Symposium Proceedings

Spruce Budworm

Dealing with the New Outbreak

Quebec City
February 19–20, 2014

Ordre des ingénieurs forestiers du Québec

Natural Resources Canada / Ressources naturelles Canada

Canada

Ressources naturelles Québec

Symposium organizers

Natural Resources Canada – Canadian Forest Service, Laurentian Forestry Centre
Ministère des Ressources naturelles du Québec
Ordre des ingénieurs forestiers du Québec

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Note to Readers

The texts included in these proceedings are printed as submitted and the authors remain responsible for both the form and content of their papers. The texts were not extensively reviewed by peers, nor by CFS-LFC editors.

Message from the Organizing Committee

Welcome to Quebec City and to the Spruce Budworm: Dealing with a New Outbreak Symposium, organized jointly by Natural Resources Canada, the Ministère des Ressources naturelles du Québec and the Ordre des ingénieurs forestiers du Québec. The Symposium program was designed to promote discussions among the participants. Your presence demonstrates very clearly the importance this topic has for you.

The last symposium of this kind was held in Shawinigan in 2001. With a new outbreak that began a few years ago in some of Quebec's regions and that is now beginning to spread across Eastern Canada, there was a need to hold a meeting during which participants could share their knowledge, strategies and research findings.

Nearly 20 guest speakers from the research community, industry and government, mainly from Quebec but also from the rest of Canada, will give presentations on topics centred on five main themes: current situation, forest planning, intervention, mitigation/salvaging activities, and perspectives.

We hope that the presence of these various research scientists and practitioners will lead to constructive and instructive discussions and that all participants will leave with information that is relevant to their work. We also invite you to actively participate in the group discussions and plenary session held at the end of the Symposium in order to share your knowledge and discuss the challenges ahead.

The Committee thanks all those who helped organize this Symposium.

The Organizing Committee

François-Hugues Bernier	Ordre des ingénieurs forestiers du Québec
Cédric Fournier	Ministère des Ressources naturelles du Québec
Francis Gaumond	Ordre des ingénieurs forestiers du Québec Jacques
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Background

The spruce budworm outbreak has been spreading across Quebec for the past few years. This past summer, the pests were very active and the size of the affected areas expanded. The outbreak now extends over 3 million hectares and affects parts of the North Shore, Saguenay–Lac-Saint-Jean, Lower St. Lawrence and Gaspé regions. It is also threatening to spread into New Brunswick and the northeastern United States. To take stock of the situation, the Ministère des Ressources naturelles du Québec (MNRQ), Natural Resources Canada and the Ordre des ingénieurs forestiers du Québec have organized this bilingual Symposium under the theme ***Spruce Budworm: Dealing with the New Outbreak***.

The Symposium is an opportunity to share new knowledge of spruce budworm acquired in the past decade, to present various approaches to managing outbreak-affected forests in Eastern Canada, and to explore what needs to be known about spruce budworm in the future.

Symposium Objectives

- Raise awareness of various approaches to managing outbreak-affected forests in Eastern Canada.
- Share new research and development knowledge with Eastern Canada forest management practitioners from the perspectives of (1) forest protection, (2) adaptation of forest management, and (3) post-outbreak salvaging of dead wood.
- Explore what needs to be known about spruce budworm in the future.

Target Clientele

Eastern Canada forest management practitioners: MRNQ (regions), managers, forest managers, industry and other forest community stakeholders who are concerned about spruce budworm and whose activities involve public or private forests in Quebec, New Brunswick, Newfoundland and Labrador, Nova Scotia or Ontario.

Program

Day 1 – February 19, 2014
(Moderator: Lise Caron)

8:00 a.m. Welcoming of participants

8:30 a.m. Introductory remarks
Jacinthe Leclerc, Director General
Laurentian Forestry Centre (LFC), Natural Resources Canada (NRCan)

Richard Savard, For. Eng.
Assistant Deputy Minister
Ministère des Ressources naturelles du Québec (MRNQ)

Current Situation

8:45 a.m. Current Status of the Outbreak in Quebec
Louis Morneau, For .Eng., M.Sc., Direction de la protection des forêts, MRNQ

9:15 a.m. Northern Expansion of the Spruce Budworm and Boreal Forest Resilience
Louis De Grandpré, Ph.D., LFC, NRCan

9:45 a.m. From There to Here: Assessing the Origin of Spruce Budworm Immigrants
Michel Cusson, Ph.D., LFC, NRCan
Lisa Lumley, Ph.D., Royal Alberta Museum

10:15 a.m. Break

10:45 a.m. Environmental Factors Influencing the Triggering and Initial Expansion of the Current Spruce Budworm Outbreak
Mathieu Bouchard, For. Eng., Ph.D., Direction de la recherche forestière, MRNQ

11:15 a.m. Spatio-temporal Analyses of Spruce Budworm Outbreaks
Hubert Morin, Ph.D., Université du Québec à Chicoutimi

Forest Planning

11:45 a.m. Dealing with a Spruce Budworm Outbreak within an Ecosystem Management Context: How to Adjust Forest Planning?
Marc Leblanc, For. Eng., M.Sc., Direction de l'aménagement et de l'environnement forestiers, MRNQ

12:15 p.m. Lunch

1:30 p.m. Consideration of Spruce Budworm in Timber Supply Analysis: Current Situation and Upcoming Developments
Philippe Marcotte, For. Eng., M.Sc., Bureau des opérations intégrées (Côte-Nord), MRNQ

2:00 p.m. Spruce Budworm: Bugging our Plans!
Jacques Duval, For. Eng., Direction des opérations intégrées (Côte-Nord), MRNQ

2:30 p.m. Integrating Spruce Budworm Ecology and Forest Management Planning Through a Risk Analysis Framework
Vince Nealis, Ph.D., Pacific Forestry Centre, NRCan

3:00 p.m. Break

Intervention

3:30 p.m. Achieving Efficiency in the Direct Protection of Forests by Making Room for Innovation
Jean-Yves Arsenault, For. Eng., Société de protection des forêts contre les insectes et maladies (SOPFIM)

4:00 p.m. The Founding Principles of the Early Intervention Strategy against the Spruce Budworm
Jacques Régnière, Ph.D., LFC, NRCan

4:30 p.m. End of the first day of presentations

5:00 p.m. Cocktail reception

Day 2 – February 20, 2014
(Moderator: Nicolas Juneau)

8:00 a.m. Welcoming of participants

8:30 a.m. Overview of the first day of presentations

Mitigation / Salvaging

8:45 a.m. Challenges Associated with Managing Volumes and Salvage of Wood Affected by the Spruce Budworm
Paul Labbé, For. Eng., M.Sc., Direction de la gestion des stocks ligneux, MRNQ

9:15 a.m. Fibre Quality in a Context of Successive Defoliation by the Spruce Budworm in the North Shore Region
Denis Villeneuve, Resolute Forest Products

9:45 a.m. Resistance of Managed Stands and White Spruce to the Spruce Budworm
Richard Berthiaume, Ph.D., Université Laval

10:15 a.m. Break

10:45 a.m. Impact of Spruce Budworm on Landscapes and Effects of Landscape Structure on Outbreaks
Daniel Kneeshaw, Ph.D., Université du Québec à Montréal

11:15 a.m. Wood Degradation Caused by Bark Beetles and Woodborers Following Spruce Budworm Outbreaks
Christian Hébert, Ph.D., LFC, NRCan

11:45 a.m. Lunch

1:00 p.m. Profitability of Spraying for Spruce Budworm and Market Opportunities for Damaged Wood
Jean-François Côté, For. Eng., M.Sc., Consulstants forestiers DGR Inc.
Jean-Philippe Brunet, For. Eng., M.Sc., Consultants forestiers DGR Inc.

Perspectives

1:30 p.m. Spruce Budworm Management Approach
Paul Lamirande, For. Eng., M. Env., Direction de la protection des forêts, MRNQ

2:00 p.m. Spruce Budworm: After a Century of Observation, Conjecture and Insight, What Can We Predict?
Barry Cooke, Ph.D., Northern Forestry Centre, NRCan

2:30 p.m. Discussion period (Vincent Roy, facilitator)

3:00 p.m. Closing remarks

3:15 p.m. End of Symposium

Guest Speaker Biographies

Jean-Yves Arsenault

Jean-Yves Arsenault, who graduated with a degree in forestry engineering from Université Laval in 1981, has acquired a considerable body of knowledge of the many facets of forestry engineering over the years. Early in his early career, he worked in the co-operative field as a production co-ordinator at the Saint-Elzéar sawmill in the Gaspe region, and later as private woodlot development plan co-ordinator and manager of the SARGIM nursery for the Syndicat des producteurs de bois de la Gaspésie. His career then took him to the pulp and paper industry where, working for the same company, he held various positions, such as timber supply co-ordinator for the New Richmond plant, chief forester for the Bathurst plant, timber supply manager for the New Richmond plant, general manager of the Bathurst Sawmill, manager of forest resources for five Canadian plants and privately owned lands, and member of the Forest Resources Management Office of the North American operations of Smurfit-Stone Container Corporation. In 2010, he launched his consulting firm, whose principal activity is to set up an overseas exporting operation for hardwood chips produced in the Maritime Provinces. In July 2012, Jean-Yves Arsenault became General Manager of the Société de protection des forêts contre les insectes et maladies (SOPFIM).

Richard Berthiaume

Richard Berthiaume graduated with a Bachelor's degree in biology from the Universié du Québec à Rimouski in 1995. In 1998, he completed his Master's degree under the supervision of Conrad Cloutier of Université Laval's Department of Biology and Christian Hébert of the Canadian Forest Service. In 2007, he completed his Ph.D. in the Department of Wood and Forest Science at Université Laval under the supervision of Éric Bauce and Christian Hébert. The focus of his doctoral research work was the evolutionary ecology of hemlock looper populations, a major insect pest in boreal forests. He then did a postdoctoral fellowship, during which he helped set up the Consortium de recherche sur les insectes forestiers (iFor). He is the author of some 20 published scientific articles. In 2007, he became an Associate Professor in Université Laval's Department of Forestry, where he teaches and co-supervises graduate students. In 2007, he was also appointed Co-ordinator of the iFor research consortium.

Mathieu Bouchard

Mathieu Bouchard is a forestry engineer with a Ph.D. in environmental science from the Université du Québec à Montréal (UQAM). Since 2008, he has been working for the Ministère des Ressources naturelles du Québec (MRNQ), where he has held a series of positions in the Forest Management and Environment Directorate and the Forest Protection Directorate. Since 2011, he has been a researcher in the MRNQ's Forest Research Directorate, where his work focuses on ecosystem management, natural disturbances and the impact of forestry practices on biodiversity.

Jean-Philippe Brunet

After graduating with a degree in forest management and environment studies in 2005, Jean-Philippe Brunet completed a Master's degree in forest science and worked for nearly three years as a researcher and co-ordinator of the Programme de recherche sur les entrepreneurs forestiers du Québec (PREFoRT). In 2011, he joined the Consultants forestiers DGR consulting firm, where he worked first as a special advisor for a sawmill company and then as operations representative for a forest management unit in the Portneuf region (management of relations with beneficiaries, transition to the new Forest Regime, supervision of planning and assistance in forestry operations).

In 2012, as part of a local forest project, he designed and developed a tool for budget planning and analysis of the economic impact of the forest sector for the Lac-Saint-Jean Model Forest. He became familiar with the matrices of the inter-sector model of the Institut de la statistique du Québec, which focuses on the socio-economic spinoffs of investments in silviculture, timber harvesting and wood processing. In connection with studies pertaining to areas of increased timber production (AITPs), he carried out two projects based on the economic assessment model of the Bureau de mise en marché des bois (timber marketing board). Since 2013, he has also been overseeing projects requiring use of the FPInterface™ software program.

Barry Cooke

After obtaining a Bachelor’s degree in forestry from the University of Toronto, Barry Cooke continued his studies and obtained a Master’s degree in forest entomology from the same university, followed by a Ph.D. in ecology and evolution from the University of Alberta in 2001. Barry Cooke currently works as research scientist in insect population dynamics at the Northern Forestry Centre of the Canadian Forest Service.

