a definitive identification of the pest. In 2009, symptoms of branch attack by *A. piceae* were reported from the Cascades Forest District immediately east of the pre-2014 quarantine zone. These reports prompted additional surveillance for *A. piceae* to determine the current extent of its range in B.C. Initial surveillance efforts focused on detection of host trees with visible symptoms of attack, such as gouting or the presence of white woolly masses associated with heavy stem attack. This study reviews the historical records of *A. piceae* detections in B.C., the history of provincial regulations to prevent anthropogenic dispersal of the adelgid to uninfested regions of the province, and reports new locations in the interior of B.C. where it is now established.

METHODS

Historical surveys and collections of *Adelges piceae* in B.C. Historical collections of *A. piceae* documented by the Canadian Forest Service Forest Insect and Disease Survey (FIDS), Pacific Forestry Centre, Victoria, B.C., and records of detections extracted from both published and unpublished file reports compiled in the CanFIAS database by Nealis *et al.* (2015) were retrieved and combined with locality records for positive and negative collections of the pest documented in this study to provide an overview of both the species' occurrence in B.C., and the areas surveyed at which *A. piceae* was not detected. Scatter plots of the positive and negative collections are also presented to visualize the pattern of spread of the pest in coastal B.C. between 1957 and 1995.

In addition to latitude and longitude, the CanFIAS database provides an estimate of the spatial accuracy of the locality information for all positive and negative collection records for both point source collections made by FIDS between 1957 and 1995 and for records generated from annual survey reports of FIDS, provincial aerial survey reports, and other miscellaneous reports. The spatial accuracy of CanFIAS records for *A. piceae* extracted from the aforementioned reports were compared to those generated during individual collection events documented by the original collection records to estimate the spatial accuracy of records derived from both types of records.

History of *Adelges piceae* Regulation in B.C. Copies of the text of all regulations enacted under the *Plant Health Act* of B.C. pertaining to *A. piceae* were obtained from the Legislative Library at the Provincial Legislature in Victoria, B.C. Titles of each regulation and date of enactment, along with comments on the purpose of the Order in Council (O.I.C.) or changes in the areas regulated, are summarized in Table 1. Maps of the areas regulated for *A. piceae* were developed from the descriptions of the areas regulated by each O.I.C. to illustrate the extent of the area regulated in each change. Significant changes to the regulations documented in the applicable O.I.C.'s were summarized.

2011–2014 Surveillance for *Adelges piceae.* In July and September 2011, *Abies* spp. branches exhibiting symptoms of attack by *A. piceae* were sampled with pole or hand pruners. Samples were collected from the lower one-third of the crown of trees that showed evidence of gouting or tree decline in the Coquihalla Summit Recreation Area. Branch samples were returned to the laboratory and held with the cut ends in water in buckets at room temperature for approximately 10 days to induce adelgid development and production of white woolly flocculence. Branch samples were inspected under a 10X magnifying stereomicroscope for evidence of *A. piceae* life stages. In October 2013, two lower branches of both mature trees and advanced regeneration of subalpine fir growing in the vicinity of Rossland, B.C., were sampled by hand. Samples from individual trees were bagged separately. Branches were examined under a stereomicroscope within 7 days of collection, and all adelgid life stages recovered were preserved in 95% ethanol. A subsequent survey was done in the Rossland area and at high-elevation sites across the southern interior of B.C. in 2014 to assess the extent of *A. piceae* establishment.

Adelgid samples were forwarded to RGF at the Canadian National Collection, Agriculture and Agri-Food Canada, Ottawa, for identification. Species identifications were based on an examination of species morphology, using slide-mounted specimens and sequencing of the barcode region of the mitochondrial gene Cytochrome C oxidase subunit I (COI). DNA was extracted from each of the submitted samples, and COI was amplified, sequenced and compared to a reference library of adelgid sequences (Foottit *et al.* 2009). COI sequences for all samples positive for *A. piceae* were deposited in GenBank, National Center for Biotechnology Information, U.S. National Library of Medicine, Bethesda MD, U.S.A. http://www.ncbi.nlm.nih.gov/genbank/.

Table 1

Chronological record of significant detections of *Adelges piceae* in British Columbia, 1937–1998.

Year	Location	*Abies* Host[1]	Reference[2]	Comments
1937	Vancouver, B.C.	*procera*	Anon. 1938	First record of detection in B.C. *Adelges nusslini* (Börner) also present on *A. procera*
1958	North Vancouver, B.C.	*amabilis*	Silver 1959	First record of establishment and damage
1959	Thetis Lake near Victoria, B.C.	*grandis*	CFS FIDS	First record on Vancouver Island
1959-1960	Mountains near North and West Vancouver; west shore of Howe Sound. Fig. 3a	*amabilis.*	CFS FIDS	*Adelges piceae* confirmed to be widespread near Vancouver across Howe Sound
1960	Near Victoria, B.C.	*concolor*	CFS FIDS record	Commercial nursery
1961-1966	Mainland NE to Jervis Inlet and east to Alouette Lake; west of Saanich Inlet north to Duncan, southern Vancouver Island, Fig. 3b.	*amabilis; grandis*	Ruppel and Allen (1964, 1965); CFS FIDS	Mainland expansion east and north-east of previous finds; first records on *A. amabilis* on Vancouver Island
1967	Mainland east and west shores of Harrison Lake from Agassiz, northwards, Fig. 3c.	*lasiocarpa*	CFS FIDS	Mainland expansion north up the Harrison Lake drainage
1967	Near Sooke, Nanaimo and Gordon River on Vancouver Island, Fig. 3c.	*amabilis*	Alexander 1967	Expansion beyond east coast of Vancouver Island
1967	Southern Okanagan near Oliver and Penticton	*alba, concolor*	CFS FIDS; Wood 1968; Wood *et al.* 1968	Heavily infested ornamental *A. alba* near Oliver, infested ornamental *A. concolor* in Penticton.
1970-1979	No significant range expansion identified on Vancouver Island or the mainland			All newly discovered populations within the Quarantine Zone boundaries
1986	Near Powell River on the mainland	Not specified	CFS FIDS	Record from provincial Forest Service collection submitted for identification

