Preliminary hazard rating for forest tent caterpillar in British Columbia

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ABSTRACT

Forest tent caterpillar (*Malacosoma disstria* Hübner) is a major defoliator of hardwoods throughout North America, including aspen (*Populus tremuloides* Michx.). *M. disstria* has been a major concern in many parts of Canada for the last two decades, but until recently in British Columbia it was considered an aesthetic concern only. However, with the increasing interest in the cultivation of hardwoods for fibre, and more recently for fuel, this insect could become a major concern in hardwood management. Records of past *M. disstria* outbreaks in British Columbia were summarized. The locations and intensity of six outbreaks were overlaid on biogeoclimatic units to determine which biogeoclimatic zones have experienced repeated outbreaks of *M. disstria*. Between 1944 and 2003, *M. disstria* outbreaks have become larger in extent and longer in duration. Analysis indicated that aspen stands in the Boreal White and Black Spruce (BWBS), Sub-Boreal Spruce (SBS) and Interior Cedar-Hemlock (ICH) biogeoclimatic zones have been most frequently attacked. In the BWBS zone, most affected areas (93.3%) were defoliated for only one year (lightly). In the SBS and ICH zones, areas attacked by *M. disstria* tended to be defoliated two or more consecutive years (40.2% and 56.2%, respectively), and had a greater chance of being more severely defoliated than aspen stands in the BWBS zone.

Key words: *Malacosoma disstria*, forest tent caterpillar, damage, outbreaks, hazard rating

RÉSUMÉ

La livrée des forêts (*Malacosoma disstria* Hübner) est un ravageur important des forêts feuillues de toute l'Amérique du Nord, dont le peuplier faux-tremble (*Populus tremuloides* Michx.). *M. disstria* a provoqué beaucoup de dégâts dans plusieurs régions du Canada, mais jusqu'à récemment en Colombie-Britannique il était considéré seulement comme un problème d'ordre esthétique. Cependant, avec l'accroissement de l'intérêt de la production de feuillus pour leurs fibres et plus récemment comme carburant, l'insecte pourrait devenir un sujet d'importantes préoccupations en aménagement des feuillus. Les données des épidémies passées de *M. disstria* en Colombie-Britannique ont été analysées. La localisation et l'intensité de ces épidémies ont été répertoriées selon les régions biogéoclimatiques afin de déterminer quelles zones avaient connu des épidémies répétées de *M. disstria*. Entre 1944 et 2003, les épidémies de *M. disstria* sont devenues de plus en plus importantes en superficie et en durée. Les analyses démontrent que les tremblaies des zones d'Épinette noire et blanche des forêts boréales (BWBS), d'Épinette des forêts boréales moyennes (SBS) et de Pruche – cèdre – intérieur (ICH) ont été les plus fréquemment ravagées. Dans la zone BWBS, les superficies les plus ravagées (93,3 %) ont été défoliées seulement une année (légèrement). Dans les zones SBS et ICH, les superficies ravagées par *M. disstria* avaient tendance à être défoliées deux années ou plus de suite (respectivement 40,2 % et 56,2 %) et avaient une plus grande probabilité d'être plus sévèrement défoliées que les tremblaies de la zone BWBS.

Mots clés : *Malacosoma disstria*, livrée des forêts, dégâts, épidémies, classification du risque

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Introduction

Most defoliation research in British Columbia (BC) (and elsewhere in Canada) has, until recently, been on insects that attack conifers. Softwoods comprise about 95% of the forests of BC (Natural Resources Canada 2006) and include the majority of the economically important tree species. Because softwoods have been the primary focus of both industry and science, no special effort has been made to study hardwood pests in BC, and records of hardwood defoliation have been collected on a largely ad hoc basis until recently. Most hardwood defoliations have been recorded coincidentally while conducting aerial and ground surveys for coniferous pests.

There are four major hardwood defoliators in BC: forest tent caterpillar (FTC) (*Malacosoma disstria* Hübner) and northern tent caterpillar (*Malacosoma californicum pluviale* [Dyar]) (Lepidoptera: Lasiocampidae), satin moth (*Leucoma salicis* [L.]) (Lepidoptera: Lymantriidae), and large aspen tortrix (*Choristoneura conflictana* [Walker]) (Lepidoptera: Tortricidae). Of these, *M. disstria* is the most widespread hardwood defoliator in BC.

M. disstria is a native hardwood defoliator, and has the widest distribution of the six species of tent caterpillars (*Malacosoma* spp.) found in North America (Stehr and Cook 1968, Fitzgerald 1995). Its preferred host is trembling aspen (*Populus tremuloides* Michx.), and *M. disstria* is considered the most important defoliator of trembling aspen (Ives and Wong 1988). However, it is a polyphagous species, and also feeds on other species of *Populus*, as well as alders (*Alnus* spp.), birches (*Betula* spp.), oaks (*Quercus* spp.), black-gum (*Nyssa* spp.), willows (*Salix* spp.), sugar maple (*Acer saccharum* Marsh.), cherries and plums (*Prunus* spp.). Based on feeding experiments, Parry and Goyer (2004) suggested *M.*

disstria is a composite of populations regionally adapted to feed on different host trees.

M. disstria is a major pest of deciduous forests in all regions of Canada, with the exception of Newfoundland and the Northwest Territories (Hall 1996), and throughout the United States as far south as Louisiana and possibly into Mexico (Fitzgerald 1995). Its populations repeatedly explode and usually persist for several years before subsiding (Sippell and Ewan 1967, Stehr and Cook 1968, Fitzgerald 1995). During severe outbreaks, when the preferred food source is exhausted, late instar larvae will wander in search of food and feed on other deciduous trees, shrubs and even conifers (Prentice 1963, Oliver 1964, Stehr and Cook 1968, Hildahl and Campbell 1975, Batzer and Morris 1978, Knight *et al.* 1991, Wood 1992, Robison and Raffa 1994). Such severe outbreak conditions are common, and occur periodically throughout most of North America. Outbreaks of *M. disstria* have been reviewed for Quebec (Cooke and Lorenzetti 2006), Ontario (Sippell 1962) and west-central Canada (Manitoba, Saskatchewan and Alberta) (Hildahl and Reeks 1960, Moody and Amirault 1992, Brandt and Amirault 1994, Brandt 1995). No such review has been prepared for outbreaks occurring in BC.