Jean-François Côté

Jean-François Côté has an undergraduate degree in forestry engineering (1985) and a Master’s degree in forest science from Université Laval (1987). He has divided his career between forest ecology research (2 years), consulting engineering with the Consultants forestiers DGR consulting firm in Quebec City (20 years) and working in the industry (6 years) for Norbord Inc. in the Abitibi Region as superintendent of supply in a plywood and oriented strand board (OSB) manufacturing plant.

As a consultant, he is proficient in many areas: timber royalties, operating costs, financial and economic analyses, supply studies, wood processing, forest management, biomass development, carbon, etc. In 2008, 2010 and 2012, he carried out various economic analyses in collaboration with the SOPFIM and the Forest Protection Directorate of the Ministère des Ressources naturelles du Québec (MRNQ).

Jean-François Côté is also co-owner of Chauffage St-Malo, a thermal heat-generating plant in Quebec City that became, in 2014, a showcase for technology used to condition biomass for use as an energy source. He also manages ARDENTE, a company that manufactures decorative items out of showy mountain ash and pin cherry wood.

Michel Cusson

Michel Cusson is a research scientist at the Laurentian Forestry Centre (NRCan–CFS) in Quebec City. He developed an interest in entomology while completing a B.Sc. degree in biology at the University of Sherbrooke, which led him to undertake graduate studies in this discipline, first at Simon Fraser University for his Master's, then at Université Laval for his Ph.D. There, he developed a passion for insect endocrinology, a field he further explored during a postdoctoral fellowship at the University of Toronto. Since taking on his position at Natural Resources Canada in 1991, Michel Cusson has developed a multidisciplinary research program with three principal components: insect biochemistry, host-parasitoid physiological/molecular interactions and insect genomics. He is currently co-leader of the Budworm Genomics Consortium whose principal mandate is to sequence the genome of the spruce budworm and explore ways to use these genomics resources to improve budworm management strategies.

Louis De Grandpré

Louis De Grandpré obtained a Bachelor's degree in biology from the Université du Québec à Montréal (UQAM) in 1985. He also has a Master's degree in biology (1992) and a Ph.D. degree in environmental science (1997), completed under the supervision of Dr. Daniel Gagnon, also from the UQAM. During his graduate studies, he studied the effects of natural disturbances on the dynamics of understorey communities in boreal forests. Since 2000, he has been working at the Canadian Forest Service as a researcher in forest ecology. His research focuses on the long-term effects of disturbances on boreal forest patterns and processes.

Jacques Duval

Jacques Duval was born in the Saguenay region and graduated from Université Laval in 1982. At the start of his career, he worked at various jobs, then joined the Ministère des Ressources naturelles du Québec (MRNQ). Initially, he was responsible for public forest operations, i.e., compliance with the *Forest Act* and timber harvesting standards, as well as for the proper performance of silvicultural work carried out by the management unit's Timber Supply and Forest Management Agreement (TSFMA) recipients. Nowadays, the focus of his work is the planning and compiling of pre-treatment inventories used to draft harvesting requirements. Over the years, he has developed a certain expertise in the drafting of special plans (fire, windthrow, ice storms, spruce budworm) and the development of various retention harvesting methods.

Christian Hébert

After obtaining a Bachelor's degree in biology and a Master's degree in environmental science from the Université du Québec à Trois-Rivières, Dr. Hébert graduated with a Ph.D. degree in biology from Université Laval in 1989. The subject of his thesis was the ecology of spruce budworm parasitoids. In 1990, he joined the Laurentian Forestry Centre (LFC) of the Canadian Forest Service, where he now supervises the Forest Insect Ecology and Diversity Laboratory. With his team, he is carrying out a research program on the ecology and natural control of several species of insect pests and the impact of natural and anthropogenic disturbances on biodiversity by using insects as indicators. The objective of his work is to improve damage forecasting and obtain a better understanding of the causes of insect pest infestations. His biodiversity research focuses on the ecology of insect communities in boreal forests, and he developed a major research program on insects associated with post-fire dead wood. He is a member of the iFor consortium and an associate professor at several universities (Université Laval, Université du Québec à Rimouski and Université du Québec à Chicoutimi) where he co-supervises the work of many graduate students.

Daniel Kneeshaw

Daniel Kneeshaw worked in coniferous forests in Manitoba and British Columbia before studying for a Master's degree in forest ecology and a Ph.D. Following an internship at Université Laval on a Natural Sciences and Engineering Research Council of Canada (NSERC) fellowship, he became a researcher at the Forest Research Directorate of the Ministère des Ressources naturelles du Québec (MRNQ). He is particularly interested in mixed forest ecology and silviculture. Since 2001, Daniel Kneeshaw has been a professor in the Biology Department and a member of the Centre for Forest Research (CEF). The focus of his research work is sustainable forest management, post-disturbance forest dynamics, mixed forest ecology, alternative silvicultural techniques, tree mortality and gap dynamics.

Paul Labbé

After obtaining his Bachelor's degree in forest resource management at Université Laval, Paul Labbé obtained a Master's degree in forest science from the same institution in 1997. The topic of his thesis was the use of forested riparian strips by small mammals in balsam fir stands in boreal forests. Upon completion of his studies, he began his career in the forest industry working for Abitibi-Price, which later became Abitibi Consolidated. He was responsible for various projects associated with the company's operations, particularly allowable cut calculations and the compiling of forest inventories. In 2004, Mr. Labbé joined the Forest Environment Directorate of the Ministère des Ressources naturelles du Québec. His main activities concern biological refuges, specifically the preservation of biological diversity through the maintenance of old-growth forests and their ecological attributes. In 2008, he became an analyst at the Timber Inventory Management Directorate. He is responsible for timber rights and wood allocations to supply North Shore region plants. His responsibilities also include the issue of timber management during spruce budworm outbreaks.

Paul Lamirande

Paul Lamirande is a forestry engineer with a Master's degree in environmental studies from the Université de Sherbrooke. He joined the Ministère des Ressources naturelles du Québec in 1984. Initially, he worked in various research positions, then became a manager in 1993. He has been Director at the Forest Protection Directorate within the Forest Sector since 2006.

Marc Leblanc

Marc Leblanc completed his Bachelor's degree in forest resource management at Université Laval in December 1993, and his Master's degree in forest science at the same university in 1998. From 1998 to 2001, he worked for Cartons St-Laurent (later to become Smurfit-Stone) in La Tuque, where he monitored plantations and developed a 10-year plan for scheduled harvests on private lands. He also helped develop the General Forest Management Plan (GFMP), made allowable cut calculations and, as assistant to the Superintendent, was responsible for supervising silvicultural operations in the field.

In September 2001, he began working for the Ministère des Ressources naturelles du Québec (Forest Sector). He has been very active in the Department's forest protection and development objectives (FPDOs), particularly the FPDO focusing on mature and over-mature forests. He has also developed methods for incorporating some of the FPDOs into allowable cut calculations.

He is currently working on the development and implementation of forest ecosystem management. He was the co-ordinator of a pilot project in the Réserve faunique des Laurentides from 2006 to 2010. He is also collaborating in the Timber Production Strategy.

Lisa Lumley

Lisa Lumley is currently working as a taxonomist for the Royal Alberta Museum in Edmonton. She developed a curiosity for taxonomy and insect pest management while completing her B.Sc. in Agriculture. These interests continued to develop while she worked in the agricultural sector over the next five years, at which point she decided to return to the University of Alberta to amalgamate the two disciplines during her Ph.D., which focused on spruce budworm systematics. In 2010, Lisa moved to Quebec City to work as a Postdoctoral Fellow with the Canadian Forest Service and Université Laval for 3 years, where her research mainly focused on demarcating population boundaries in the spruce budworm and the hemlock looper, and on developing genetics-based methods to study spruce budworm dispersal. Lisa's continued interest in species/population delimitation has led her to the exploration of morphology and morphometrics, life-history and behavioural traits, genetic markers and genomics to attempt to find traits or markers that can be used for identification and to determine how and why species/populations are different. She is particularly fascinated with the study of adaptive traits, and their potential role in linking genetic markers for species identification with genes of biological significance in maintaining species boundaries. Ultimately, her research is intended to contribute new tools to taxonomists and systematists, and to aid in developing species– and population–specific pest management practices. When she isn't working, Lisa loves spending time with her family, is an avid outdoor enthusiast, traveller and gardener, and is a hobby apiarist who is completely enthralled with her bees.

Philippe Marcotte

Philippe Marcotte has been working at the Bureau du forestier en chef (BFEC; Chief Forester's Office) since 2007. He is currently the Technical Co-ordinator for Eastern Quebec allowable cut calculations in the Service du calcul des possibilités forestières de l'Est, which includes the Gaspe, Lower St. Lawrence, North Shore and Quebec City regions. Prior to joining the BFEC team, he worked from 2005 to 2007 as a forest planning analyst in the Gaspé Management Unit of the Ministère des Ressources naturelles du Québec. Mr. Marcotte has a Master's degree in forest hydrology and a Bachelor's degree in forest management and environment studies from Université Laval.

Hubert Morin

After completing his Bachelor's degree in biology, Hubert Morin went on to complete a Master's degree and a Ph.D. degree in plant biology. In parallel with his research projects, he teaches at the Université du Québec à Chicoutimi.

Since the start of his career, Hubert Morin has been interested in natural disturbances in the boreal forest, particularly spruce budworm. His forest ecology research projects are outstanding for their originality, quality and scope. His work on the dynamics of spruce budworm outbreaks and on the growth of balsam fir and black spruce stands in boreal forests have contributed significantly to laying the groundwork for ecosystem management in Quebec.

The study of the dynamics of insect outbreaks is not Professor Morin's sole area of interest. He has also distinguished himself as a world leader in his research on the radial growth of trees in boreal forests, and is now recognized as a pioneer in the study of intra-annual cell growth in trees. Professor Morin and his team were among the first in the world to associate weather variables with wood formation, either continuously (automatic dendrometers) or at the cell level (micro-cores). This new knowledge will give foresters a better understanding of the effects of climate change on the future of our forests.

Louis Morneau

A forestry engineer since 1997, Louis Morneau completed a Master's degree in biology at the University of Alberta in 2002. That same year, he joined the Forest Pest Management Unit of the Forest Protection Directorate of the Ministère des Ressources naturelles du Québec. He has put his expertise in entomology and forestry to good use in the activities of various committees and working groups, in special projects involving indigenous pest detection, monitoring and management, and in tackling problems related to invasive exotic species.

Vince Nealis

Vince Nealis is an insect ecologist with the Canadian Forest Service in Victoria, British Columbia. He has directed research programs on population biology of budworms in eastern and western Canada with a focus on trophic interactions over the duration of outbreaks. Recently, he has been coordinating the development of a risk analysis framework for the National Forest Pest Strategy.

Jacques Régnière

Jacques Régnière is a research scientist at the Canadian Forest Service's Laurentian Forestry Centre (CFL) in Quebec City. He has a degree in biology from Université Laval (1976) and a Ph.D. in entomology with a specialization in ecology and biomathematics from North Carolina State University (1980). He has been a research scientist at the Canadian Forest Service since 1980, and is also an associate professor in Université Laval's Department of Forest and Wood Science and in the Faculty of Forestry at the University of Toronto, where he supervises graduate students. He is a specialist in quantitative ecology and his research focuses on the dynamics of forest insect populations, including spruce budworm, mountain pine beetle and gypsy moth populations, as well as on integrated management, and the seasonality and impact of climate change on these organisms. He is the author of numerous scientific articles.

Denis Villeneuve

Denis Villeneuve completed his studies in forest technology at the Cégep de Sainte-Foy in 1984. He then worked in various jobs as a silvicultural worker. In 1986, he started his own forest management and technical services company. In 1994, he sold his company and joined the Coop forestière Laterrière as a silviculture supervisor. He then became superintendent of planning and moved up in the company, working in various positions. His career subsequently took him to Produits forestiers Saguenay, where he was appointed Director of the Forestry Department, and later to Resolute Forest Products in the North Shore region, where he was appointed Director of Forestry in early 2011.