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Year	Location	*Abies* Host[1]	Reference[2]	Comments
1987	West Thurlow Island east of Sayward, Fig. 3e	*amabilis*	CFS FIDS	Infested trees at 10 locations north of 1977 Quarantine Zone boundary
1989	China Creek near Port Alberni, Vancouver Island, Fig. 3e	*amabilis*	Humphreys and Clarke 1990	2 ha stand near Quarantine Zone boundary
1993	Chute Creek near Campbell River; Nahmint Lake near Port Alberni, Fig. 3f	*amabilis; grandis*	CFS FIDS	Gouting and adelgids in foliage samples; in grand fir plantation. Beyond 1992 Quarantine Zone boundary
1994	Mainland east of Lillooet Lk.; Birkenhead River area, Fig. 3f	*amabilis; lasiocarpa*	CFS FIDS; Turnquist *et al.* 1995	In mature stands beyond the 1992 Quarantine Zone boundary
1995	Infested mature stands on central Vancouver Island at five locations; grand fir at Menzies Bay near Campbell River; Anderson River east of the Fraser River, Fig. 3f	*amabilis; grandis*	CFS FIDS; Turnquist and Humphreys 1996	Expansion northward on Vancouver Island beyond 1992 Quarantine Zone boundary; first record east of the Fraser River
1998	Davis Bay on Texada Island, Fig. 3f	*amabilis*	CFS FIDS	Record from provincial Forest Service collection

[1] *alba* = *Abies alba* Mill.; *amabalis* = *Abies amabilis* (Douglas *ex* Loud.) Dougl. *ex* J. Forbes; *concolor* = *Abies concolor* (Gord. & Glend.); *grandis* = *Abies grandis* (Douglas *ex* D. Don) Lindl.); *lasiocarpa* = *Abies lasiocarpa* (Hook.) Nutt.); *procera* = *Abies procera* Rehder

[2] CFS FIDS = original collection records of the Forest Insect and Disease Survey, Canadian Forest Service, Victoria, B.C.; available in the CanFIAS database (Nealis *et al.* 2015)

RESULTS

Historical surveys and collections of *Adelges piceae* in B.C. The original dataset extracted from the CanFIAS database on 2 Sept. 2015 contained 480 positive records and 1318 negative records (i.e., records of collections made specifically to detect the adelgid in which it was not found) for *A. piceae*. Two hundred and twelve of the positive records documented actual collection events with the remaining 268 records being derived from published and unpublished reports. The mean (± standard deviation) and maximum spatial accuracy of records derived from collection events were 6.18 ± 2.1 km and 8.8 km, respectively, while the mean and maximum spatial accuracy of records derived from literature were 67.9 ± 61.8 km and 219.5 km, respectively. Sixty-five of the positive records extracted from reports or literature exceeded the maximum spatial accuracy for collection events (8.8 km) and all but one were excluded from mapping. The single literature record that exceeded the spatial accuracy limit by 1.08 km was found to represent a valid collection made on urban ornamentals in Penticton in 1967 (Wood 1968) and was retained. The final dataset of positive records from CanFIAS consisted of the 212 collection events and 205 records generated from the literature. These occurrence records, as well as the locations of positive collections obtained in this study, are mapped in Fig. 1. Similarly, 47 literature records that exceeded the spatial accuracy limit and one literature record based on damage only included in the negative collection records for *A. piceae* extracted from the CanFIAS database were excluded from mapping. In total, 1270 CanFIAS negative records were mapped along with the 10 negative collection records derived from this study to document the areas surveyed for *A. piceae* at which the pest was not detected (Fig. 2).

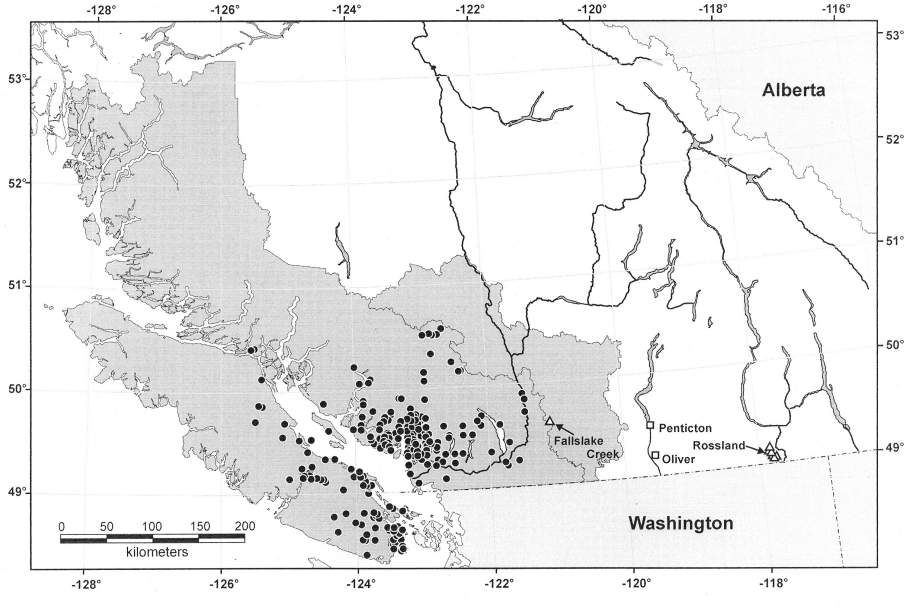

Figure 1. Location of positive detections of *Adelges piceae* in British Columbia between 1958 and 2014; locations denoted by red circles denote positive collection records extracted from the CanFIAS database (Nealis *et al.* 2015); locations denoted by red squares are derived from this study (see Table 2). The two collections denoted by red triangles represent detections on urban ornaments that were eradicated.