M. disstria was first recorded causing noticeable defoliation on fruit and ornamental trees in British Columbia as early as 1907 or 1908 (Bush 1911), but annual recording of defoliation by this insect in BC was not started until 1944. Tree-ring evidence from Manitoba (Sutton and Tardif 2007) and Quebec (Huang *et al.* 2008) suggests that FTC outbreaks occurred in Canada, and by inference in BC, at least 100 to 150 years before these early records. Since 1944, six outbreaks of *M. disstria* have been recorded in BC. Between 1985 and 2003, *M. disstria* caused more damage to hardwoods than the other three defoliator species combined (Fig. 1), and poses a threat to hardwoods in managed and natural forest stands, as well as in urban areas. However, the unprecedented outbreak of *C. conflictana* that took place from 2003 to 2005 in BC may alter the importance of *M. disstria* in the future.

Once an outbreak has fully developed, populations are difficult, if not impossible to control by human intervention. In the past, outbreaks of *M. disstria* have been left to subside on their own through the effects of natural control agents and fortuitous cold and/or rainy weather at larval hatch (Hodson and Weinman 1945, Oliver 1964, Goyer 1991, Knight *et al.* 1991). *Bacillus thuringiensis* subsp. *kurstaki* (Btk) was registered for control of *M. disstria* in the early 1970s (Hildahl and Campbell 1975, Health Canada 2010)

Fig. 1. Comparison of total annual hardwood defoliation (light, moderate and severe) by *Malacosoma disstria* with the combined total damage by *Malacosoma californicum pluviale*, *Leucoma salicis* and *Choristoneura conflictana* in British Columbia and Yukon from 1985 to 2002.

and has been used effectively to control *M. disstria* in Manitoba (Shillinglaw 2001).

Severe FTC defoliation can result in significant growth reduction, crown dieback and tree mortality (Hildahl and Reeks 1969, Duncan *et al.* 1956, Hogg *et al.* 2002). Two or three years of consecutive and severe defoliation by *M. disstria* can result in up to 90% reduction in incremental growth. Complete recovery and resumption of normal growth after the trees have been stripped repeatedly can take several years, depending on the severity of the defoliation (Duncan and Hodson 1958; Hogg *et al.* 2002, 2005). This type of damage could severely impact harvest levels and rotation age of aspen in plantations, reducing both production and turnaround time of harvesting. In addition, massed larval incursions on residential and recreational properties can upset and irritate the general public, while mass migrations of larvae across roads and railways can reduce traction, making travel hazardous (Hildahl and Campbell 1975, Wood 1992).

Tree mortality rarely occurs as a direct result of *M. disstria* defoliation during outbreaks. Mortality usually occurs after the trees are weakened by severe defoliation and are subsequently attacked by opportunistic diseases and secondary insects (Duncan *et al.* 1956, Churchill *et al.* 1964, Moody and Amirault 1992). Drought can hasten this process (Cooke and Roland 2007). Armillaria root rot (*Armillaria* spp.) (Basidiomycetes: Agaricales), Cytospora canker (*Cytospora chrysosperma* [Pers.:Fr. (Fr.)] in the asexual stage and *Valsa sordida* Nitschke in the sexual stage) (Ascomycetes: Diaporthales), and Cryptosphaeria canker (*Cryptosphaeria lignyota* [Fr.:Fr.] Auersw.) (Ascomycetes: Diatrypales), are the most common disease agents causing mortality to aspen (Callan 1998). Trees weakened by defoliation are also susceptible to wind breakage, and often endure secondary insect attacks by wood borers such as the poplar and willow borer (*Cryptorhynchus lapathi* [L.]) (Coleoptera: Curculionidae) or long-

horn beetles (*Saperda* spp.) (Coleoptera: Cerambycidae) (Duncan *et al.* 1956, Churchill *et al.* 1964).

Records indicate that *M. disstria* has frequently defoliated thousands of hectares of aspen in BC since consistent insect damage monitoring was initiated in 1936 by the Forest Insect Survey (FIS), as it was then called. The Forest Disease Survey (originally a separate survey organization) was formally merged with FIS in 1962 and the combined survey was called the Forest Insect and Disease Survey (FIDS) of the Canadian Forest Service (McGugan 1958, Van Sickle *et al.* 2001). Because the FIDS reports are well known, all such reports on insects will be referred to as the FIDS reports in this paper. These surveys were conducted annually from 1936 until the service was discontinued in 1995 (Van Sickle *et al.* 2001), and the British Columbia Ministry of Forests and Range (BCMFR) assumed this role in 1996. Although the first mapping of insect infestations from aerial surveys was published in 1920 (followed by periodic mapping of major outbreaks), it was not until the early 1950s that aerial mapping of insect outbreaks were done annually (Van Sickle *et al.*

2001). Prior to the 1950s, insect damage was estimated from ground surveys, which were limited to areas that were accessible by road or boat. These surveys focused mainly on coniferous pests, with no special effort made to monitor hardwood insects. However, outbreaks were recorded coincidentally during surveys for coniferous pests. Thus, outbreak records for *M. disstria* and other hardwood defoliators prior to 1950 are probably incomplete, and it is likely that the damage caused by this pest and other insects feeding on hardwoods prior to 1950 is greater than the historical records indicate. After the 1950s, outbreaks were mapped using both ground and aerial surveys; the addition of the latter improved mapping accuracy. The size and intensity of defoliation was recorded in three defoliation classes (light, moderate and severe)⁶, and total areas in each category were estimated (Shore 1985). Defoliation records were incorporated into annual reports prepared by FIDS. The quality of this captured data has improved through time with technological improvements such as GIS and improved inventories.

In British Columbia, management of hardwood stands, and the insects and diseases that attack them, have become increasingly important only in recent years due to the new-found and increasing economic value of hardwoods in the forest industry (Sorensen 1984, Forest Ecosystem Solutions Limited 2005). Poplars (*Populus* spp.) and willows (*Salix* spp.) are the main hardwood species considered for short-rotation plantations using genetically improved hybrids for either fibre and/or energy production in North America (Ek and Brodie

⁶Light = discoloured foliage, barely visible from the air, some branch tip and upper crown defoliation; Moderate = pronounced discoloration, noticeably thin foliage, top third of trees more than 50% defoliated, some completely stripped; Severe = bare branch tips and completely defoliated tops, most trees more than 50% defoliated (Shore 1985).

1975, Sorensen 1984, Morley and Balatinecz 1993, Tolbert and Wright 1998, Tuskan 1998). Trembling aspen, the preferred host of *M. disstria*, is a fast-growing pioneer species that naturally colonizes areas exposed to natural (fire, insect and disease) and anthropogenic (clearcutting) disturbances. Aspen rapidly establishes itself on these cleared lands (Stehr and Cook 1968). In Canada, *P. tremuloides* comprises >80% of the total merchantable poplar (Morley and Balatinecz 1993), and it is estimated from Canada's Forest Inventory 2001 database that the merchantable volume of aspen is between 2202 and 2454 million m³ (K. Power⁷, 2010, personal communication). Aspen logging in British Columbia is increasing. It is actively logged in the Fort St. John Timber Supply Area, northeastern British Columbia, and from 2000 to 2010 accounted for 50% of the volume of timber, both hardwood and softwood, harvested in the region (Forest Ecosystem Solutions Limited 2005; J. Gibbons⁸, 2010, personal communication).