1. Current Status of the Spruce Budworm Outbreak in Quebec

Louis Morneau
Ministère des Ressources naturelles du Québec
Cédric Fournier
Ministère des Ressources naturelles du Québec

The spruce budworm, *Choristoneura fumiferana*, is an indigenous, outbreak-prone insect that has played a role in shaping Quebec forests since the last ice age, particularly in the balsam fir–white birch and balsam fir–yellow birch bioclimatic domains. It is the main insect defoliator of balsam fir and spruce in North America. The Ministère des Ressources naturelles du Québec (MRNQ) operates a provincial monitoring network to detect and monitor spruce budworm infestations and other insect-related problems and tree diseases. Aerial surveys are also carried out to identify and characterize spruce budworm damage.

For many people, the most recent spruce budworm outbreak, which caused damage from 1967 to 1992, still evokes images of vast forested areas devastated by the insect in a Quebec whose forest profile is fairly vulnerable to the insect because of its broad expanses of mature coniferous stands. While the outbreak ended in the eastern part of the province, there were new outbreaks in the western part of the province in 1992.

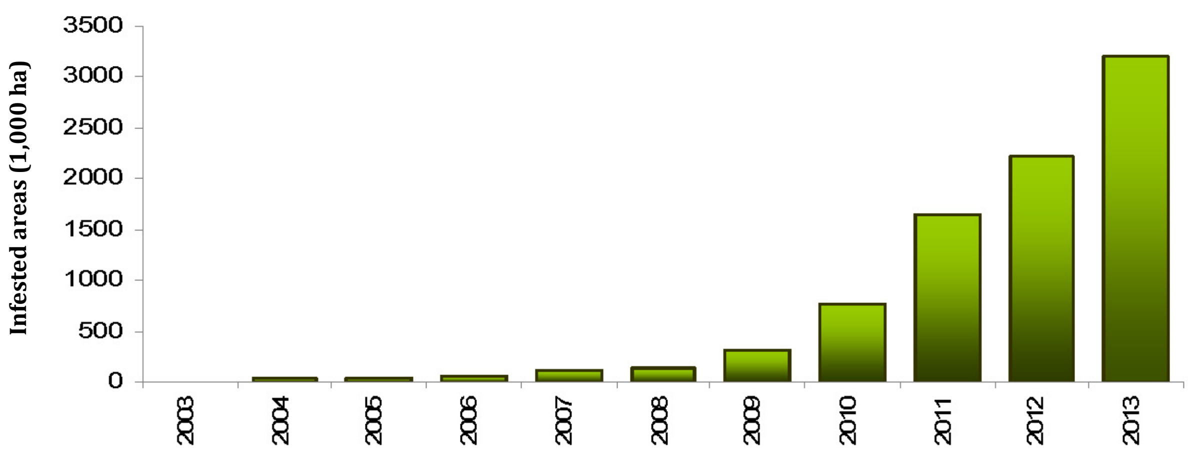

Figure 1 – Changes in spruce budworm-affected areas in Quebec in the past 10 years

Although this outbreak has not spread at the rapid rate of the previous outbreak, it has nonetheless expanded over time, and it has done so at an accelerating pace in the past few years. Since 2006, the affected areas have often doubled in size from year to year (Figure 1). The outbreak covered an area of more than 3.2 million hectares in 2013 (Figure 2).

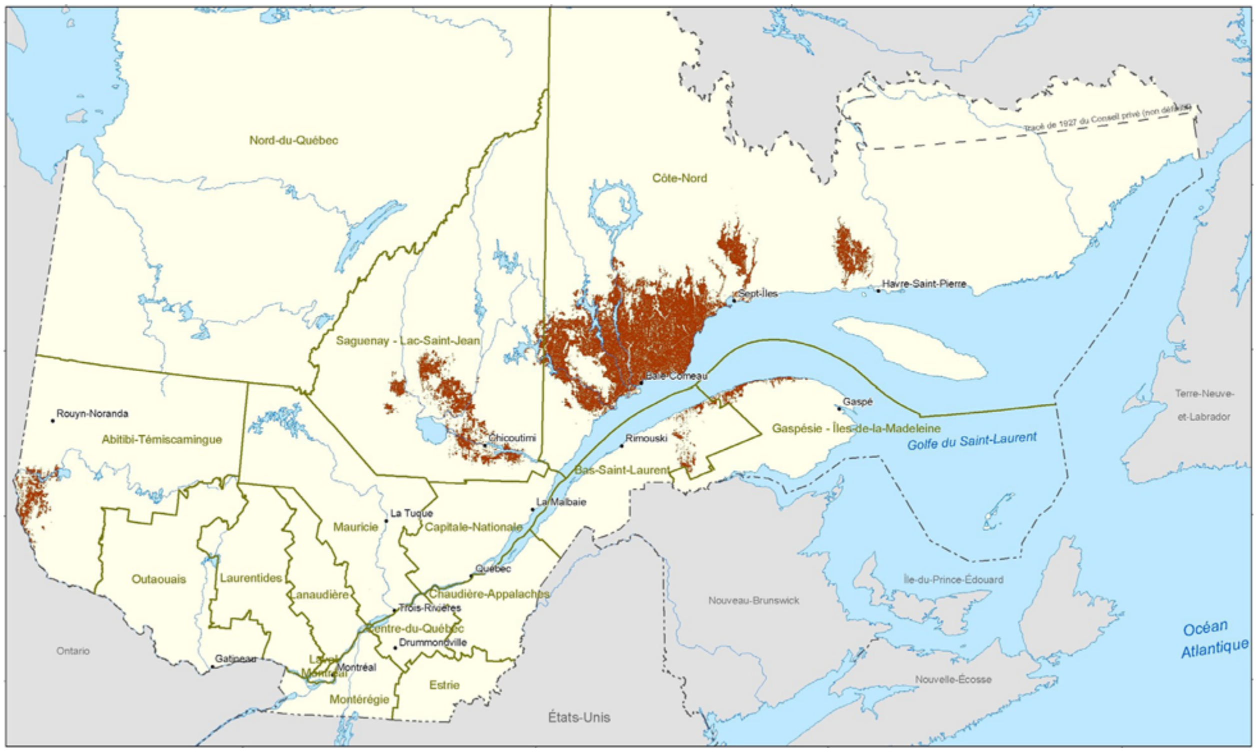

Figure 2 – Defoliation caused by the spruce budworm in Quebec in 2013

The most affected regions are the North Shore with 77% of the total spruce budworm-defoliated area in the province, the Saguenay–Lac-Saint-Jean with 15%, and Abitibi–Témiscamingue with 5%.

In the North Shore Region, the first defoliated areas since 1992 were observed north of Baie-Comeau and west of Port-Cartier in 2006. In the following years, new outbreaks occurred along the coast and on Anticosti Island, and the affected areas expanded. The northward progression of the damage often followed river valleys where the milder microclimate seemed to be favourable to spruce budworm.

It should be noted that through the use of remote sensing (satellite imagery), two major outbreak sites were discovered in 2009 in remote locations in the Moisie and Saint-Jean river basins. The year 2009 was also the first year of implementation on the North Shore of the government's plan to control spruce budworm through aerial spraying of the biological insecticide *Bacillus thuringiensis* var. *kurstaki* (*B.t.k.*). Starting in 2011, the damaged areas began to merge to form a nearly continuous damaged area between Forestville and Sept-Îles (Figure 3).

Defoliation in 2013
- Light
- Moderate
- Severe

Figure 3 – Defoliation caused by the spruce budworm in the North Shore region in 2013

In 1998, spruce budworm began to be active in the Saguenay–Lac-Saint-Jean region, within the boundaries of the City of Saguenay, but it was only in 2006 that the damage, although very widespread, began to extend along the Saguenay River and into the lowlands around Lake Saint-Jean. In 2008 and 2009, the defoliation increased and extended northward into the hills surrounding the lowlands around the lake. Because of the increasing size of the damaged areas, the scale of the government's spruce budworm control plan was expanded to include this region in 2010. In 2013, the defoliated area comprised more than 470,215 hectares of forest (Figure 4).

Defoliation in 2013
- Light
- Moderate
- Severe

Figure 4 – Defoliation caused by the spruce budworm in the Saguenay–Lac-Saint-Jean region in 2013

The damage caused by the spruce budworm in the Abitibi–Témiscamingue region since 2007 is a consequence of the natural expansion of the outbreak, which has been active for several years on the Ontario side of the border, in the North Bay area. The most recent substantial defoliation caused by the spruce budworm in this region dated back to 1985. In 2013, there were 152,483 hectares affected by spruce budworm-caused defoliation (Figure 5).

Defoliation in 2013
- Light
- Moderate
- Severe

Figure 5 – Defoliation caused by the spruce budworm in the Abitibi–Témiscamingue region

Since 2012, damage has been observed in aerial surveys conducted by the MRNQ in the Lower St. Lawrence and Gaspé–Magdalen Islands regions, 20 years since the end of the last outbreak. Although these areas amount to less than 4% of the provincial total, they expanded in size significantly in a single year. Starting in 2010, the forecast inventories showed an increase in spruce budworm populations in these two regions. In 2011, local damage was observed in ground surveys, and the inventories of spruce budworm larvae in hibernation (L2) indicated a high probability of damage in 2012, which was the case in a 12,474-hectare area along the coast and in the Matapedia River valley. In 2013, the affected areas had clearly expanded to a total of 117,580 hectares (Figure 6).

Figure 6 – Defoliation caused by the spruce budworm in the Lower St. Lawrence and Gaspé–Magdalen Islands regions

In the Mauricie region, defoliation was observed in an area comprising only 25 hectares in 2013, whereas it was slightly more extensive a few years earlier (2,769 hectares in 2010). Spruce budworm-related damage in the Outaouais region reached a peak of 46,121 defoliated hectares in 2006 before decreasing and disappearing in 2012. The damage was concentrated mainly in an area of private forests south of the Outaouais Region and bordered by Fort-Coulonge, Maniwaki and Buckingham.

There was no damage reported elsewhere in Quebec in 2013. In some regions of the province, the most recent spruce budworm-caused damage occurred a few years ago (Laurentians in 2011, Central Quebec in 2009, Eastern Townships in 2004) or, in other regions, at the time of the last outbreak (Lanaudière in 1988, Quebec City region in 1987, Chaudière–Appalaches in 1986, Montérégie in 1985, Northern Quebec in 1982). In several cases, for example near Drummondville (Central Quebec) and Compton (Eastern Townships), the outbreaks occurred in blocks of old-growth white spruce and persisted locally.

Since 2011, inventories have been developed and compiled in order to assess the mortality risks of stands affected by accumulated damage over several years and to monitor mortality in the most severely affected sectors, i.e., in sectors where defoliation has occurred in the past several years. Until now, only a low tree mortality rate has been observed in the most affected sectors. Managed stands have also been monitored (e.g., thinned stands) to assess the impact of the outbreak on stands.

The forecast inventories compiled in the fall make it possible to predict the changing trends of populations and the damage that may occur in the following year. The results indicate that the outbreak will continue to spread. Defoliation will be even more significant in infested areas in 2013. Spruce budworm populations are very large on the periphery of some affected sectors in the North Shore, Saguenay–Lac-Saint-Jean, Lower St. Lawrence and Gaspé–Magdalen Islands regions.

There is consequently a risk that the defoliated areas will expand in these regions in 2014.

Notes

2. Northern Expansion of the Spruce Budworm and Boreal Forest Resilience

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Climate has a significant influence on spruce budworm (SBW) dispersal. Unlike the insect's hosts, which are sessile organisms, spruce budworms produce one generation per year and can disperse over very great distances. This gives them the potential to respond quickly to climate change. Temperature plays a key role in this insect's spatial distribution by controlling the southern and northern boundaries of their range. To the south of their range, late summer and fall temperatures control overwintering survival at young larval stages. Thus, during an overly warm fall, the young larvae (L2), which do not feed during this period, delay their diapause and use up their reserves. To the north of their range, temperatures during the growing season limit the insect's northward expansion. Overly cool spring and summer temperatures result in the insect's inability to complete its life cycle.