We also mapped the positive and negative detections of *A. piceae* generated from point source collection data pooled with records with equivalent spatial accuracy derived from survey reports and literature from 1958–1998 to illustrate the spread of *A. piceae* in coastal B.C. (see Fig. 3). The importance of the latter data sources in documenting spread is illustrated in Fig. 3b. Records to the northwest of the dashed line on the mainland represent areas infested by the adelgid, as determined by surveys records documented in unpublished reports (Ruppel and Allen 1964, 1965) that were not reported in collection records. A chronology of significant range expansions of the adelgid in coastal B.C. are summarized in Table 1.

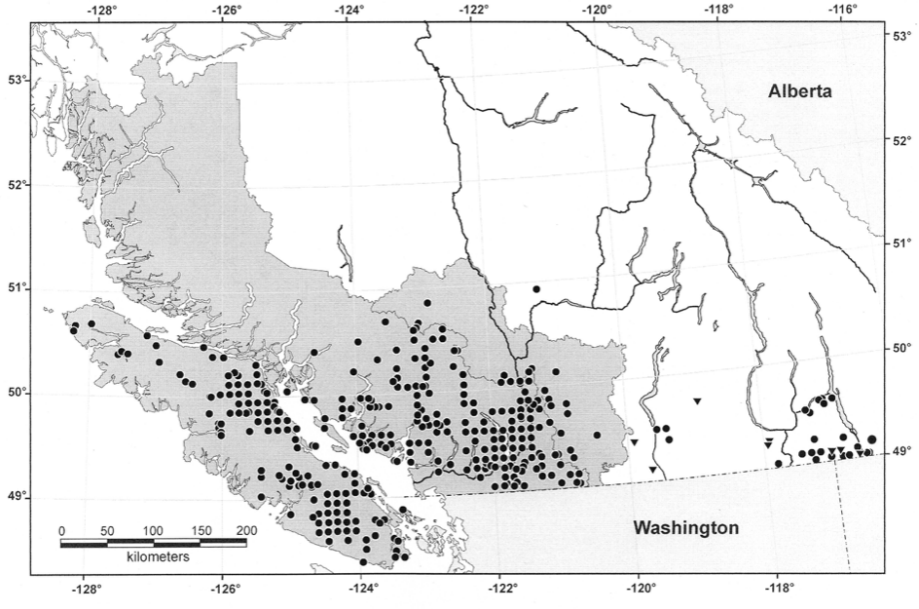

Figure 2. Locations surveyed for *Adelges piceae* in British Columbia between 1958 and 2014, at which the pest was not detected; locations denoted by unfilled circles denote locations negative collection records extracted from the CanFIAS database (Nealis *et al.* 2015); locations denoted by unfilled squares are derived from this study (see Table 3).

In the two years following the discovery of *A. piceae* in North Vancouver, populations were detected in the mountains north of Vancouver and across Howe Sound, as well as at a few localities near Victoria on Vancouver Island (Table 1; Fig. 3a). From 1959–1964, infestations were discovered on the mainland as far northwest as Jervis Inlet, on the Sunshine Coast, and as far east as Alouette Lake, in the Fraser Valley. On Vancouver Island, expansion was limited to a few additional populations discovered on the west shore of Saanich Inlet (Table 1; Fig. 3b). By 1969, additional infested stands had been discovered on the east coast and interior of Vancouver Island as far north as Nanaimo, and a significant northward expansion of the infested area in the Harrison Lake drainage had been found on the mainland (Table 1; Fig. 3c). Between 1970 and 1979, the range of *A. piceae* expanded slightly eastward on the mainland, and a further expansion to the north within the quarantine zone was detected on Vancouver Island (Table 1; Fig. 3d). By 1989, the adelgid had been found in stands near the quarantine zone boundary on Vancouver Island and near Powell River on the mainland. However, the most significant event during the decade was the detection of mature stands of *A. amabilis* infested by the adelgid on West Thurlow Island (WTI), between northern Vancouver Island and the adjacent mainland coast, 100 km and 140 northwest of previously detected infestations on the mainland and Vancouver Island, respectively (Table 1; Fig. 3e). The last

collections of *A. piceae* documented in the CanFIAS database were made between 1990 and 1998. Expanded surveys to delimit the range of the adelgid on northern Vancouver Island after the detection of infestations on WTI (Fig. 3e) led to the detection of *A. piceae* as far north of Campbell River (Table 1; Fig. 3f). On the mainland, expansion of *A. piceae* to both the north and east was detected in the Fraser River drainage, with the adelgid being found for the first time east of the Fraser River. The adelgid had also expanded northward along drainages emptying into the Squamish River and was present beyond the 1992 regulated area at multiple locations in the Birkenhead Lake area (Table 1; Fig. 3f). After the completion of the 1995 survey year, organized surveys for forest pests were no longer conducted by the Canadian Forest Service. In subsequent years, surveys for *A. piceae* were conducted by provincial forestry staff. The single record from 1998 in the CanFIAS database was submitted by provincial forest service staff and documents the presence of *A. piceae* on Texada Island in the Strait of Georgia, south of Powell River (Fig. 3f).