This paper brings together the scattered published and unpublished information on *M. disstria* outbreaks in BC. It provides: a) a brief history of the documented *M. disstria* outbreaks, b) a preliminary hazard rating of trembling aspen stands, based on past outbreaks, c) determination of biogeoclimatic units common to the outbreak areas, and d) identification of biogeoclimatic units where planting aspen should be reduced or avoided. This is the first step in the development of a hazard rating system for *M. disstria* in BC.

Materials and Methods

Digitized defoliation maps

The first published record of *M. disstria* activity from BC is from 1911, and states that the insect had been prevalent for the last three or four years attacking fruit and ornamental trees. No mention was made, however, of the location or extent of the affected area (Bush 1911). The first confirmed collection of *M. disstria* by FIS in BC was in 1935 at Pemberton Meadows in the Vancouver Forest Region (Ferris 1994). However, because FIS did not keep consistent records of insect infestations until the 1940s, *M. disstria* outbreaks prior to this are not included in this report. The history of *M. disstria* outbreaks and information on location, size and intensity of defoliation were gleaned from annual FIS and FIDS reports dating back to the 1940s.

Aerial survey maps of *M. disstria* outbreaks, as well as other insect outbreaks, were prepared by FIS and FIDS of the Canadian Forest Service from 1950 until 1995 (Van Sickle *et al.* 2001). These aerial survey maps were prepared and reported for each Forest Region by identifying the location and severity of defoliation (light, moderate, severe), and dead stands, and drawing defoliation polygons onto National Topographic Series (NTS) 1:100 000 or 1:250 000 map sheets.

Fig. 2. Total annual defoliation (light, moderate and severe) by *Malacosoma disstria* in British Columbia from 1944 to 1995, recorded by the former Forest Insect and Disease Survey (FIDS) and from 1996 to 2003 from surveys conducted by the British Columbia Ministry of Forests and Range (BCMFR).

Between 1985 and 1995, FIDS staff used a Geographic Information System (GIS) to digitize annually the sketch-mapped areas defoliated by *M. disstria*. Defoliation prior to 1985 was digitized by one of the authors (SF). Since 1996, the BCMFR has been conducting annual aerial surveys of pest damage in the province (<http://www.for.gov.bc.ca/hfp/health/overview/overview.htm>). Digitized data on defoliation from 1996 to 2003 were obtained from the BCMFR. The area of aspen stands defoliated by *M. disstria* were obtained from these digitized maps and plotted from 1944 to 2003 (Fig. 2). Efforts were made to standardize defoliation data obtained from these four sources (FIDS reports, FIDS ground surveys, FIDS aerial surveys, BCMFR aerial surveys).

Digitized data were summarized both by biogeoclimatic zone and Forest Region to assist forest managers in BC interpret the results and use this information to make management decisions. Smaller administrative units, such as Forest Districts and Tree Farm Licences, were not used because they would have been cumbersome to deal with in a paper like this.

Hardware and software

Details of the computer hardware used are described in Parfett *et al.* (1995). All available *M. disstria* infestation data (size and intensity of each outbreak), were transformed into a standardized digital format. The GIS software used to complete this task was a combination of ARC/INFO[®] 7 and ArcGIS 9.1 Workstation, both products designed by Environmental System Resource Institute, Inc. (ESRI[®], Redland, CA).

The locations of past *M. disstria* outbreaks (defoliation data 1944 to 2003) were superimposed over biogeoclimatic units (BCMFR 2010) to determine the biogeoclimatic (BGC) units that were common to the defoliated stands. Subsequently, levels of hazard were assigned to these areas based

⁷Natural Resources Canada, Canadian Forest Service

⁸Canfor, Fort St. Johns Division

upon frequency of consecutive⁹ years of defoliation during all outbreak periods.

Analysis

The total annual defoliation caused by *M. disstria* was plotted over the 60-year period from 1944 to 2003 during which defoliation was mapped (Fig. 2). Hazard rating analyses were completed in GIS using ArcGIS 9.1 to determine both the total number of consecutive (Fig. 3) or cumulative¹⁰ years (Fig. 4) that aspen stands were defoliated.

Further analyses were completed using VBA ArcObject (ESRI®, Redland, CA) programming language to determine the cumulative and consecutive number of years of defoliation each of the aspen stands experienced. The possibility that an area will be defoliated in the future was estimated by analyzing past occurrences, assuming that future attacks will most likely occur in stands with a previous history of *M. disstria* activity, unless the stand was killed during an earlier outbreak or harvested.

Results

Between 1944 and 2003, six *M. disstria* outbreaks occurred in BC (Fig. 2), with only a few years between outbreaks when no defoliation was recorded in at least one Region (Table 1). The duration of each subsequent outbreak seems to have increased through time. The second outbreak lasted four years, the third, eight; the fourth, nine; the fifth, 15; and the sixth, five years, respectively. The geographic location where defoliation occurred shifted spatially during each outbreak, so no single stand (polygon) was ever defoliated for more than four to seven years during a single outbreak.

Most of the defoliation during the six *M. disstria* outbreaks occurred in the old¹¹ Prince George (76.5%), Cariboo (14.5%) and Nelson (7.1%) Forest Regions. These regions contain 75.2%, 6.5% and 1.9% of the aspen in the Province (Table 1). The remaining 1.9% of the defoliation occurred in the other three Forest Regions (Kamloops, Prince Rupert and Vancouver) having 3.0%, 12.7% and 0.7 % of the aspen in the Province, respectively.

When stands defoliated during each of the *M. disstria* outbreaks were overlaid on the bio-

Fig. 3. Consecutive years of defoliation by area by *Malacosoma disstria* in British Columbia, 1944 to 2003.

Fig. 4. Total number of years aspen stands were defoliated by *Malacosoma disstria* (including defoliation in non-consecutive years and which occurred in the same stand during different outbreaks) in British Columbia, 1944 to 2003.

⁹“Consecutive years of defoliation” refers to the total number of successive years of defoliation that occurred in a particular stand during one outbreak.

¹⁰“Cumulative years of defoliation” refers to the maximum number of years the aspen stand was considered damaged between 1944 and 2003, regardless of whether defoliation of the stand occurred during only one or more than one of the six outbreaks.