Considerable variability in space and time has been observed in the severity of spruce budworm outbreaks. A study by Simard et al. (2006) demonstrates that the insect's presence during a time sequence of more than 6,000 years in the same location varied considerably over time. This observation confirms the impact of past climate change on the insect's dispersal and abundance. In addition, dendrochronological studies reconstructing outbreaks over the last 200 years show a northward movement of the insect, probably associated with the end of the Little Ice Age around 1850. The forecasts of models linked to the recent warming of temperatures and to the warming predicted for the current century show that the insect should continue its northward movement and end up in the black spruce bioclimatic domain (Régnière et al. 2012). The current defoliation patterns seem to corroborate these forecasts because the sites where the outbreak has spread are much farther north than those of previous outbreaks in 20th century. In these sectors, black spruce is a major component of forest composition.

Until now, the black spruce domain has been little affected by the spruce budworm for two main reasons. First, the more northern range of black spruce, compared with that of balsam fir, is characterized by cool summers that are short enough to often prevent the insect from completing its life cycle. Second, the budbreak of black spruce is nearly 2 weeks later than that of balsam fir, causing a high rate of mortality in spruce budworm larvae (L2) that emerge in the spring and attempt to feed on this host species (Blais 1957; Nealis and Régnière 2004). However, despite this lack of synchronicity, black spruce is still a good host for the spruce budworm in terms of nutrients, oviposition and diapause (Nealis and Régnière 2004). With climate change, the risk of severe defoliation of black spruce may increase significantly, particularly if a warmer climate promotes the emergence of a better phenological synchronicity between the two species and warmer summers allow the insect to complete its life cycle. The long-term impact of a northward shift of the insect's range on the structure and functions of the boreal ecosystem will certainly be different from that of previous episodes and is still unknown.

In collaboration with a multi-disciplinary research team, we are assessing the impact of an expanding SBW outbreak in the boreal forest of Quebec's North Shore region on several ecological processes, including forest productivity, regeneration, growth and tree mortality, based on various forest conditions. Using these same conditions as a basis, we are also assessing how the dynamics of insect populations and tree defoliation change over time. There is little documentation on the impact of SBW in regions where black spruce is a major component of forest composition, although we know that they cause reduced growth as well as mortality (Pham et al. 2004; Tremblay et al. 2012). In the context of climate change and a probable northward shift of the insect's range, it is important to document the impact of SBW on black spruce in order to understand how this ecosystem could be affected during future SBW outbreaks and provide better direction for forestry activities so as to limit the negative impact on productivity.

The impact of the outbreak was monitored in sectors north of Baie-Comeau, some of which have experienced defoliation since 2006. We established a permanent plot design of 4,000 m², within which all of the trees are measured and mapped. Samples are collected across a compositional gradient of coniferous stands ranging from pure balsam fir to pure black spruce. In these stands, we monitor tree defoliation annually (Fettes method) as well as spruce budworm population dynamics. Each tree is also monitored annually to assess its condition (defoliation/mortality class). The impact of defoliation on fertility is also measured using exchangeable resins. We also monitor the demographics of balsam fir and black spruce regeneration as well as understorey communities in order to understand the mechanisms associated with the regeneration process and how some vascular plants interact with it. We also set up experiments to verify how the phenological synchronicity between the spruce budworm and its hosts is influenced by microclimate variations, the objective being to verify whether or not this synchronicity could be modified as a result of the effects of climate change.

Since the summer of 2013, we have also been conducting a project involving salvage cutting in spruce budworm-affected stands. The overall objective of the project is to establish the scientific basis for developing guidelines for post-SBW outbreak salvage cutting. In parallel with this project, we are also planning to set up an experimental plot for monitoring the impact of some post-SBW outbreak salvage cutting methods (e.g., biological legacies, standing dead wood retention in salvage areas) on the restoration stand productivity and the maintenance of key ecological processes. These projects are only in their initial stages and we will not provide any results during this presentation. However, they are a logical continuation of what we have undertaken in the past few years.

Results and Discussion

Defoliation of stands since 2006

The estimates of site defoliation show a progression of defoliation that varies by stand type (Figure 1). However, we find that regardless of the composition, all stand types sustain defoliation. The greater the balsam fir component in stands, the more rapid the increase in defoliation over time, reaching defoliation rates above 70% in 2012. Pure black spruce stands have shown continual progression since 2006 to reach the current defoliation rate of more than 50%. Although these rates are lower than what has been observed in stands in which balsam fir is present, an increase in the severity of outbreaks in the black spruce domain could have a considerable impact on this ecosystem. In some balsam fir stands, the rate of defoliation in 2013 reached 100%, and we may see local decreases in SBW populations in 2014. However, because black spruce stands are currently less defoliated, this may be conducive to keeping the insect in the forest landscape for a longer time period and thus facilitate a renewed outbreak in balsam fir stands where the populations decreased.

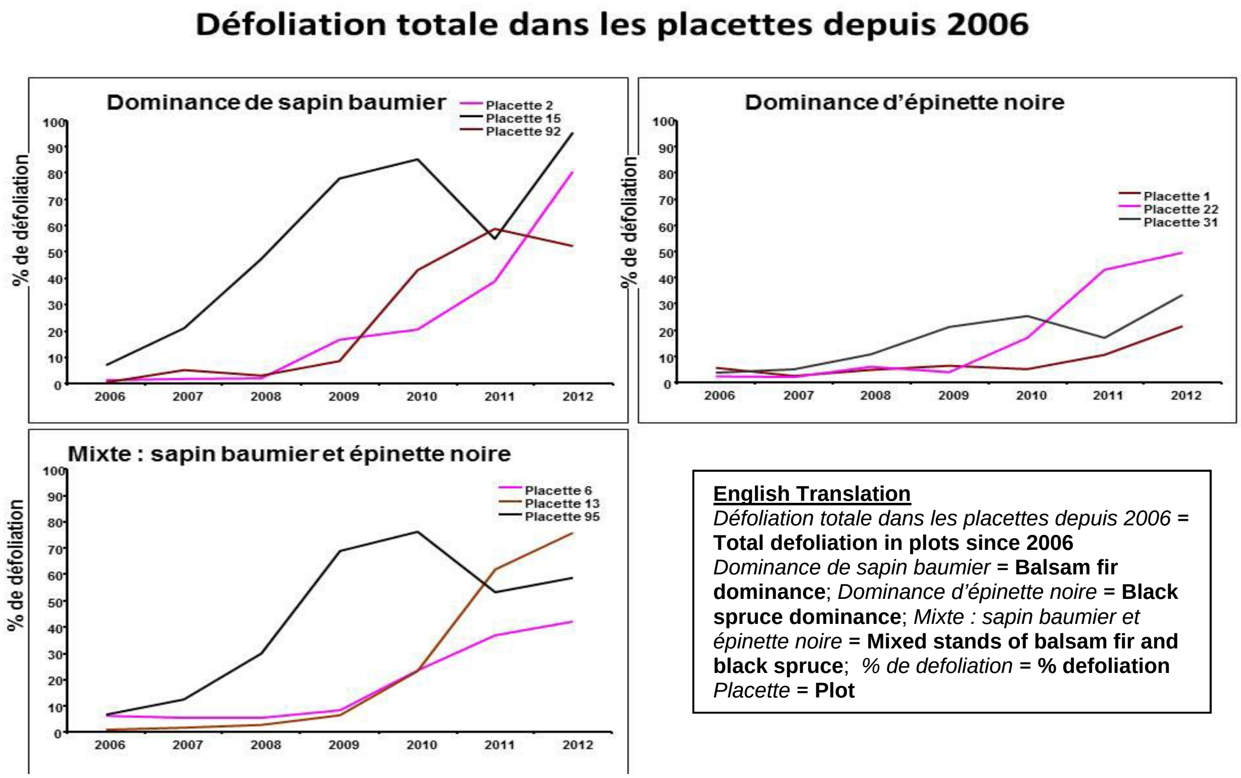

Figure 1 – Progression of annual of defoliation by stand type

Our findings also show that the presence of spruce does not provide balsam fir with any protection against defoliation. Balsam fir trees are defoliated just as much whether they are in pure stands or well isolated in stands dominated by black spruce. However, we noted that black spruce trees in pure stands are less susceptible to defoliation during some years. This may be attributable to the fact that SBW populations fluctuate more quickly on sites where balsam fir trees are more abundant, whereas they increase in size at a more continuous rate in pure black spruce stands.

Population dynamics

There is greater emergence of adults (2012) in stands where balsam fir is dominant, but we nonetheless noted annual increases in insect numbers in black spruce stands. Overall, the emergence of adults follows defoliation patterns, where we note a slower progression in black spruce stands. The insect's performance (pupa weight) is more related to recent defoliation history than to the species. However, we noted better performance of females on balsam fir trees in mixed stands of balsam fir and spruce.

Site fertility

Defoliation is reflected in the soil where we observed annual increases in measured concentrations of ammonium and nitrate. We are also seeing a stand effect with balsam fir stands having more abundant nitrogen components than mixed stands and black spruce stands. Balsam fir stands demonstrate a good ability to maintain these elements in the system, compared with black spruce stands where we notice greater losses through leaching of these elements. Given that black spruce stands are already lacking in nutrients, these losses may result in decreased productivity. Longer-term monitoring is required in order to properly document inter-annual variability in measured concentrations and thus to identify actual trends in the fertility of these stands within an SBW outbreak context.

Phenology

Our findings relative to budbreak in the two species indicate a time lag of about 10 to 15 days between the budbreak of balsam fir and that of black spruce. For both species, we also observed that budbreak extended over a longer period of time during cooler springs. In addition, a higher heat accumulation rate shortened the budbreak period of both species. We noticed in regard to phenological synchronicity that the emergence of larvae and the budbreak period of both balsam fir and black spruce are closer together when temperatures are higher.

Conclusion

Although historically, SBW infestations have previously occurred in the black spruce domain, the amount of defoliation and tree mortality were minor. Potential increases in the severity of outbreaks and in tree mortality raise concerns about the future condition of this northern ecosystem, given that a new outbreak is in its development stage much further north than the outbreak that began in the mid-1960s. Severe SBW outbreaks in the black spruce domain could reduce the productivity of stands compared with outbreaks in the balsam fir domain, where the forests are more diversified and better adapted to recurring outbreaks. Moreover, depending on the proportions of balsam fir and hardwood species in the stands, changes in regeneration patterns and the cycling of nutrients could alter the dynamics of the ecosystem and cause black spruce to be replaced by a more productive mixed forest or by a less productive open forest dominated by ericaceous species (Figure 2).

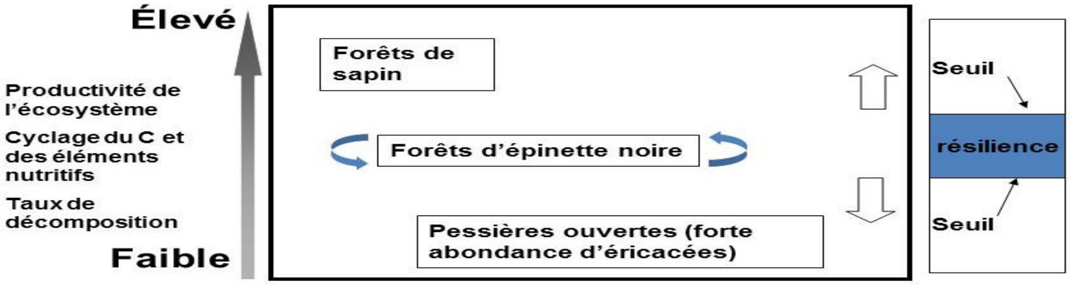

Figure 2 – Potential consequences of more severe SBW outbreaks for black spruce ecosystems

<u>**English translation**</u>: *Élevé* = **High**; *Faible* = **Low**; *Productivité de l'écosystème* = **Ecosystem productivity**; *Cyclage du C et des éléments nutritifs* = **Carbon and nutrient cycling**; *Taux de decomposition* = **Decomposition rate**; *Forêts de sapin* = **Balsam fir forests**; *Forêts d'épinette* noire = **Black spruce forests**; Pessièr*es ouvertes (forte abundance d'éricacées)* = **Open black spruce stands (great abundance of ericaceous species**; *Seuil* = **threshold**; *résilience* = **resilience**

Notes

3. From There to Here: Assessing the Origin of Spruce Budworm Immigrants

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The role of spruce budworm (SBW) moth dispersal in the development and spread of outbreaks has been the subject of speculation and debate for many years. Indeed, although the occurrence of SBW migratory flights is well documented (e.g., Greenbank 1957; Greenbank et al. 1980; Hensen 1951; Miller et al. 1978), the impact of such movement on the insect's population dynamics has been difficult to assess, in part because dispersal processes are difficult to quantify precisely (Sturtevant et al. 2013).