History of *Adelges piceae* Regulation in B.C. By 1965, *A. piceae* was recognized as a serious potential threat to *Abies* in B.C., and steps were taken to manage its impact through establishment of quarantine regulations, supported by surveys of infestation boundaries and damage, a ban on movement of logs from infested areas during periods when the adelgid was actively reproducing, and expansion of research programs (Vyse 1971). These activities were cost-shared between the federal and provincial governments and initially were enabled provincially through enactment of Order in Council (O.I.C.) 1137 (14 Apr. 1966). They were completed the following year under a second agreement (O.I.C. 2363, 25 July 1967; Table 2). The collaborative surveys enabled by these O.I.C.'s led to the discovery of limited northwards range expansion on southern Vancouver Island and no range expansion on the Lower Mainland. A benefit of these surveys was the first extensive documentation of stands in the Lower Mainland and on Vancouver Island that were free of *A. piceae* infestations (Table 1; Fig. 3d). Additionally, these extensive surveys led to the discovery of *A. piceae* in Penticton, B.C.

Adelges piceae was first regulated under the *Plant Protection Act* (chapter 287 of the *Revised Statutes of British Columbia, 1960*) with the approval of *B.C. Reg. 58/66* (Table 2). The regulation prohibited the shipment or transport of any living *Abies* spp., as well as the production of all *Abies* species for commercial purposes, eliminating the production of *Abies* seedlings for reforestation, as well as the commercial production of *Abies* species grown as ornamentals or Christmas trees. The initial regulation applied province-wide to protect the highly susceptible *A. lasiocarpa* in the high-elevation Interior forests of B.C. and slow the spread of the insect (Wood 1968). *Abies* seedling stocks at forest nurseries were destroyed and operational planting of all *Abies* ceased with the imposition of the 1966 regulation (Vyse 1971), even though species of *Abies* such as Pacific silver fir (*A. amabilis*) were desirable for silviculture at mid-elevations in coastal forests where other conifers frequently failed to establish (Carrow 1973).

In 1977, the provisions of *B.C. Reg. 58/66* were rescinded by O.I.C. 44 and replaced by *B.C. Reg. 7/77*, the *British Columbia Balsam Woolly Aphid Regulations, 1976* (Table 2). Annual permits were required to grow and sell *Abies* provincially and the first regulated area, based on known infestations in Ranger Districts (Fig. 4a), was established. Movement of all *Abies* species grown within the regulated area to areas beyond its boundaries was prohibited, as was movement of cut trees or foliage of *Abies* spp. between January 31 and November 1. The latter regulation allowed for the movement of cut Christmas trees and foliage after research demonstrated that the adelgid did not survive on cut trees (Woods 1967).

New finds of the adelgid beyond the boundaries of the area regulated by *B.C. Reg. 7/77* (Table 1) led to an expansion of the regulated area (Table 2; Fig. 4b) with the adoption of *B.C. Reg. 414/92* established by O.I.C. 1604, approved on October 22, 1992 (Turnquist and Harris 1993). Movement of trees (living trees with roots, including both seedlings and those produced by tissue culture) from inside to outside of quarantine area