¹¹There were six Forest Regions in BC prior to 2003, when the provincial government restructured the Ministry of Forests and Range, and divided the province into three new Forest Regions (BCMFR 2003).

geoclimatic zones of BC, further interesting trends emerged. Defoliation was recorded in 10 of the 14 biogeoclimatic zones, with over 90% of all the damage occurring in two zones: 46.4% in the Boreal White and Black Spruce (BWBS) and 45.5% in the Sub-Boreal Spruce (SBS) zones (Table 2). The next largest area (5.1%) prone to defoliation was in the Interior Cedar–Hemlock (ICH) zone. Four of the seven remaining biogeoclimatic zones, Engelmann Spruce–Subalpine fir (ESSF 1.2%), Sub-Boreal Pine–Spruce (SBPS 0.9%), Interior Douglas–fir (IDF 0.5%) and Montane Spruce (MS 0.4%), had about 3% of the total *M. disstria* defoliation. The remaining three

Table 1. Total area of defoliation (ha) by *Malacosoma disstria*, percent of total area defoliated suffering moderate and severe damage^a, and the proportion of aspen in each Forest Region as determined from data digitally recorded for each Forest Region in British Columbia from 1944 to 2003.

Year ^b	Prince George	Cariboo	Nelson	Kamloops	Prince Rupert	Vancouver	Total
Outbreak 1							
1944	1918 (100%)	1265 (100%)	3758 (100%)	–	–	–	6941 (100%)
1945	3855 (100%)	–	–	–	–	–	3855 (100%)
Subtotal	5773 (100%)	1265 (100%)	3758 (100%)	–	–	–	10 796 (100%)
Outbreak 2							
1951	1383 (92%)	–	–	–	–	–	1383 (92%)
1952	2341 (80%)	832 (100%)	–	86 (100%)	–	–	3259 (86%)
1953	56 457 (100%)	6286 (100%)	1307 (100%)	91 (100%)	–	–	64 141 (100%)
1954	56 283 (100%)	17 150 (100%)	11 584 (100%)	–	–	–	85 017 (100%)
Subtotal	116 464 (99%)	24 268 (100%)	12 891 (100%)	177 (100%)	–	–	153 800 (99%)
Outbreak 3							
1957	2968 (100%)	–	–	–	–	–	2968 (100%)
1958	3156 (100%)	–	–	–	–	–	3156 (100%)
1959	–	–	5203 (100%)	–	–	–	5203 (100%)
1960	4118 (100%)	–	8170 (100%)	–	–	–	12 288 (100%)
1961	15 937 (100%)	–	12 903 (100%)	–	–	–	28 840 (100%)
1962	12 748 (100%)	–	13 776 (100%)	–	3197 (100%)	–	29 721 (100%)
1963	16 330 (90%)	–	8340 (80%)	–	1101 (100%)	–	25 771 (87%)
1964	2272 (90%)	–	359 (100%)	–	–	–	2631 (91%)
Subtotal	57 529 (97%)	–	48 751 (97%)	–	4298 (100%)	–	110 578 (97%)
Outbreak 4							
1971	–	–	4669 (100%)	948 (60%)	–	–	5617 (93%)
1972	176 (100%)	288 (100%)	12 957 (100%)	4368 (100%)	–	–	17 789 (100%)
1973	18 154 (100%)	22 343 (98%)	10 086 (100%)	1040 (100%)	–	–	51 623 (99%)
1974	19 552 (100%)	3767 (100%)	5383 (3%)	–	–	–	28 702 (82%)
1975	9388 (100%)	–	–	–	–	–	9388 (100%)
1976	13 016 (100%)	–	8270 (100%)	–	–	–	21 286 (100%)
1977	18 575 (87%)	–	–	1116 (100%)	–	–	19 691 (88%)
1978	4004 (51%)	–	–	–	–	–	4004 (51%)
1979	–	–	–	587 (0%)	–	–	587 (0%)
Subtotal	82 865 (95%)	26 398 (98%)	41 365 (87%)	8 059 (88%)	–	–	158 687 (93%)
Outbreak 5							
1982	–	448 (22%)	–	–	–	–	448 (22%)
1984	26 632 (60%)	–	1 894 (100%)	–	–	–	28 526 (63%)
1985	49 869 (80%)	–	–	–	–	–	49 869 (80%)
1986	47 944 (69%)	–	–	–	–	–	47 944 (69%)
1987	16 441 (42%)	–	7001 (100%)	–	–	–	23 442 (59%)
1988	48 774 (82%)	158 (100%)	494 (100%)	–	1565 (100%)	199 (100%)	51 190 (83%)
1989	109 127 (96%)	3348 (100%)	8913 (100%)	807 (94%)	–	–	122 195 (96%)
1990	191 300 (81%)	4771 (92%)	1364 (3%)	7681 (69%)	–	–	205 116 (80%)
1991	85 154 (27%)	20 893 (96%)	–	6355 (98%)	–	–	112 402 (44%)
1992	21 192 (46%)	25 980 (93%)	–	1120 (29%)	–	–	48 292 (71%)
1993	38 227 (90%)	47 303 (100%)	–	–	–	–	86 025 (95%)
1994	41 565 (100%)	52 030 (83%)	–	–	–	–	93 595 (91%)
1995	53 214 (100%)	47 544 (86%)	–	–	–	–	100 758 (93%)
1996	88 760 (51%)	2481 (27%)	–	–	3012 (33%)	–	94 253 (50%)
1997	–	201 (0%)	–	–	–	–	201 (0%)
Subtotal	818 694 (74%)	205 157 (90%)	19 666 (93%)	15 963 (79%)	4577 (56%)	199 (100%)	1 064 256 (77%)
Outbreak 6							
1999	–	699 (0%)	–	–	–	–	699 (0%)
2000	211 754 (40%)	203 (96%)	–	–	464 (0%)	–	212 421 (40%)
2001	60 422 (31%)	–	27 (0%)	–	–	–	60 449 (31%)
2002	4116 (12%)	–	–	–	–	–	4116 (12%)
2003	89 (0%)	–	–	–	–	–	89 (0%)
Subtotal	276 381 (38%)	902 (22%)	27 (0%)	–	464 (0%)	–	277 774 (38%)
Total:	1 357 706 (71%)	258 026(91%)	126 458 (94%)	24 199(82%)	9 339(73%)	199(100%)	1 775 927(76%)
%	76.5%	14.5%	7.1%	1.4%	0.5%	<0.1%	100.0%
Aspen	3 026 134	262 508	77 438	120 490	511 630	27 202	4 025 402
	75.2%	6.5%	1.9%	3.0%	12.7%	0.7%	100.0%

^aPercentages in brackets represent the proportion of aspen that suffered moderate and severe defoliation.

^bYears during which no defoliation occurred are excluded from table.

Table 2. Area of aspen defoliated in each biogeoclimatic zone (BGCZ) during the six outbreaks of *Malacosoma disstria* that occurred between 1944 and 2003 in British Columbia, Canada.