Two existing theories about SBW population dynamics give moth dispersal strikingly different roles in outbreak initiation and spread. According to Clark's "double equilibrium theory" (Clark et al. 1979), moth migration from high density stands is a key factor in the initiation of outbreaks in fir and spruce forests where SBW populations had, until then, been low. However, according to Royama's "oscillatory theory" (Royama 1984), outbreaks are not triggered by moth dispersal, but result from cyclical changes in mortality factors such as predation, parasitism and diseases, with migratory movement playing a secondary role in population fluctuations (Royama et al. 2005). Régnière's group (Béchard et al. 2014) pointed out that these two theories were developed from data collected only during the high density and decline phases of the SBW outbreak cycle, rendering them speculative with respect to what actually happens during the period when populations transition from the endemic to the outbreak phase. Work is currently underway in the Lower St. Lawrence area of Quebec, where SBW populations have been rising for the past several years, and long-term annual surveys of endemic populations provide new insights into the factors that could trigger outbreaks. Not only is there no evidence for the gradual release of endemic populations from mortality caused by natural enemies (Béchard et al. 2014), but mating success displays a strong density dependence, with population levels failing to rise as a result of both mortality inflicted by natural enemies and poor mating success, thus keeping populations under the so-called "Allee threshold" (Régnière et al. 2012). Under such conditions, immigration is presumed to be the factor that allows these populations to cross the Allee threshold and begin rising to outbreak levels (Béchard et al. 2014).

Suppression of influxes of migratory moths into low-density populations could thus become a legitimate component of a SBW management "early intervention strategy", where actions are taken to prevent or slow the rise of populations to outbreak levels over a given territory. However, effective application of such a strategy would require that the sources of potential moth invasions be identified. The question that arises then is: how far from the borders of the territory we want to protect do we need to be concerned about potential dispersers, and from what direction?

Migratory events involving small insects such as SBW moths are difficult to track and quantify. Nonetheless, the early work of Greenbank et al. (1980) provided some invaluable information about basic SBW dispersal parameters using various monitoring tools such as ground-based and airborne radars, nightviewing telescopes, observation platforms (above the canopy), aircraft insect-collection nets, light traps and meteorological towers (Greenbank et al. 1980). This work pointed to the important role of winds associated with cold fronts and storm cells in carrying moths over relatively long distances after they have actively "climbed" over the canopy in early evening and indicated that the majority of dispersing moths were mated females that still had about half of their egg complement (see also Rhainds and Kattela 2013). The distance travelled by such dispersing moths appears to vary widely and could be as little as a few kilometres to as much as 450 km (Dobesberger et al. 1983). Given the observation that migrants will sometimes undertake a second dispersal flight on a separate evening (Greenbank et al. 1980), the total theoretical distance travelled by migrants could be close to 1000 km.

With the movement of individuals across a landscape there is also the movement of genes, which means that the use of population genetics methods for measuring dispersal have been studied extensively (Broquet and Petit 2009). These techniques can help us to measure both "effective dispersal", which is of particular interest in terms of pest management as it refers only to those migrants that reproduce in the population where they have settled, as well as "non-effective dispersal", which refers to all dispersers irrespective of their reproductive capacity (Broquet and Petit 2009). In an effort to identify the origin of SBW immigrants in experimental plots in Quebec, we recently undertook the study of this insect's genetic structure over its entire geographic range (Alaska to Newfoundland to West Virginia). The intent of this work is to study changes in gene flow over time, which can help us to better understand the extent to which SBW undergo effective dispersal, to use analytical measures such as assignment tests to directly determine the origin of immigrants, and to select genetic markers that are specific to regional populations. Although it is possible that these markers will be ineffective in terms of providing useful information for immigrants having travelled over relatively small distances, they may prove informative for those coming from afar. Thus, our objective is to measure the level of geographic resolution afforded by the markers we develop.

To lay the foundations of this work, in 2012, we collaborated with provincial and USDA (U.S. Department of Agriculture) forest entomologists to obtain larvae and adults collected in the same localities, or to solely collect adults in regions where larval collections were not feasible. We aimed to collect approximately every 200 km across the spruce budworm range. The larvae are assumed to be locally produced or "residents" due to their limited abilities to disperse, whereas the adults are of unknown origin in that they may be residents or immigrants due to their long-range dispersal capabilities. The collection of both life stages allows us to compare the population genetic structure of larval and adult populations to determine if there are differences that may be due to dispersal, and the larval populations can further be used as the basis for determining the origin of adults using assignment tests.

To further these studies, it was necessary to first develop genetic markers. We used a marker discovery and genotyping system called "genotyping-by-sequencing" (GBS) to develop a suite of single-nucleotide polymer-phisms (SNPs), a marker type that has not been previously developed for the spruce budworm but has proved useful for population genetics analysis in other systems. All genomic DNA extractions, quality testing, and concentration normalizations were completed at the Canadian Forest Service, and then we collaborated with Université Laval (remaining preparations of the genomic DNA for sequencing) and McGill University (Illumina sequencing) to complete the process required to obtain the GBS raw data. We analyzed these data using the UNEAK pipeline in TASSEL 3.0 (Bradbury et al. 2007) to discover SNPs with a minimum 20X read depth per individual, and then both the SNP loci and taxa were filtered using TASSEL to produce a set of SNPs in which each locus was genotyped for at least 90% of individuals, and each individual was genotyped for at least 80% of the SNPs. The final result is a dataset that includes 1639 individuals genotyped for 1028 SNP loci, collected from 81 localities. Of these, 23 localities are represented by both larval and adult collections, located in Quebec, Manitoba, Saskatchewan and Alberta.

Preliminary analysis with discriminant analysis of principal components (DAPC) (Jombart 2008) indicates that there is population differentiation across the SBW range, and we are currently completing additional analyses to determine if it is possible to differentiate populations at a finer spatial scale (provincial, regional).

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N.B.: Lisa Lumley's studies were carried out while she was still working at the Laurentian Forestry Centre.

Notes

4. Environmental Factors Influencing the Triggering and Initial Expansion of the Current Spruce Budworm Outbreak

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From a forest management perspective, it is important to know whether or not the development of spruce budworm (SBW) outbreaks is influenced by forest composition and structure. In the short term, the existence of a relationship with these factors may give us a better understanding of the development of the current outbreak across the province. In the longer term, the existence of such a relationship may help us to mitigate the impact of future outbreaks by implementing forest management measures that modify forest structure and composition.

However, it is difficult to answer these questions directly. Spruce budworm outbreaks spread across vast, extremely heterogeneous areas, and the direct relationships between population dynamics and specific environmental factors are difficult to determine. Over the years and in the studies that have been carried out, several factors have been identified to explain the insect's dynamics, including climate, the activities of natural enemies and forest characteristics, but these results sometimes appear to be contradictory from one study to the next because of either regional disparities or the fact that the variables used were not measured in the same way, or because of a different analytic approach. Some divergences may also be explained by the use of different analytical scales because the effects of outbreaks can be analysed at the local scale (demographics), or at the stand, landscape or even at the province level, and results may vary from one scale to the next. For example, some studies have shown that at a province-wide scale, mixed forests were more affected than coniferous forests (Hardy et al. 1983), while at the stand and landscape levels, the opposite was observed (Bergeron et al. 1995).

Another important factor is attributable to the fact that the insect's dynamics can vary, depending on the advancement stage of the outbreak: some environmental factors may be more important when the populations are sparse (for example, at the very start of the outbreak) compared with later stages, when the populations have greater densities and when mechanisms regulating populations, such as competition for food or the activities of natural enemies, start to have a greater impact. It is therefore worthwhile to separate the development of outbreaks into distinct phases and to look at the impact of environmental factors during these various phases separately.

In this study, we have looked at the development of the current outbreak on a province-wide scale, using defoliation surveys conducted by the Ministère des Ressources naturelles du Québec (MRNQ) during the 2002–2011 period (see Bouchard and Auger [2014] for more details on the study). The main objective was to examine the main environmental factors, such as climate and forest characteristics (forest composition and age), that influence the development of the current outbreak. The analysis was carried out province-wide in order to identify factors that can be incorporated into recommendations that apply across the province because their influence is not apparent only at the local level. The development of the outbreak was separated into distinct phases in order to verify whether or not the influence of the factors varies in time and space. The area affected by the outbreak during the 2003–2011 period was subdivided into cells measuring 15 x 15km and the defoliation in each cell was quantified for each year (Figure 1). The influence of environmental factors during the following three phases of the development of the outbreak was examined: initial locations of defoliation sites, inter-annual progression within the cells (on a landscape scale) and inter-annual progression from one cell to another (on a regional scale). The environmental factors whose influence was examined were climate (degree days > 5°C), forest composition (abundance of stands dominated by balsam fir, black spruce or other species), altitude, drainage, and age of stands (Figure 2).

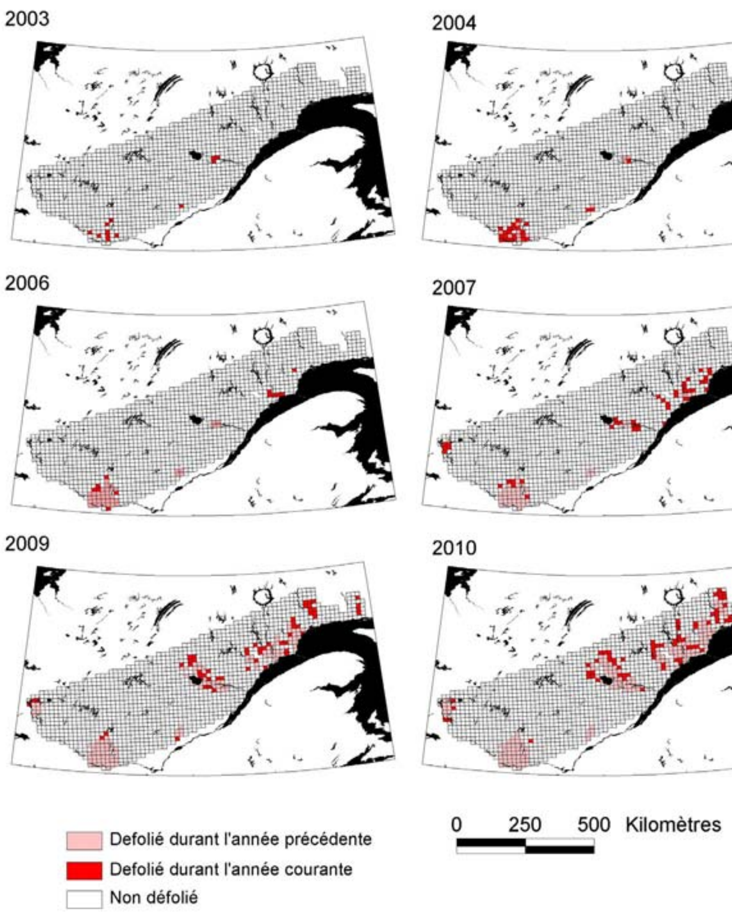
The results indicate that the influence of the factors varies according to the outbreak development phase. The location of the epicentres was influenced mainly by altitude because they were usually located in low-altitude cells. The outbreak's progression from these sites during both the intra- and inter-cell phases was influenced primarily by forest composition and climate: the progression was slower in the south part of the gradient, where the climate was comparatively warmer and where there were fewer stands of susceptible species (balsam fir) (Figure 3).

The relationships observed are not always easy to explain. The pronounced effect of altitude on the initial location of epicentres is probably associated with factors that are not included in the statistical models. The sole climate variable included in the statistical models is the degree days variable. It is possible that other climate or weather factors related to the altitudinal gradient are conducive to the emergence of epicentres; it is a question that could be the subject of future research. As for the negative effect of warmer temperatures on the spread of defoliation from the epicentres, there appears to be supporting evidence in the literature: warmer temperatures observed in the southern part of the province (Outaouais and Mauricie regions) were not very conducive to the insect's development, compared with the more northern parts of the province (North Shore region) (Régnière et al. 2012). This effect has also become more pronounced in recent years because of climate change (Régnière et al. 2012).