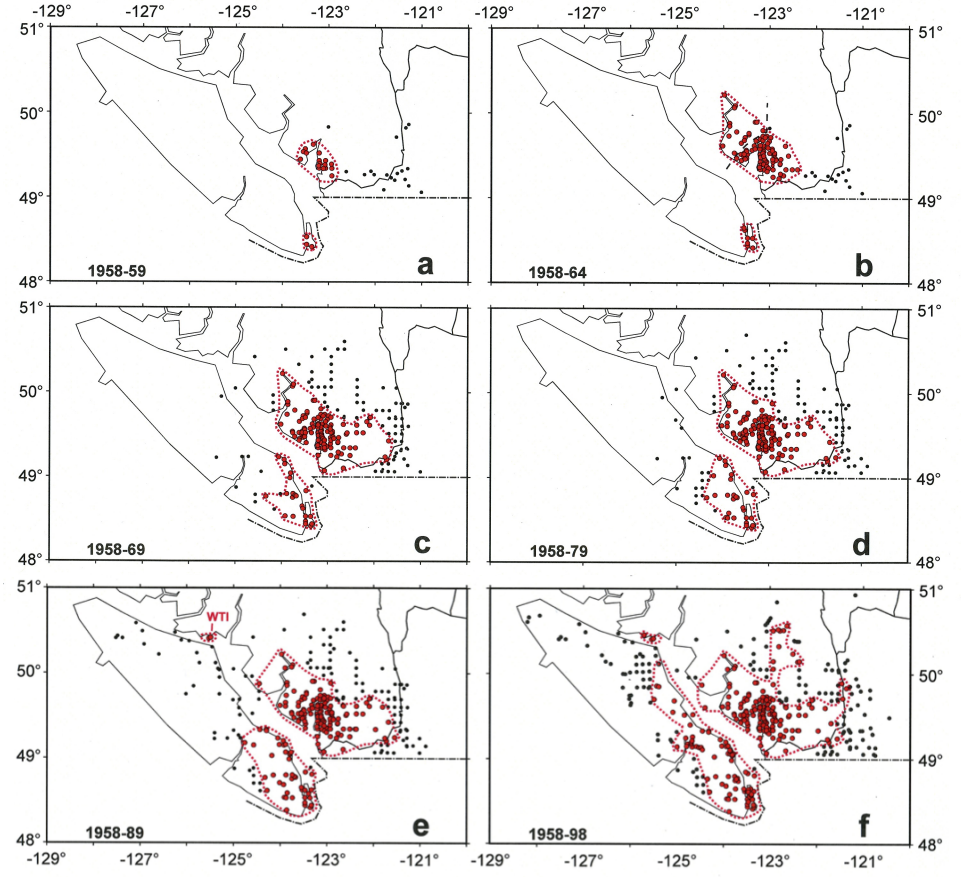

Figure 3. Expansion of *Adelges piceae* in coastal British Columbia between 1957 and 1995, as documented by positive and negative collection records (denoted in red and black, respectively), extracted from the CanFIAS database (Nealis *et al.* 2015). Islands between Vancouver Island and the mainland have been omitted for clarity. Red dashed lines delimit areas in which *A. piceae* has been detected: **a.** collections recorded in 1958 and 1959; **b.** cumulative collections between 1958 and 1964. Positive records to the northwest of the dashed line on the mainland are derived from aerial survey records documented in Ruppel and Allen (1964, 1965). Note significant expansion of the area infested to the southeast and northwest; **c.** cumulative collections between 1958 and 1969. Expansion to the northwest is evident on southern Vancouver Island and to the northeast on the mainland; **d.** cumulative records between 1958 and 1979; **e.** cumulative records between 1958 and 1989. Populations on the mainland and on Vancouver Island expanded to the northwest, and a satellite population was discovered on West Thurlow Island (WTI); and **f.** cumulative records from 1958 to 1998. Between 1990 and 1995, survey efforts documented significant northward expansion of *A. piceae* in the Fraser, Lillooet and Squamish river drainages on the mainland, as well as expansion to the northwest along the east coast of Vancouver Island to Campbell River.

boundaries continued to be prohibited; however, the modified regulations allowed the movement of logs of *Abies* spp. out of a quarantine zone if the logs were transported and stored in water and promptly processed as research had found that they posed minimal risk for dispersal of the adelgid (Atkins and Woods 1968). The sale of cut trees or foliage continued to be prohibited in B.C. between January 31 and November 1.

In 2000, a minor change was made to the *Balsam Woolly Adelgid Regulation* (Table 2). *B.C. Reg. 169/2000,* enabled by O.I.C. 726/2000, eliminated the need for the tagging of trees offered for commercial sale to identify that they had been grown under permit.

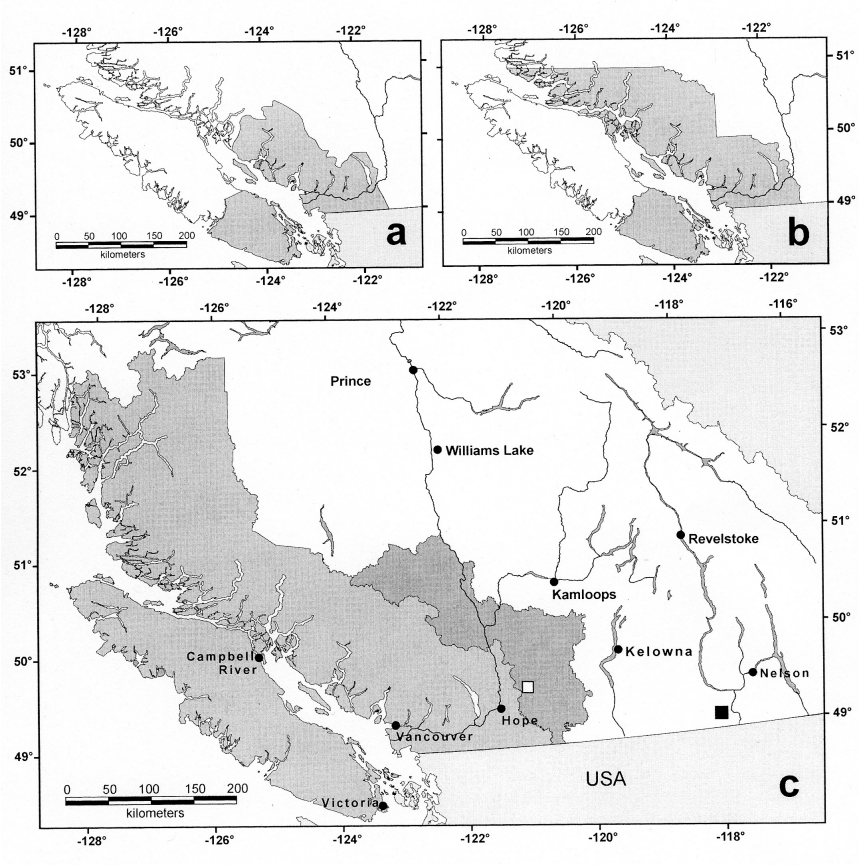

Figure 4. Historical change in areas of southwestern British Columbia regulated for *Adelges piceae*: **a.** area regulated in 1977. As no official record of the boundaries of the "Ranger Districts" named in Order in Council (O.I.C.) 1977-44 was retained, the area regulated on the mainland was approximated from other sources; **b.** area regulated by O.I.C. 1992-1604; and **c.** area regulated by O.I.C. 2006-493 (light grey) and the area added by O.I.C. 2014-361 (dark grey). The locations of the *Adelges piceae* detections at Falls Creek and Rossland are designated by unfilled and filled black squares, respectively.