Biogeoclimatic unit description		Total Area (ha)			Defoliation by		
		BGCZ	Area of aspen in BGCZ	% area aspen in BGCZ	Area (ha)	% of BGCZ variant ^a	% total area
Alpine Tundra^b							
ATun	undifferentiated	–	–	–	919.4	<0.1	0.1
Total		17 158 900.0	754.0	<0.1	919.4	–	0.1
Boreal White and Black Spruce							
BWBSdk1	dry cool, <i>Stikine</i>	–	–	–	2 611.5	0.1	0.3
BWBSmw1	moist warm <i>Peace</i>	–	–	–	315 771.7	10.9	35.1
BWBSmw2	moist warm <i>Fort Nelson</i>	–	–	–	89 261.2	1.2	9.9
BWBSwk1	wet cool, <i>Murray</i>	–	–	–	2 419.5	0.7	0.3
BWBSwk2	wet cool, <i>Graham</i>	–	–	–	7 472.9	2.1	0.8
Total		15 300 416.6	2 532 711.9	16.6	417 536.8	–	46.4
Coastal Western Hemlock							
CWHdm	dry maritime	–	–	–	80.5	<0.1	<0.1
CWHxm1	very dry maritime, <i>eastern</i>	–	–	–	118.6	<0.1	<0.1
Total		8 881 668.1	3 890.6	<0.1	199.1	–	<0.1
Engelmann Spruce – Subalpine Fir							
ESSFdc2	dry cold, <i>Thompson</i>	–	–	–	48.4	<0.1	<0.1
ESSFmc	moist cold	–	–	–	250.8	<0.1	<0.1
ESSFmm1	moist mild, <i>Raush</i>	–	–	–	2 223.0	0.8	0.3
ESSFmmp	moist mild parkland	–	–	–	908.6	0.3	0.1
ESSFmv1	moist very cold, <i>Nechako</i>	–	–	–	97.8	0.1	<0.1
ESSFmv2	moist very cold, <i>Bullmoose</i>	–	–	–	906.4	0.2	0.1
ESSFmv3	moist very cold, <i>Omineca</i>	–	–	–	347.0	<0.1	<0.1
ESSFmv4	moist very cold, <i>Graham</i>	–	–	–	3 199.6	0.4	0.4
ESSFmvp	moist very cold parkland	–	–	–	102.4	<0.1	<0.1
ESSFwc1	wet cold, <i>Columbia</i>	–	–	–	1.7	<0.1	<0.1
ESSFwc2	wet cold, <i>Northern Monashee</i>	–	–	–	204.0	<0.1	<0.1
ESSFwc3	wet cold, <i>Cariboo</i>	–	–	–	172.2	<0.1	<0.1
ESSFwk1	wet cool, <i>Cariboo</i>	–	–	–	576.9	0.1	0.1
ESSFwk2	wet cool, <i>Misinchinka</i>	–	–	–	1 250.9	0.2	0.1
ESSFwm	wet mild	–	–	–	0.2	<0.1	<0.1
Total		12 390 913.5	71 039.6	0.6	10 289.8	–	1.2
Interior Cedar - Hemlock–							
ICHdk	dry cool	–	–	–	59.2	0.1	<0.1
ICHdw1	dry warm, <i>West Kootenay</i>	–	–	–	7 263.8	1.7	0.8
ICHmc2	moist cold, <i>Hazelton</i>	–	–	–	3 014.2	0.9	0.3
ICHmk1	moist cool, <i>Kootenay</i>	–	–	–	3 966.8	1.2	0.4
ICHmk2	moist cool, <i>Thompson</i>	–	–	–	2.2	<0.1	<0.1
ICHmk3	moist cool, <i>Horsefly</i>	–	–	–	13 118.8	11.7	1.5
ICHmm	moist mild	–	–	–	10 323.7	6.8	1.2
ICHmw1	moist warm, <i>Golden</i>	–	–	–	1 723.7	1.2	0.2
ICHmw2	moist warm, <i>Columbia-Shuswap</i>	–	–	–	71.3	<0.1	<0.1
ICHmw3	moist warm, <i>Thompson</i>	–	–	–	4 109.7	0.8	0.5
ICHvk2	very wet cool, <i>Slim</i>	–	–	–	5.3	<0.1	<0.1
ICHwk1	wet cool, <i>Wells Gray</i>	–	–	–	150.2	<0.1	<0.1
ICHwk2	wet cool, <i>Quesnel</i>	–	–	–	448.6	0.3	0.1
ICHwk3	wet cool, <i>Goat</i>	–	–	–	990.1	1.0	0.1
ICHxw	very dry warm	–	–	–	263.6	0.6	<0.1
Total		4 456 593.9	140 103.9	3.1	45 511.3	–	5.1
Interior Douglas-fir							
IDFdk1	dry cool, <i>Thompson</i>	–	–	–	73.1	<0.1	<0.1
IDFdk2	dry cool, <i>Cascade</i>	–	–	–	133.3	<0.1	<0.1
IDFdk3	dry cool, <i>Fraser</i>	–	–	–	457.8	<0.1	0.1
IDFdm1	dry mild, <i>Kettle</i>	–	–	–	47.1	<0.1	<0.1
IDFdm2	dry mild, <i>Kootenay</i>	–	–	–	93.5	<0.1	<0.1
IDFmw1	moist warm, <i>Okanagan</i>	–	–	–	0.9	<0.1	<0.1
IDFmw2	moist warm, <i>Thompson</i>	–	–	–	2 267.6	1.2	0.3
IDFhx2	very dry hot, <i>Thompson</i>	–	–	–	1 053.5	0.4	0.1
IDFhx4	very dry hot, <i>Boundary</i>	–	–	–	2.2	<0.1	<0.1
Total		3 822 312.1	98 380.6	2.6	4 129.1	–	0.5

Table 2. Area of aspen defoliated in each biogeoclimatic zone (BGCZ) during the six outbreaks of *Malacosoma disstria* that occurred between 1944 and 2003 in British Columbia, Canada (continued).