Furthermore, the negative effect of deciduous species and the positive effect of balsam fir on the progression of defoliation have been observed for a long time, and may be related to the increased presence of natural enemies in deciduous stands (Quayle et al. 2003), or to the fact that the larvae have greater difficulty in dispersing among the host trees (Nealis and Régnière 2004). An increase in the quantity of deciduous trees in the western part of the area in the past 30 to 40 years (Bouchard and Auger 2014) may also partially explain why the expansion of the current outbreak is less spectacular than what was observed during the previous outbreak (1970–1984).

What are the implications of these findings for our forest management practices? The predominant influence of an abiotic factor (altitude) on the locations of epicentres suggests that our capacity to control the emergence of these sites through silvicultural and forest management practices is limited. As for the outbreak's expansion, our results suggest that composition modification (for example, by reducing balsam fir content) may curb the spread of outbreaks. Nevertheless, this interpretation should be considered very prudently for three main reasons. First, because the predictive ability of the statistical models is still fairly low and the composition effect interacts with the climate effect (Bouchard and Auger 2014); it is therefore impossible to guarantee that changing the composition will have an effect on the course of future outbreaks. Second, the area concerned is immense and making significant changes to forest composition over such a huge area would involve a considerable amount of silvicultural work. Third, reducing the coniferous component and increasing the deciduous component may have a negative impact on the wood processing information and on the objectives of maintaining biodiversity: two aspects that must be taken into account in an integrated forest management context.

To sum up, this work made it possible to (1) propose a new "phase-based" approach for studying the progression of outbreaks in the areas concerned, and (2) suggest potential areas of research in order to identify the mechanisms responsible for the patterns observed. More concretely, it suggests that our capacity to influence the course of an outbreak through the use of short- or long-term forest management strategies continues to be limited, and that forest management strategies should probably start by focusing more on limiting damage by implementing salvaging strategies that reconcile economic and ecological issues. However, it is important to point out that these conclusions are still preliminary ones until such time as the outbreak is over and the actual damage caused by defoliation is known. Ultimately, the recommendations in terms of forest management must be based more on the damage sustained in stands (tree mortality, reduced growth) than on defoliation.



English translation
Défolié durant l'année précédente = **Defoliated during the previous year**
Défolié durant l'année courante = **Defoliated during the current year**
Non défolié = **No defoliation**; *Kilomètres* = **Kilometres**

Figure 1 – Locations of defoliation sites in each cell (15 x 15 km) of the study area during the 2003–2011 period.

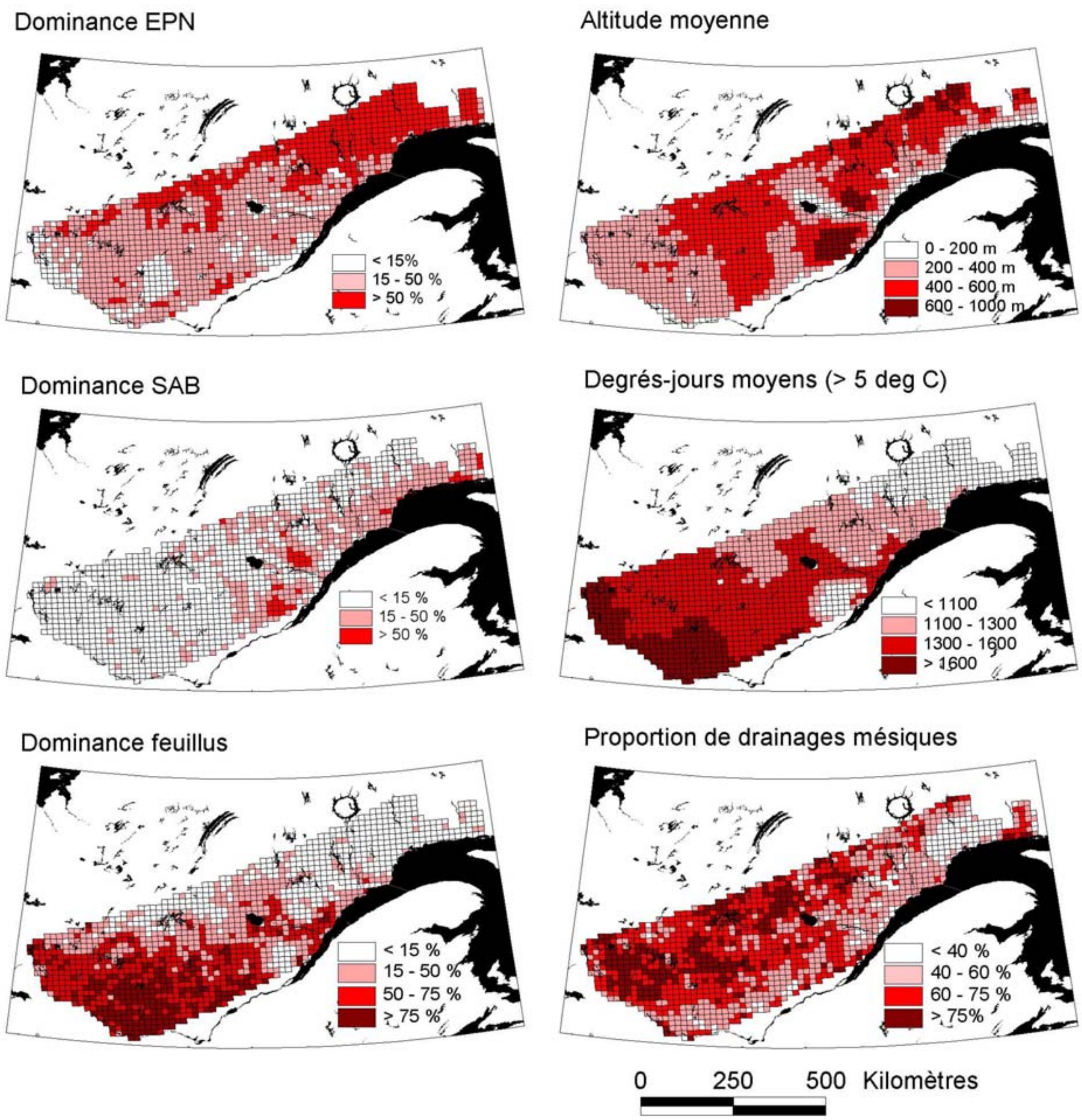


Figure 2 – Spatial distribution of environmental variables within the study area.

English translation
Dominance EPN = **Black spruce dominance**; *Altitude moyenne* = **Average altitude**
Dominance SAB = **Balsam fir dominance**; *Degrés-jours moyens (> 5 deg C)* = **Average degree days (>5°C)**
Dominance feuillus = **Deciduous dominance**; *Proportion de drainages mésiques* = **Mesic drainage percentage**; *Kilomètres* = **Kilometres**

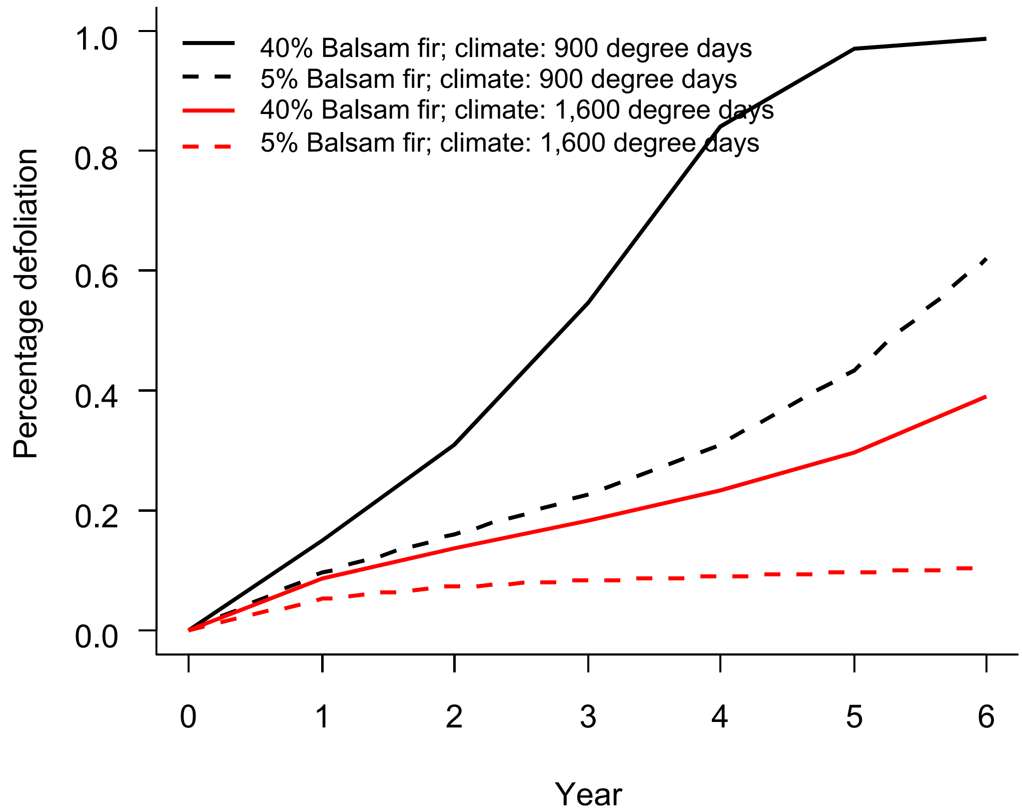


Figure 3 – Forecast of host species stands sustaining defoliation within a 15 x 15 km cell as a function of time (Year 0 corresponds to one year prior to the first defoliation observed in the cell. The model's forecasts vary according to the percentage of the cell dominated by balsam fir and the sum of degree days >5°C).

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Notes

5. Spatio-temporal Analyses of Spruce Budworm Outbreaks

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Insects are highly climate-sensitive. The spatial and temporal dynamics of insects, such as spruce budworms (SBW), whose populations reach outbreak levels and have a major impact on forest dynamics, are affected by climate change. The impacts of climate warming have already been observed in numerous insects whose populations reach outbreak levels. For example, in the Alps, the cycle of *Zeiraphera diniana Gn.*, which had been very regular for centuries, has been interrupted in recent decades (Esper et al. 2007; Büntgen et al. 2009). In Western Canada, mountain pine beetle outbreaks, previously limited to a few valleys in the Rocky Mountains, have affected an area of unprecedented size because of a favourable climate. Thus, the emergence of favourable climate conditions in the northern margins of the ranges of these insects may promote the occurrence of outbreaks where such outbreaks were rare or non-existent in the past.

During their larval stages, spruce budworms defoliate conifers. Their main hosts are balsam fir and white spruce trees, but they also affect black and red spruce trees. Their range is primarily in the southern part of the boreal forest, in the balsam fir–white birch domain, but it can extend up to the 54th parallel, into the black spruce–moss domain (Levasseur 2000).

Dendrochronological studies are particularly useful for monitoring the spatial and temporal dynamics of spruce budworms. These analyses allow us to go back in time and to several locations to monitor the development of outbreaks, which are traceable on the growth curves of the insects' host trees owing to reductions in characteristic growth. By conducting dendrochronological analyses of spruce beams (probably white or red spruce) from old buildings in southern Quebec, particularly old churches, it was possible to construct one of the longest chronologies of this insect's outbreaks (Boulanger et al. 2013) (Figure 1). The use of old churches is particularly relevant since they were often built quickly in the early stages of colonization of an area, and it can therefore be assumed that the beams used in their construction came from nearby natural forests that represent the natural dynamics of those forests. An analysis of this chronology revealed a remarkable regularity in the recurrence of outbreaks in the southern part of the insects' range. However, chronologies from the boreal forest zone always show an increase in regularity, impact and synchronicity across vast areas of the boreal forest, including the southern part of the black spruce–moss domain, during the 20th century (Figure 2). A similar pattern is seen in subfossil trees that came from the boreal forest zone and were found buried in peat bogs. The 20th-century outbreaks are easily identifiable, but it is sometimes necessary to go back several millennia before finding signs equivalent to outbreaks in the past (Simard et al. 2011; Lapointe 2013).