With the detection of new finds east of the known distribution (Table 1), the *Balsam Woolly Aphid Regulation* was amended by *B.C. Reg. 213/2006*, established by O.I.C. 493/2006. The definition of "log" was changed to clarify that branches were not permitted on logs, and the definition of "quarantine zone" was repealed and replaced by "quarantine area" (described in the regulation's appendix). The only substantive change to the regulation was that Appendix A of *B.C. Reg. 414/92* was repealed and an expanded quarantine area defined in the Appendix to *B.C. Reg. 213/2006* was created (Table 2; Fig.

4c). The most recent amendment to the *Balsam Woolly Adelgid Regulation*, *B.C. Reg. 137/2014,* of June 30, 2014, added the Cascade Forest District to the quarantine area after recent surveillance indicated establishment of the adelgid beyond the boundaries of the 2006 regulated area (Table 2; Figure 4d).

Table 2
Summary of the provincial Orders in Council and regulations arising from each Order in Council (O.I.C.) enacted against *Adelges piceae*. Changes to the area regulated for *Adelges piceae* by specific O.I.C. are noted in the comments.

Order in Council[1]					
Year	**Number**	**Enactment Date**	**Regulation**	**Name**	**Comments**
1966	460	16 Feb. 1966	*B.C. Reg. 58/66*		All of British Columbia
1966	1137	14 Apr. 1966			Cost sharing agreement for surveys and acquisition of contaminated nursery stock
1967	2363	25 Jul. 1967			Cost sharing agreement for surveys and acquisition of contaminated nursery stock
1977	44	7 Jan. 1977	*B.C. Reg. 7/77*	*British Columbia Balsam Woolly Aphid Regulations, 1976*	All portions of 10 mainland and Vancouver Island Ranger Districts and the infested portions of two Ranger district in Vancouver Region (see Fig 3a)
1992	1604	22 Oct. 1992	*B.C. Reg. 414/92*[2]	*Balsam Woolly Adelgid Regulation*	
2000	726	18 May 2000	*B.C. Reg. 169/2000*[2]	*Balsam Woolly Adelgid Regulation*	
2006	493	13 Jul. 2006	*B.C. Reg. 213/2006*[2]	*Balsam Woolly Adelgid Regulation*	South Coast Forest Region and West Coast Forest Region
2014	361	5 Jun. 2014	*B.C. Reg. 137/2014*[2]	*Balsam Woolly Adelgid Regulation*	Cascades Forest District; South Coast Forest Region and West Coast Forest Region

[1] Text of all Orders in Council for British Columbia, including amendments up to *B.C. Reg. 137/204*, June 30 2014, pertaining to *Adelges piceae* were accessed at the following URL: http://www.bclaws.ca/Recon/document/ID/freeside/11_414_92 (accessed 10 October 2015).
[2] Amendment to *B.C. Reg. 414/92*

2011–2014 Surveillance for *Adelges piceae.* Locations sampled between 2011 and 2014 at which the presence of *Adelges piceae* was confirmed are documented in Table 3 and mapped in Figure 1; locations negative for the presence of *A. piceae* are presented in Table 4 and mapped in Figure 2. The presence of the adelgid in the Coquihalla Summit Recreation Area in the Cascades Forest District is not surprising, as the adelgid was known to be present in high-elevation coastal forests to the west of the detection. The Cascade Forest District was added to the quarantine area in June 2014 as a result of the surveys conducted. However, the presence of established populations of *A. piceae* in the Southern Interior of the province around Rossland (Table 2; Fig. 1), more than 200 km east of known infestations in B.C., was unexpected.

DISCUSSION

The discovery of *A. piceae* at multiple locations near Rossland is the first detection of this pest in the subalpine-fir forests in the interior of the province. Infested stands were detected in this study up to 9.5 km north and 3.8 km south of Rossland. Although *A. piceae* was detected in the southern Okanagan in 1967, the incursions were restricted to a few non-native urban ornamentals (*A. alba* and *A. concolor*) in Oliver and Penticton, and the populations were subsequently eradicated. Surveys of subalpine fir from Penticton south to the U.S. border provided no evidence that *A. piceae* had dispersed from the two low-elevation urban infestations into natural stands (Wood 1968; Wood *et al.* 1968). Symptoms of attack were not evident at the majority of the locations surveyed for *A. piceae* in the Rossland area. Severe gouting, stem attack and limited mortality were only evident at the golf course in Rossland, the lowest-elevation site sampled. Gouting was also documented on subalpine fir at the Highway 3B location (Table 2). At all other locations sampled, gouting was not evident, although a slight thickening of some nodes was noted at two other locations (Table 3; LH, personal observations).

It is unlikely that the *A. lasiocarpa* growing at the Rossland golf course was infested with *A. piceae* when planted some 60 years ago, as subalpine fir is highly susceptible to infestations and generally succumbs rapidly after infestation. Those subalpine firs that succumb first after infestation by *A. piceae* are often growing on the best sites (stream bottoms, benches and around meadows), with the severest damage occurring at the lowest elevations starting at around 915 meters (3000 ft.; Mitchell 1966), a description that closely resembles the golf course site. The source of this infestation could not be determined with any certainty; however, it is suspected that it has arisen from aerial dispersal of crawlers from nearby counties in Washington or Idaho, where populations of *A. piceae* have been documented (Liebhold *et al.* 2015). Alternatively, because asymptomatic *A. lasiocarpa* infested with *A. piceae* were easily found within Rossland and adjacent forested areas, the possibility remains that the adelgid may have originally been introduced on ornamental firs transported from other infested regions of the province. Unlike earlier detections of *A. piceae* on non-native urban ornamentals in the southern Okanagan (European silver fir, *Abies alba* Mill. and white fir, *A. concolor*; Wood 1968; Wood *et al.* 1968), plantings of non-native firs were not observed during surveys in Rossland. In addition, the latter scenario is improbable, as quarantine regulations have restricted the movement of ornamental *Abies* spp. from infested areas of the province to uninfested areas since 1966. While quarantine restrictions were also in place in 1967, the infested *A. alba* detected at Oliver were imported from Europe 29 years prior to the discovery of the adelgid. Neither the origin nor date of planting for the two white firs in Penticton was determined, although the trees were of similar height and diameter at breast height to the silver firs in Oliver, suggesting that they also were planted prior to the introduction of any quarantine regulations. Neither of these ornamental firs were killed by *A. piceae*, and gouting is not expressed on either species in the Pacific Northwest (Mitchell 1966).