Biogeoclimatic unit description		Total Area (ha)			Defoliation by		
		BGCZ	Area of aspen in BGCZ	% area aspen in BGCZ	Area (ha)	% of BGCZ variant ^a	% total area
Montane Spruce							
MSdk	dry cool	—	—	—	2 928.9	0.5	0.3
MSdm2	dry mild, <i>Thompson</i>	—	—	—	653.7	0.2	0.1
MSsk	very dry cool	—	—	—	54.9	<0.1	<0.1
Total		2 282 352.4	9 051.1	0.4	3 637.5	—	0.4
Ponderosa Pine							
PPdh2	dry hot, <i>Kootenay</i>	—	—	—	255.7	0.3	<0.1
Total		276 750.9	2 778.8	1.0	255.7	—	<0.1
Sub-Boreal Pine - Spruce							
SBPSdc	dry cold	—	—	—	777.1	0.2	0.1
SBPSmc	moist cold	—	—	—	40.1	<0.1	<0.1
SBPSmk	moist cool	—	—	—	6 864.5	1.2	0.8
SBPSxc	very dry cold	—	—	—	20.2	<0.1	<0.1
Total		2 400 648.1	72 709.5	3.0	7 702.0	—	0.9
Sub-Boreal Spruce							
SBSdh1	dry hot, <i>McLennan</i>	—	—	—	14 064.7	20.6	1.6
SBSdk	dry cool	—	—	—	6 708.1	0.6	0.7
SBSdw1	dry warm, <i>Horsefly</i>	—	—	—	85 789.6	22.3	9.5
SBSdw2	dry warm, <i>Blackwater</i>	—	—	—	7 153.6	1.6	0.8
SBSdw3	dry warm, <i>Stuart</i>	—	—	—	85 885.2	9.0	9.5
SBSmc1	moist cold, <i>Moffat</i>	—	—	—	751.4	1.8	0.1
SBSmc2	moist cold, <i>Babine</i>	—	—	—	4 125.8	0.2	0.5
SBSmc3	moist cold, <i>Kluskus</i>	—	—	—	1 128.8	0.5	0.1
SBSmh	moist hot	—	—	—	28 892.3	28.6	3.2
SBSmk1	moist cool, <i>Mossvale</i>	—	—	—	122 694.7	8.7	13.6
SBSmk2	moist cool, <i>Williston</i>	—	—	—	1 533.3	0.4	0.2
SBSmw	moist warm	—	—	—	26 306.0	12.6	2.9
SBSvk	very wet cool	—	—	—	785.0	0.2	0.1
SBSwk1	wet cool, <i>Willow</i>	—	—	—	20 898.6	2.7	2.3
SBSwk2	wet cool, <i>Finlay – Peace</i>	—	—	—	2 622.2	0.5	0.3
SBSwk3	wet cool, <i>Takla</i>	—	—	—	906.4	0.2	<0.1
SBSwk3a	wet cool, Douglas-fir phase, <i>Takla</i>	—	—	—	57.4	0.2	0.0
Total		9 559 693.7	733 010.4	7.7	410 302.9	—	45.5
Spruce Willow Birch							
SWBmk	moist cool	—	—	—	511.9	<0.1	0.1
SWBmks	moist cool scrub	—	—	—	13.4	<0.1	<0.1
Total		7 440 751.0	178 722.3	2.4	525.3	—	0.1
Grand Total		83 971 000.3	3 843 151.7	4.6	901 009.0	—	100.0

^aa total for percent defoliation within biogeoclimatic subzone variants cannot be calculated because defoliation may have occurred in the same stand during the same or different outbreaks.

^bprobable mapping error.

zones, Coastal Western Hemlock (CWH), Ponderosa Pine (PP) and Spruce Willow Birch (SWB), each had less than 0.1% of the total defoliation. This would be expected because both aspen extent and volume decrease from the more boreal BGC zones to the more temperate and coastal BGC zones. Although defoliation polygons were also recorded in the Alpine Tundra (AT) zone, the area is small (ca. 0.1%) and likely represents mapping errors rather than actual defoliation.

Defoliation was not evenly distributed throughout the various biogeoclimatic variants within BWBS and SBS zones (Table 2). In the BWBS zone, the greatest area of defoliation occurred in the two moist warm variants, BWBSmw1 (35.1%) and BWBSmw2 (9.9%). In the SBS zone, most of the past *M. disstria* outbreaks occurred in

the dry warm variants SBSdw1 (9.5%) and SBSdw3 (9.5%), the moist cool SBSmk1 (13.6%), moist hot SBSmh (3.2%), moist warm SBSmw (2.9%) and wet cool SBSwk1 (2.3%) variants. In the ICH, ESSF and CWH biogeoclimatic zones past defoliation by *M. disstria* was more evenly distributed among the variants, and only two variants, ICHmk3 and ICHmm, comprised more than 1% (1.5% and 1.2%, respectively) of the area defoliated by *M. disstria* (Table 2).

When defoliation within an area was examined for number of years of consecutive defoliation during each of the six outbreaks, most of the defoliation in all three severity classes occurred over 96.9 % of the aspen in the first three consecutive years. Of the total area infested during the six outbreaks,

74.8% was attacked for one year, 15.8% for two years, 6.3% for three years, and remaining 2.5% of the stands were defoliated for four consecutive years (Fig. 3). Fig. 3 shows that the remaining small fraction (0.5%) of the stands could be defoliated from five to seven years. Although it is very likely that this small fraction represents errors, either during aerial mapping or digitization of the data, we could not disregard them because they may represent core areas where the outbreaks lingered for longer than four years (Cooke *et al.* 2009).

The total cumulative area defoliated over the 60-year period during the six outbreaks covered by this study was calculated at 1 775 927 ha (Table 1). Analysis of the cumulative years of defoliation of aspen stands during the six documented outbreaks indicates that some aspen stands were defoliated in 17 different years (Fig. 4). However, most (64.5%) of the stands were defoliated only once. A much lower proportion of stands were defoliated in two different years (14.4%), and only 7.9% were defoliated in three different years. Another 11.3% of stands within the documented outbreaks were defoliated in four to 7 different years, around 1.8% were defoliated in eight to 10 different years, around 0.3% were defoliated in 11 to 13 different years, and <0.1% were defoliated in 14 to 17 different years. Some of these smaller fractions, perhaps those below 1%, may also represent errors in mapping the outbreaks or digitizing the data. Analysis of cumulative defoliation data shows that some stands had high probability (86.8%) of being defoliated for one to three years. Two biogeoclimatic zones (BWBS and SBS) contain about 92%, and ICH another 5%, of the aspen attacked by *M. disstria*.

Three damage classes were determined from the frequency analysis of past defoliation using defoliation data from six outbreaks: areas with low potential for damage (stands defoliated for one year), areas with moderate potential for damage (stands defoliated for two to three consecutive years) and areas with high potential for damage (stands defoliated for more than three consecutive years). These damage classes are shown in Fig. 5.

Discussion

Between 1944 and 2003, six *M. disstria* outbreaks were recorded in BC, with defoliation occurring in at least three of the six former Forest Regions (Table 1). There was also a substantial increase in the area defoliated during each of the six recorded outbreaks (Fig. 2).