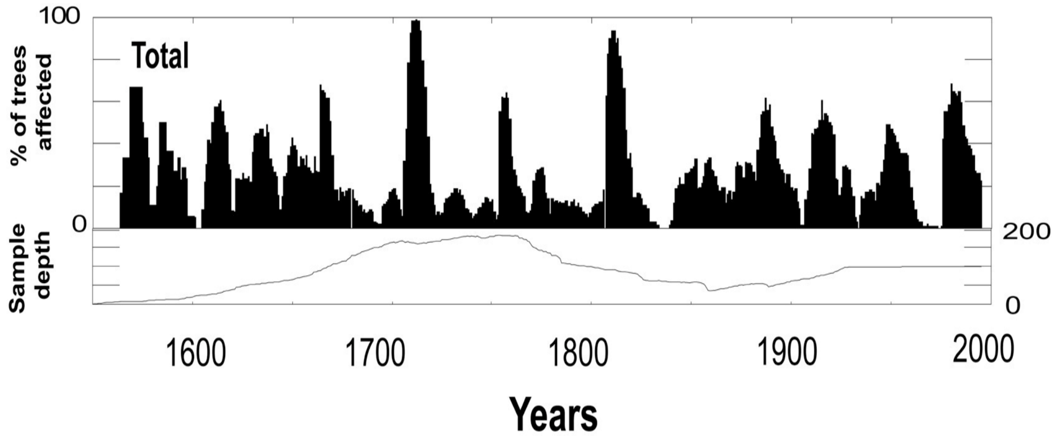

Figure 1 – Percentage of trees (probably white spruce) whose wood in samples collected in old churches show a significant reduction in growth caused by spruce budworm.

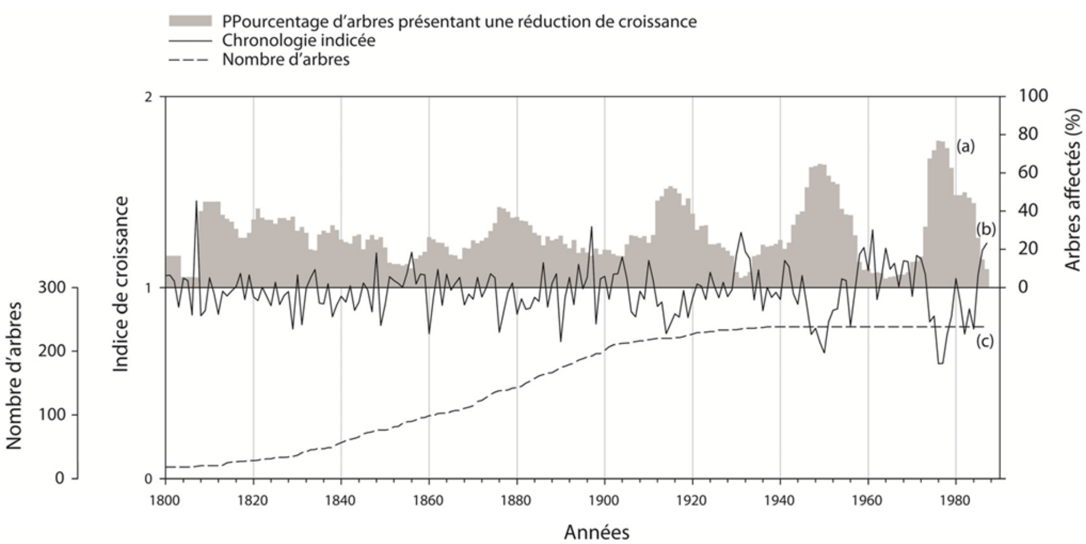

Figure 2 – Percentage of living trees (white spruce) affected by spruce budworm in the boreal forest zone: (a) percentage of white spruce showing a significant reduction in growth (standard deviation of -1.28 for a minimum of 5 years); (b) indexed chronology of white spruce; and (c) number of trees.

<u>English Translation</u>: *Pourcentage d'arbres présentant une réduction de croissance* = **Percentage of trees showing reduced growth**; *Chronologie indicée* = **Indexed chronology**; *Nombre d'arbres* = **Number of trees**; *Indice de croissance* = **Growth index**; *Années* = **Years**; *Arbres affectées (%)* = **Affected trees (%)**

Several hypotheses have been put forward to explain this increase in the impact of outbreaks during the 20th century: (1) an increase in the percentage of balsam fir, the principal host of spruce budworm, because of logging systems; (2) control of fires that could preserve more susceptible old-growth forests; and (3) landscape changes caused by decreased frequency of fires at the end of the Little Ice Age (Blais 1983; Jardonet et al. 2003; Morin et al. 2008). Several dendrochronologists and entomologists have put forward another hypothesis—climate warming—according to which the spruce budworm range will extend into the boreal forest zone when the climate is conducive (Régnière et al. 2012), thus causing severe defoliation that will be detectable in reduced growth of the host trees, making it possible to locate the outbreaks. When the climate is less conducive, the spruce budworms will be concentrated in the centre of its range in the southern part of the boreal forest, as was the case during the Little Ice Age, and reduced growth caused by defoliation will be much more difficult to locate. Although there is still much more work to be done to fully understand these dynamics, this hypothesis is supported by independent paleoecological analyses using macrofossils of the insect found in peat bogs that show the same trend (Simard et al. 2006; Morin et al. 2008).

Notes

6. Dealing with a Spruce Budworm Outbreak within an Ecosystem Management Context: How to Adjust Forest Planning?

Marc Leblanc
Ministère des Ressources naturelles du Québec

For centuries, spruce budworm (SBW) outbreaks have played a major role in the dynamics of Southern Quebec's ecosystems. In balsam fir domains, this natural disturbance even is the main driver of forest dynamics. Recurring and periodic outbreaks have been occurring in these forests for a long time. Through various mortality patterns resulting from the insects' behaviour and owing to the variable vulnerability of trees and stands, spruce budworms are largely responsible for shaping stands and natural landscapes. The scope of the disturbance, i.e. its extent, the quantity of trees killed and the mortality patterns (species and percentages of trees killed, topographical position, etc.), determines attributes such as the composition, structure and spatial organization of stands that will emerge following the disturbance. In turn, the arrangement of various ecological attributes that result from the disturbance regime determines the habitats of various wildlife and plant species that may occupy the area. The type of disturbance also influences the ecological processes that are essential to the resilience and productivity of these forests. In short, the impact of the natural disturbance determines the typical biodiversity of an area, given the area's climate and soil.

With its new Forest Regime, Quebec has chosen ecosystem management as the preferred way to implement sustainable forest management.[1] To achieve the latter, it is important to understand the natural dynamics resulting from SBW outbreaks in order to develop forest management methods that help maintain the main attributes and processes of natural forests in order to preserve the biodiversity and viability of ecosystems. During an outbreak period, this understanding of natural dynamics must be used to make changes to existing forest management strategies so as to take into account the insects' effect on the condition of forests and on timber supplies.

It is difficult to predict with certainty how the outbreak will unfold. However, it can be expected that a high mortality rate leading to timber losses (at least in some places) may result and that current forest management scenarios may be affected. In these circumstances, the Ministère des Ressources naturelles du Québec (MRNQ) should adopt an approach that will allow it to adjust its activities to take the course of the outbreak into account, while continuing to work towards the achievement of sustainable forest management objectives, as required under legislation.

However, when faced with a spreading outbreak, it is necessary to refrain from rushing the implementation of measures

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[1] Section 1 (Chapter A-18.1), *Sustainable Forest Development Act.*

or drawing overly hasty conclusions. Not all forest stands that sustain defoliation will die. Some of them will sustain losses, perhaps all of their merchantable volume will be lost, but new stands will emerge following the outbreak. In other cases, there will be partial mortality resulting in lost timber volume, but the SBW will have a more or less severe thinning effect and the stand will survive the outbreak. Moreover, studies describing natural forests show that# despite recurring SBW outbreaks, the landscape was dominated by mature and old-growth stands (Leblanc and Bélanger 2000; Barrette and Bélanger 2007; Pinna et al. 2009; Boucher et al. 2009). Lastly, some stands are not very vulnerable to this insect and the latter will have a minor effect, although defoliation can sometimes occur during the outbreak. In this situation, the challenge for the MRNQ is to properly assess the mortality risks in order to target its activities in space and time and minimize the outbreak's harmful consequences.

Objectives

In that regard, the MRNQ adopted four objectives to be achieved as part of its approach to managing the SBW outbreak. Given the damage that the outbreak may cause, the first objective is to **minimize timber volume losses that may result from SBW-caused mortality**. Efforts must be made to use or preserve timber volumes that may be lost. In particular, it is a matter of setting harvesting priorities based on stand vulnerability and preserving part of the affected stands through direct control measures (aerial spraying). These measures will be carried out primarily to maintain timber supplies in the short and medium terms.

Because the SBW outbreak will result in partial mortality in a large number of stands, it is possible to adjust intervention measures in such a way as to optimize medium- and long-term timber flow. This will help to achieve the second objective of **promoting medium- and long-term timber yield in SBW-disturbed forests**. This implies that wise choices have to be made to prevent the unwarranted harvesting of stands that may survive the outbreak. These stands will play a major role in maintaining a timber flow that can supply processing plants in the medium and long terms. This objective also involves combining silvicultural scenarios with the effects of the SBW outbreak to ensure the regeneration and satisfactory performance of stands.

During an outbreak period, it can be expected that a portion of old-growth stands will be affected by a major disturbance that may lead to the regeneration of the stands, i.e. to the "birth" of a young stand. However, this is not the case for all old-growth (or future old-growth) stands. Some will endure after the outbreak passes and may continue to play their key ecological role. Given that one of the inescapable issues in ecosystem management is the maintenance of an age structure that is similar to that of a natural forest, every effort must be made to **avoid compromising the attainment of age structure targets and prevent the depletion of stands capable of exercising the ecological roles of old-growth forests**. This is the third objective to be achieved. Given the irreplaceable character of old-growth stands in the short term, it is necessary to prevent the combined effects of the outbreak and salvage operations from resulting in an even greater depletion of these stands in the disturbed landscapes.

The fourth objective is to **preserve or restore the natural attributes of disturbed stands where silviculture activities are carried out**. The preservation of natural attributes, such as the composition, structure and spatial organization of disturbed forests, helps to preserve biodiversity and it also has a direct impact on resistance and resilience factors that enable forests to withstand future outbreaks that are bound to occur in the subsequent decades.

Adjustment approach

To help forest managers achieve these objectives, the MRNQ has developed a forest management adjustment approach that essentially consists in compiling information on the current status of forests in order to assess their vulnerability to SBW. An age structure analysis is also carried out to achieve set targets, while taking into account the probability of persistence of old-growth stands in relation to outbreaks. By monitoring insects and defoliation every year, looking at the history of defoliation and carrying out periodic health assessments of the most affected stands, it is possible to monitor changes in the situation as the outbreak takes its course. By using all of this information as a basis, forest managers will be able to make decisions in order to more accurately target activities to be implemented at every stage of the outbreak.

It is vitally important to assess the vulnerability of stands in order to anticipate the effects of the outbreak on stand dynamics and probable mortality. These assessments of both stands and the area undergoing analysis will help to identify, from among all of the SBW-affected areas, those areas that are at the greatest risk of sustaining a high rate of mortality and consequent timber losses that may affect wood supplies. The variables selected for the vulnerability assessment are forest composition, stand age and site characteristics.

Probable persistence of stands

The MRNQ has developed a new tool for predicting the probable evolution of existing old-growth stands as well as the emergence of new trees in order to obtain a projection of the age structure status following insect outbreaks. The information obtained with this tool can be used to adjust forest management choices in order to optimize the maintenance or restoration of age structure, while taking into account estimated timber volume and yield losses in preserved stands (wood flows). In that regard, it is recommended that a vulnerability assessment be carried out to obtain a more accurate idea of the probability of persistence of stands (existing old-growth and new-growth trees) in relation to insect outbreaks. Information on the longevity of species and their susceptibility to SBW has been added to the above-mentioned parameters (Table 1). By using this typology, it is possible to obtain an image of each portion of the area in order to make adjustments to forest management methods as the outbreak runs its course.