Table 3

Collection data, observations on tree condition, and GenBank Accession numbers for partial COI sequences from samples positive for the presence of *Adelges piceae* documented in this study.

Collection Location	Lat., Long. (Dec. Deg.)	Year	Elev. (m)	Comments	GenBank Accession No.
Falls Creek, Coquihalla Summit Recreation Area	49.6101, –121.0559	2011	1210	Tree decline, gouting, numerous adelgids in buds, on *Abies amabilis*	KJ445727
Rossland, Redstone Golf Course	49.0677, –117.7844	2013	825	Heavy stem and branch attack by adelgids, gouting, tree decline and mortality on 60 year old *A. lasiocarpa* planted on the golf course	KJ445729
Rossland, junction of Plewman Way and Spokane St.	49.0836, –117.8016	2013	1100	Large populations of *A. piceae* present on two mature *A. lasiocarpa*, no evidence of gouting, irregular branching at nodes. Two lower branches sampled, terminal buds with adelgids in buds, all life stages present	KJ445725
Rossland, 2nd Av. and St. Paul St.	49.0794, –117.7971	2013	1060	Single *Abies lasiocarpa* on boulevard. Minor enlargement evident at nodes. Two lower branches sampled; all life stages present	KJ445726
Red Mountain Ski area, Olaus Way	49.1049, –117.8232	2013	1180	*Abies lasiocarpa* young regeneration, 2 trees sampled; branches with slightly enlarged nodes; lightly infested with adelgids	KJ445728
Red Mountain Ski area, Olaus Way	49.1049, –117.8232	2014	1180	Mature *Abies lasiocarpa*, one tree sampled; branches without enlarged nodes; lightly infested with adelgids	NS[1]
Rossland, Whiskey Trail	49.055, –117.794; 49.045, –117.791	2014	946 1128	*Abies lasiocarpa*, no gouting evident	KR260474 KR260470
Rossland, Larch Ridge Trail	49.158, –117.84	2014	1476	*Abies lasiocarpa*, no gouting evident	KR260469
Rossland, gravel pit	49114, –117.823	2014	1216	*Abies lasiocarpa*, no gouting evident	KR260473
Rossland, Hwy 3B	49.094, –117.804	2014	1140	*Abies lasiocarpa,* gouting evident	KR260466 KR260472 KR260471 KR260472

NS[1] - not sampled for mtDNA as tree was from the same location as 2013 sequence KJ445728

The detection of *A. piceae* at Falls Creek in the Cascades Forest District (Table 2) was the first detection of the adelgid east of the Coast Mountains in B.C. The collection site is to the northeast of the previously most-eastern collections of *A. piceae* (Fig. 1, 3f), and appears to represent an eastward range expansion in B.C. Gouting was evident on *A. amabilis* infested by *A. piceae* at the sites sampled.

The implementation of provincial regulations defining regulated areas for *A. piceae* in B.C., which are supported by federal restrictions, has been successful in slowing the expansion of the infestation boundary of *A. piceae* in southwestern B.C. (Coulson and Witter 1984). As the range of the adelgid infesting Pacific silver fir and grand fir in the coastal forests of B.C. has slowly expanded (Fig. 3), the quarantine boundaries have been expanded and strategies have been developed to produce and distribute clean *Abies* seedlings for reforestation to prevent anthropogenic dispersal of *A. piceae*. Additionally, the growth, sale and distribution of ornamental *Abies* spp. within the province has been restricted, as have imports of all *Abies* spp. into B.C. to prevent redistribution of the pest to uninfested regions.

The records presented in this study document the known distribution of *A. piceae* in B.C. from historical survey records and recent detections. The records noted in Anon. (1938) indicate that *A. piceae* was introduced into southwestern B.C. on ornamental *Abies* before 1937, at least 20 years prior to the first reports of damage in North Vancouver (Silver 1959). Vyse (1971) states that the adelgid was first introduced into southwestern B.C. in about 1938, although no evidence is provided to document that assertion. The rapid expansion of the infested area detected in the first seven years after its initial discovery on the mainland (Fig. 3a, b) may not represent active dispersal and rapid range extensions of the pest from the infestations detected in 1957 (Silver 1959), but rather may have arisen from the detection of previously established populations introduced in the late 1930s. It is apparent from the historical records that the distribution of this destructive forest pest was actively expanding when federal survey efforts ceased after 1995 (Fig. 3f). The recent detections at Falls Creek demonstrate that this adelgid has continued to expand its range inland beyond the coastal forests during the last two decades.