The increase in the area defoliated over the years could, in part, be due to improved detection of outbreaks by more accurate aerial defoliation surveys initiated in the 1950s (i.e., the increase could be virtual, not real). This is reflected in the recording of larger proportions of the areas being lightly defoliated during Outbreaks 5 and 6 (Table 1). In addition, a number of anthropogenic factors may also play a part in the increasing size of *M. disstria* outbreaks. We feel this increase could also be the result of human activities, either logging or fire prevention, or perhaps both (BCMFR 2006; J. Gibbons, 2010, personal communication). Aspen has been shown, at least on a moderate scale, to expand into areas previously sup-

Fig. 5. Susceptibility of aspen stands to *Malacosoma disstria* attack based on cumulative years of defoliation in the Boreal White and Black Spruce (BWBS), Interior Cedar Hemlock (ICH) and Sub-Boreal Spruce (SBS) biogeoclimatic zones. A) Susceptibility of BWBSmw1 subzone versus B) all other subzones. Note differences in scale on y-axes. Biogeoclimatic subzones where <3000 ha were defoliated are not shown.

porting other tree species when naturally occurring forest fires are suppressed (Kulakowski *et al.* 2004). It may also be caused, in part, by human encroachment into and development in previously remote regions (Stehr and Cook 1968, Goyer 1991).

Forest practices and other human activities have altered the original vegetation in many parts of North America, increasing the amount of aspen available to *M. disstria* (Stehr and Cook 1968). In certain biogeoclimatic zones, if measures are not taken, areas that have been logged or burned by forest fires can be quickly invaded and colonized by aspen, a pioneer species (Peterson and Peterson 1992) favoured by *M. disstria*. It has been suggested that the man-made changes (to date only on the small scale) and natural monoculture conditions that increase the abundance and distribution of potential host trees have played a role in increasing the frequency and extent of *M. disstria* outbreaks (Stehr and Cook 1968, Goyer 1991). At first glance, this may appear to contradict Rothman and Roland (1998), who indicated that fragmentation increased outbreak intensity. However, we suggest there may have been an increase in the number of small aspen stands in BC, replacing the conifers that originally grew in these areas (BCMFR 2006; J. Gibbons⁸, 2010, personal communication). The damage *M. disstria* does to these trees is becoming increasingly difficult to ignore because of aesthetic concerns in urban and rural areas and because of potential economic impact in areas where aspen is becoming a major fibre source or used for generating power. The effects of defoliation are dependent on the interaction of many factors, including: severity, frequency and timing of defoliation, weather and growing conditions, presence of secondary insects and disease organisms, and tree vigour (Mattson and Addy 1975).

When FTC-damaged stands were proportioned according to potential damage classes (low, moderate or high), some

interesting trends were revealed. Although the areas defoliated by *M. disstria* in the BWBS and SBS biogeoclimatic zones were nearly identical (417 537 ha and 410 325 ha, respectively), the duration and severity of defoliation differed (Table 3; Fig. 5). In the BWBS zone, 93.3% of the attacked stands were defoliated for only one year compared to 59.8% in SBS zone, while 6.5% and 35.3% were defoliated two or three years in the BWBS and SBS zones, respectively. Only about 0.2% of the stands were defoliated for four to seven years in the BWBS zone compared with 4.9% in the SBS zone. These results show that aspen stands in the SBS biogeoclimatic zone are more likely to be defoliated longer by forest tent caterpillar than those in the BWBS zone. In the ICH biogeoclimatic zone, which contains only about 5% of the *M. disstria*-damaged stands (Table 2), about 11.0% of the stands were defoliated from four to seven years, while 43.8% and 45.2% of the stands were defoliated for one and two or three years, respectively.

The area defoliated during the last six outbreaks of *M. disstria* was in proportion to the aspen present only in the Prince George Forest Region. In contrast, only 0.5% of *M. disstria* defoliation occurred in the Prince Rupert Region, even though 12.7% of the total aspen in BC is in this Forest Region. Conversely, 7.1% of the forest tent caterpillar defoliation occurred in the Nelson Region even though only 1.9% of the aspen stands in BC are in this Forest Region. Aspen stands suffered proportionally more defoliation by area in the Cariboo and Nelson Forest Regions and considerably less defoliation by area in the Prince Rupert Region than one would expect based on the proportion of the aspen present in these three Forest Regions. One possible explanation for this may be that the mountainous topography in the Prince Rupert Region fragments aspen stands and confines aspen to river valley bottoms and interior plateaus. Weather conditions may be more important. The northern part of this Region has cool summers, with below-freezing temperatures occurring even in the middle of summer (Environment Canada 2010). Frost or unseasonably late freezing weather has been observed to cause the collapse of *M. disstria* outbreaks in central Canada (Blais *et al.* 1955) and, similarly, cool, rainy springs and cool summers likely prevent outbreaks from developing in the Prince Rupert Region.

Table 3. Duration of *Malacosoma disstria* outbreaks and proportion of defoliated area in each of the three most commonly affected biogeoclimatic zones, 1944 to 2003.

Biogeoclimatic zone	Area defoliated (ha) ^a			
	1 year	2–3 years	4–7 years	Total
BWBS	389 594.3 (93.3%)	27 286.2 (6.5%)	656.3 (0.2%)	417 536.8
SBS	245 406.0 (59.8%)	144 962.0 (35.3%)	19 956.9 (4.9%)	410 324.9
ICH	19 915.7 (43.8%)	20 552.6 (45.2%)	5 043.0 (11.1%)	45 511.4
Total	654 916.1 (75.0%)	192 800.8 (22.1%)	25 656.2 (2.9%)	873 373.1

^aPercentages in brackets represent the proportion of aspen that suffered moderate and severe defoliation.

Aspen is physiologically adapted to be an early successional species by storing most of the trees' nutrients below ground in the roots; therefore, defoliation generally has less effect on them (Bryant *et al.* 1983, Peterson and Peterson 1992). Early successional plants, such as aspen, are adapted to frequent natural disturbances and are able to regenerate quickly with rapid shoot growth by utilizing nutrients in their roots (Garrison 1972).

Forest tent caterpillar outbreaks can also be of concern in mixed-wood stands. Volney (1988) demonstrated that in mixed stands of aspen and spruce, the overmature aspen overstory protected the immature spruce trees from attack by the white pine weevil, *Pissodes strobi* Peck (Coleoptera: Curculionidae). Premature harvesting or severe defoliation of the aspen overstory made the spruce more susceptible to weevil attack (Volney 1988). Therefore, in a mixed stand where the softwoods are of primary commercial concern, it may be advantageous to monitor and control hardwood defoliators to minimize secondary or indirect negative impacts to the conifer understorey. In contrast, in mixed stands where the spruce weevil is not a concern, defoliation of aspens has been found to benefit understorey trees by allowing an influx of sunlight to the light-deprived undergrowth (Mattson and Addy 1975).

Aspen stands in BWBS and SBS zones are at greater risk of future defoliation than stands in the other biogeoclimatic zones. Both the BWBS and SBS zones have highly successional forests, where aspen is the dominant pioneer species in the seral stage (Peterson and Peterson 1996). Although the total area of aspen stands defoliated in these two zones is about the same, damage in the SBS zone tends to be more widespread. Over 93% of the stands in the BWBS zone were defoliated for only one year, and only about 7% of aspen stands were defoliated for two or more years. In contrast, about 60% of stands in the SBS zone were defoliated for one year and about 40% of the stands were defoliated for two or more years. Although ICH only has about 10% of the area of BWBS or SBS, about the same proportions, 44% versus 45%, of the aspen suffered defoliation for one year and two or three years, respectively, and 11% for four to seven years (Table 3). Outbreaks of *M. disstria* in both the SBS and ICH zones last somewhat longer than in the BWBS zone (Fig. 5).

Several studies have shown that both duration and intensity of defoliation affect the impact (growth loss and tree mortality) of FTC outbreaks on host trees (Duncan and Hodson 1958, Hildahl and Campbell 1975, Brandt 1995). Tree growth may take up to three years to return to normal after an outbreak has collapsed (Churchill *et al.* 1964, Moody and Amirault 1992). Forest managers should be aware of the impacts of *M. disstria* outbreaks on aspen in the most susceptible biogeoclimatic zones, and should, whenever possible, either attempt to ameliorate the risk of attack by silvicultural and other means, or accept the damage that will occur in the SBS and ICH biogeoclimatic zones. In this study, we determined that past FTC outbreaks caused the most damage (moderate to severe defoliation and/or lasted longer) on aspen in the BWBS, SBS and ICH biogeoclimatic zones, and which subzones within these were most affected. We are currently preparing a manuscript on the impact of *M. disstria* outbreaks on aspen in BC, using a modified version of Brandt and Amirault's (1994) definitions for impact classes (which links severity and duration of defoliation to growth loss and tree mortality) to esti-

mate growth loss and mortality caused by FTC outbreaks in the most severely impacted biogeoclimatic subzones. We feel this information will help forest managers determine which stands are likely to suffer the greatest impact in the future and should be monitored, if aspen is an important tree species (either economically or aesthetically) in their region.

The development of fast-growing hybrid poplars that reach rotation age quicker than natural hardwood stands may be one way to reduce damage by *M. disstria*. Other recent studies investigated whether defoliation-resistant hybrids can be produced (Robison and Raffa 1994). However, hybrid strains need to be screened for disease resistance and habitat suitability before widespread planting of these insect-resistant hybrids is recommended. This latter option may be less promising in the long term, because insects are generally able to adapt faster than resistant strains can be developed.

The use of transgenic hybrid poplars may be another means of reducing herbivory by *M. disstria*. Hybrid poplar became the first woody plant to receive the *Bacillus thuringiensis* (*Bt*) *cry* IA(a) d-endotoxin gene (McCown *et al.* 1991). These transgenic trees demonstrated resistance to herbivory by *M. disstria* (Robison *et al.* 1994, Kleiner *et al.* 1995). In our opinion, the use of Bt-transgenic plants must be tempered with the knowledge that: a) insects may evolve resistance to Bt toxins over the rotation age of the host tree even if the hybrid poplar plantations are planted on a short-rotation basis; b) more importantly, Bt genes can be transferred via pollen or other (non-sexual) means to nearby trees; c) genetic modification of the organism may affect other functions and defence mechanisms in the tree; and d) the possibility of unforeseen impacts on non-target organisms (van Frankenhuyzen and Beardmore 2004, Close 2005). In addition, it has been conclusively demonstrated in agriculture systems that insects develop resistance to Bt toxins after prolonged exposure, such as spraying Btk 50 to 100 times over a five-year period (Tabashnik *et al.* 1990). Because *P. tremuloides* can regenerate from suckers, the entire stump and root system must be removed, otherwise the original tree will continue producing clones expressing the Bt toxins. Some *P. tremuloides* stands in North America are clones of trees that first re-colonized the land following the end of the last glaciation, or may even be clones of survivors from even earlier times (Mitton and Grant 1996). This suggests that improper removal of transgenic aspen following harvesting could result in re-sprouting and spreading of transgenic trees for many years afterwards.

In our opinion, the use of transgenic aspen trees may present a Pandora's Box, potentially risking the future use of Btk sprays for defoliator control. Although some countries, like China, seem to be aggressively pursuing this avenue of research and planting transgenic *Populus* spp. (Ewald *et al.* 2006, Huang *et al.* 2007), we feel this risk should not be taken in North America. Long-term trials should be conducted on transgenic poplar trees, either in the laboratory or on potted caged trees, to demonstrate the "safety" of these trees (i.e., no Bt-resistant insect species are likely to occur) before the transgenic trees are ready for use in plantations.

Conclusions

Of all the hardwood defoliators in British Columbia, *M. disstria* has caused the most widespread and eruptive infestations

on aspen. Although large aspen tortrix, *Choristoneura conflictana* Walker, can defoliate more extensive areas than *M. disstria* (shown by the recent outbreak in British Columbia from 2003 to 2008), its impact tends to be less, usually resulting in reduction of radial growth and bud damage, and only occasionally some tree mortality (Coulson and Witter 1984, Cerezke and Volney 1995, Brandt *et al.* 2003). This paper summarizes *M. disstria* defoliation events using GIS to map the details of location, extent, length and severity of the six *M. disstria* outbreaks that occurred from 1944 to 2003. Each successive outbreak has grown in size and intensity during this period and occurred mainly within BWBS (46.4%) and SBS (45.5%) biogeoclimatic zones (Table 2).

Potential damage assessment of stands susceptible to *M. disstria* attack was conducted by determining the number of consecutive years that a stand has been defoliated from 1944 to 2003. The analysis revealed that the SBSmk1, dw1, and dw3 subzones have the greatest risk of longer term of defoliation, while subzone BWBSmw1 is at a somewhat lower potential risk of defoliation and BWBSmw2 is only defoliated for one year (Fig. 5). Managing susceptible stands is an important factor in reducing the impact of *M. disstria* outbreaks. Several options are available for this, including: avoiding planting *Populus* spp. in SBSmk1 biogeoclimatic unit (should replanting replace natural regeneration in the future), restocking and development of resistant hybrid tree species in plantations, manipulating natural control agents, and altering forest stand structure and forest heterogeneity in the biogeoclimatic zones having the greatest risk for defoliation and subsequent damage by *M. disstria*. The impacts of *M. disstria* defoliation on aspen and other *Populus* spp. may be reduced by the use of transgenic *Populus* spp. However, the use of transgenic *Populus* spp. may pose an unacceptable risk to the future use of Btk, the only biopesticide currently available commercially for defoliator control.

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