The historical detections of the adelgid in mature stands have generally occurred well after its initial establishment in the stand—most often when visible damage such as gouting or mortality is discovered at any one location. Subsequent delimitation surveys beyond the initial find have often demonstrated that the pest is more widely distributed. The detection of *A. piceae* beyond the regulated area on Vancouver Island in 1993 led to the discovery of multiple infested stands well north of the boundary in subsequent years (Table 1). Negative survey records from northern Vancouver Island made after the discovery of populations on WTI (Fig. 3e, f) suggest that the adelgid was not yet active in those areas. However, difficulty of access has limited survey efforts on the adjacent mainland between WTI and known infested areas near Powell River first discovered in 1986. It is highly probable that *A. piceae* was established at least as far north as the mainland adjacent to WTI by 1987. Vyse (1971) estimated that over the two decades ending in 1987, the maximum range expansion of *A. piceae* to the northwest along mainland would reach the Campbell River area. The WTI infestations exceed the estimated maximum range expansion along the coast under the most pessimistic scenario discussed by Vyse (1971) by more than 50 km.

The first detections of *A. piceae* in Interior *A. lasiocarpa* stands near Rossland pose serious challenges to the quarantine management of this pest in B.C. The cryptic nature of *A. piceae* in the initial stages of an infestation makes detection of attacked stands and thus delimitation of boundaries for regulated areas extremely difficult. Although Mitchell (1966) noted that "significant gouting always accompanies the decline of subalpine fir, but is often not conspicuous because the trees die so quickly", gouting was not apparent at many of the locations sampled near Rossland. The absence of such readily apparent symptoms of attack makes detection of infested trees considerably more difficult,

requiring the collection and microscopic examination of branch samples for presence of the adelgid under bud scales, at the base of staminate flowers, or at branch nodes. The massive numbers of white woolly masses associated with stem attack by *A. piceae* are more visually apparent than life stages associated with branch attack; however, stem attack usually begins high in the crown on subalpine fir and progresses down the stem (Mitchell 1966), also making the initial stages of such attacks difficult to detect. The presence of a native adelgid, *Pineus abietinus* (Underwood & Balch), attacking true firs in B.C. (Underwood and Balch 1964; Maw *et al.* 2000) further complicates recognition of stem attack by *A. piceae*, as the former species also develops dense populations on *Abies* stems.

Current quarantine regulations were developed to address potential sources of anthropogenic dispersal of *A. piceae* during harvest and reforestation activities in coastal forests, as well as to address that risk also posed by commercial distribution of potentially infested ornamental *Abies* spp. in urban areas. Regulations related to the movement of logs from within a regulated area will likely need to be modified, should quarantine restrictions be considered for management of this pest in Interior stands. Current regulations requiring the transport and storage of *Abies* logs in water are not feasible in the Interior of the province. Furthermore, current restrictions related to the production of seedlings for reforestation rely on the production of clean nursery stock in nurseries situated well beyond areas of known infestation to prevent infestation of the seedlings by aerially dispersed crawlers. To ensure that any sites used for the production of reforestation seedlings are free of populations of *A. piceae*, true firs present in the surrounding forests or cultivated as ornamentals near nurseries should be surveyed for the presence of *A. piceae*. Ideally, nursery stock should be produced in nurseries situated well beyond the range of native fir stands or ornamental plantings. Should this not be feasible, we recommend the use of sentinel plantings of *Abies* species that easily express persistent and apparent symptoms of infestation (e.g., gouting) by low numbers of *A. piceae*. Trees to be planted as sentinels should be grown from seed at nurseries remote from any populations of *A. piceae* in B.C.

Subalpine fir in southeastern B.C. is restricted to the upper elevations in the mountains, resulting in an extremely patchy distribution with very limited road access in most areas. Given the constraints noted above, development of a survey strategy will be extremely difficult. Should surveys for *A. piceae* be undertaken in subalpine fir forests, we recommend that presence of the pest be documented with properly preserved samples of life stages suitable for both morphological (i.e., preserved in 70% ethanol) and molecular identification (preserved in 95% ethanol). These samples are also essential to separate attack by *Adelges piceae* from that of the non-damaging native species, *Pineus abietinus* (Cook *et al.* 2010).

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Table 4

High-elevation locations at which *Abies lasiocarpa* was sampled in southern British Columbia and no evidence of *Adelges piceae* infestations was detected in 2014.

Location	Latitude (Dec. Deg.)	Longitude (Dec. Deg.)	Elevation (m)	No of trees	Comments
Mt. Baldy	49.1534	–119.2393	1780	5	2-4 m regeneration; no visible signs of gouting
Mt. Kobau	49.1147	–119.6749	1860	10	Scattered mortality in mature trees at summit; yellowing foliage; no visible signs of gouting or stem attack. Heavy populations of Pseudococcidae on lower branches
Apex Mountain Ski Hill	49.3925	–119.9037	1690	10	Mature trees; no visible signs of gouting
Big White Ski Hill (base)	49.7259	–118.9227	1820	10	2-4 m regeneration; no visible signs of gouting
Glenmerry FSR	49.2348	–117.9646	1340	10	Advanced regeneration; no evidence of gouting
Nancy Green Lk Prov Pk	49.2596	–117.9414	1274	1	Roadside tree; no visible signs of gouting
Bridal Lake	49.0621	–117.0387	1790	10	Advanced regeneration; no evidence of gouting
Maryland FSR	49.0650	–116.9155	1011	10	Advanced regeneration to 4m in height; no evidence of gouting; immature Coccidae under bud scales at nodes of a single tree.
Dodge Creek FSR	49.0113	–116.6370	1425	10	Mature trees with no evidence of gouting
Kimberly, North Star Ski Hill	49.6833	–116.0090	1325	5	Advanced regeneration at base of ski hill; no evidence of gouting

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