Table 1
Typology of the probable persistence of stands against a spruce budworm outbreak.

Type	Description	Species Groups	Contribution to Flow of Old-Growth Stands
Type A – Persistent stands little affected by an outbreak	These stands are dominated by long-lived, non-vulnerable species or non-susceptible species. Their post-outbreak persistence is certain and timber volume losses due to the outbreak are negligible.	The first species code of the species group is a long-lived species that is susceptible, but with little or no vulnerability, or a non-susceptible species. No vulnerable species in the species group, e.g. EnTo, EnPt or EsBj.	These stands constitute a solid basis for achieving age structure targets and have a composition associated mainly with late-succession development phases that are often depleting elements in the range of old-growth forests. In cases of depletion, these stands should be preserved as a priority.
Type B – Persistent stands that may be affected by an outbreak	These stands are dominated by long-lived, non-vulnerable species or non-susceptible species, as with Type A, but they have a minor balsam fir component. Despite balsam fir mortality, these stands are not very prone to rebirth and will persist (or evolve) into an old-growth phase. However, significant timber volume loss is sometimes foreseeable in the event of a prolonged outbreak.	The first species code of the species group is a susceptible, long-lived species, but with little or no vulnerability, or a non-susceptible species. There are vulnerable species within the species group (Code 2 or 3), e.g. EnSb or BjFtSb.	These stands also constitute a solid basis for achieving age structure targets and have a composition associated mainly with late-succession development phases that are often depleting elements in the range of old-growth forests. In cases of depletion, these stands should be preserved, but anticipated timber volume losses should be taken into account (second priority).
Type C – Persistent short-lived stands that are sometimes affected by an outbreak	These are stands that consist of short-lived species and sometimes include a minor balsam fir component.	The first species code of the species group is a non-susceptible, short-lived species. There may or may not be vulnerable species within the species group (Code 2 or 3), e.g. BbBb or PeFiSb.	These stands contribute to the achievement of age structure targets, but their contribution is short-lived and representative of the late-succession development phases that generally occur less frequently in natural forests.
Type D – Stands with variable persistence that are affected by an outbreak	These are stands that consist mainly of balsam fir with a minor component of long-lived or short-lived susceptible species. They have little or no vulnerability or no susceptibility.	Only the first species code of the species group is a vulnerable species, e.g. SbEn or SbBb.	It is not always possible to regenerate these stands. Sometimes the result is a low-density stand with several old-growth forest attributes. In cases of depletion, they can be a good basis for achieving age structure targets, in which case accumulated defoliation and the actual mortality rate should be closely monitored before any salvage operations are carried out.
Type E – Stands with low persistence that are affected by an outbreak	These are stands that consist mainly of balsam fir and are subject to high mortality rates and substantial timber losses in probable areas of prolonged outbreaks.	The first two species codes of the species group are vulnerable species, e.g. SbSb.	Because these stands can lead to rebirth, they are a very poor basis for achieving age structure targets. However, in cases of depletion, they can provide conditions that are close to those of old-growth forests because of the abundance of dead wood in the post-outbreak years.

Response Options

There are several methods forest managers can use to achieve the four objectives of the outbreak management approach. They will have to decide on the right proportions of these methods throughout the course of the outbreak. During the outbreak period, **preventive harvesting** involving the total or partial cutting of the most vulnerable (current and future) stands is one of the methods recommended by the Ministère des Ressources naturelles du Québec (MRNQ) in its Forest Protection Strategy (MRNQ 1994) to reduce the vulnerability of forests and stands to SBW.

At the start of the outbreak, before significant mortality is observed, total or partial **pre-salvage cutting** is a way to adjust forest planning to deal with insect activity. Pre-salvage cutting is carried out in the most vulnerable stands already affected by the outbreak, before significant mortality is observed.

Salvage cutting is also carried out in the most vulnerable stands affected by significant mortality (at least 10% of the volume). It involves the total or partial cutting mostly of balsam fir trees that are more or less severely defoliated, but are healthy, dying or dead usually for less than three years, and relatively deteriorated (crown fallen to the ground, fungal sap coloration and sapwood decay, holes made by wood-boring insects), depending on the intended use to be made of the wood. Salvage cutting is the last-chance method of minimizing volume losses and it helps reduce pressure on healthy stands.

Direct control through aerial spraying of a biological insecticide is an additional method with relatively limited scope, depending on the forest profile of the area, for achieving the first two objectives of the SBW outbreak management approach.

Forest managers can also **preserve key stands** so that they can perform the ecological functions associated with structure and spatial distribution issues or to address the concerns of various area users (Aboriginal people, wildlife managers, cottagers, etc.). Stands to be preserved will be selected according to their probability of persistence and location.

In addition, **the retention of trees or patches of trees** within harvested stands is intended to ensure the presence of structure and composition attributes within new stands. These ecological attributes promote the return of a forest that more closely resembles the natural forest. Special attention will be given to the retention of long-lived species that are typical of the natural forest in order to help reconstitute stands that are more resistant and resilient to future outbreaks.

The **spatial pattern of salvage cutting** helps to distribute the harvested areas so that a landscape containing spatial attributes similar to those observed in the disturbed natural forest is reconstituted. Attributes, such as the percentage, size, configuration and arrangement of residual forest within the salvage-cutting sites, will be taken into account. The vulnerability of stands will also be taken into consideration when spatial organization choices are made.

Portions of the stands that have been regenerated through harvesting or SBW infestation, or a combination of both, may have to be **brought back into production**, particularly in intensive forest management areas, if the regeneration strata are not deemed to be adequate because of the regeneration quantity and quality.

Conclusion

The information provided above is the essential part of the document prepared by the MRNQ to serve as a guide in adjusting forestry activities to deal with SBW outbreaks in an ecosystem management context. An expanded version based on the first year of implementation will be produced in the next few months to provide forest managers with the tools they need to satisfactorily achieve the objectives set out in the SBW outbreak management approach.

NB: The lecture consists of a summary of the preliminary version of a document prepared by the MRNQ entitled *Modulation des activités forestières pour faire face à une* *outbreak de la tordeuse des bourgeons de l'épinette dans un contexte d'aménagement écosystémique* [Translation: adjustments of forestry activities to deal with a spruce budworm outbreak in an ecosystem management context] (Jetté and Chabot 2013).

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Notes

7. Consideration of Spruce Budworm in Timber Supply Analysis: Current Situation and Upcoming Developments

Philippe Marcotte
Bureau du forestier en chef

The calculation of allowable cuts (CAC) is a continuous improvement process that is reviewed every 5 years. During each 5-year CAC period, there are changes in the way natural disturbances, such as spruce budworm (SBW), are taken into account. This presentation will provide a chronological profile of the incorporation of SBW into CAC procedures during the previous (2008–2013) and the current (2013–2018) CAC periods, and we will discuss the development options under consideration for the 2018–2023 period.

Among the improvements made for the 2013–2018 period, we should first take note of the inclusion of a dynamic vulnerability indicator that is used to document changes in vulnerability in an area over time. This indicator is used to draw up a current profile of vulnerability in Quebec and to assess the effects of forest management strategies on vulnerability in Quebec over the longer term.

It should also be noted that some forest management units (FMUs) have been deemed more at risk based on their vulnerability and the current presence of SBW-related damage. In these FMUs, impact analyses have been carried out in order to document the possible impact of the current outbreak on sustained-yield harvesting levels. This impact varies considerably from one area to another. There are still several unknown factors, the most important ones being (1) the actual extent of areas where tree mortality occurs, and (2) the effectiveness of salvage operations to be carried out. These unknown factors prevent us from knowing with a high degree of certainty the actual impact that the current outbreak will have on allowable cuts.

Three main improvements are being considered for the future. The first is the optimization of forest management strategies to reduce the overall vulnerability of areas. Optimizing forest management strategies makes it possible to see that the future vulnerability of areas can be significantly reduced and that similar harvest levels can be maintained by making changes to silvicultural methods.

The second improvement consists of a better integration of SBW impact into growth assumptions. As a result of recent work done by the Forest Research Directorate of the Ministère des Ressources naturelles du Québec, it is now possible to isolate the SBW factor in growth assumptions. The Natura-2009 and Artemis-2009 growth models can be used to generate growth patterns with or without the effect of SBW. This new knowledge will be used to update the impact studies conducted by the Bureau du forestier en chef (Chief Forester’s Office).

Lastly, the third improvement concerns a shift from the annual allowable cut principle to the concept of sustainable forest yields. The new Forest Regime makes provision for replacing the annual allowable cut principle by the sustainable forest yield principle, which would allow a degree of fluctuation in harvest levels over time. This fluctuation will make it possible to respond more effectively to SBW outbreaks. However, the technical criteria associated with this principle have yet to be determined.

Notes

8. Spruce Budworm: Bugging Our Plans!

Jacques Duval
Ministère des Ressources naturelles du Québec

The following is a summary of how the Manicouagan-Outardes Management Unit (093) of the Ministère des Ressources naturelles du Québec is dealing with the current spruce budworm (SBW) outbreak. It includes concrete examples of decisions taken and adjustments made to the management methods and practices used.

The following examples illustrate the consequences of the "SBW effect."

- A moratorium on precommercial thinning during outbreak periods was imposed on the region in 2010. This measure was introduced in accordance with a Forest Protection Strategy recommendation. The objective was to manage the reduced volume of work in accordance with the progress of the outbreak and to incorporate a degree of risk management into all of the other brush clearing activities.
- Adoption of the ecosystem management concept for balsam fir forests and implementation of methods adapted to a pre-salvage cutting and salvage cutting context. This mainly involves a review and comparison of harvesting arrangements in a variety of landscapes with the recommended mosaic-cutting method, as defined in Quebec's *Regulation respecting standards of forest management for forests in the domain of the State*. The management unit also ensures that various residual forests are able to exercise their long-term role.
- Implementation of the Forest Management Strategy: SBW places a significant limitation on the achievement of objectives for partial cutting and harvesting with protection of small merchantable stems (HPSMS) in the affected areas, resulting in changes to the silvicultural strategy. To compensate, we developed an alternative type of clump cutting, called targeted clump cutting (with 10% retention). Another component of the strategy that should be highlighted is the determination of the percentage of balsam fir for which there is allowable cut. For 093-51, the estimated limit is nearly 30%.
- Development of special SBW management plans (pre-salvage cutting and salvage cutting methods): A special plan has been implemented since 2011. It contains measures for speeding up the harvesting of balsam fir (possibility of leaving balsam fir with 10 cm and 12 cm at dbh and crowns at 12 cm). In addition, there may be financial assistance measures. Because the current method is not adapted to SBW, discussions are under way to correct the situation.
- Harvest guidelines to reduce anticipated balsam fir losses: This is an ongoing initiative to determine the additional knowledge required with respect to area accessibility and the progression of damage, and how all of this relates to the specific requirements of the region's industrial sector and the current state of the lumber market. After quickly reviewing the situation, we can see the difficulty in taking action on small scattered sites at the same time.

In all cases, it is necessary to have a consensus among the various stakeholders concerned in order to search for solutions and options for making improvements. It is imperative that this knowledge be updated and the information shared. Nonetheless, it is still difficult to respond quickly enough because of the differing perceptions that people have of the impact of SBW on forests. Perceptions may differ because the disturbance is occurring over a fairly long time period during which spectacular episodes sometimes occur. In addition, few people have an “opportunity” to obtain a good overview along a time line of several years in the same area, which adds to the challenges facing forest managers.

Notes

9. Integrating Spruce Budworm Ecology and Forest Management Planning Through a Risk Analysis Framework

Vince Nealis
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Integrated pest management (IPM) emerged more than a generation ago when the agricultural industry realized that reliance on systematic application of pesticides was not sustainable. Pests were becoming resistant and society was becoming aware that dependence on pesticides and fertilizers was environmentally damaging. There was a deliberate shift from pest management practices dominated by chemistry to one where the life sciences played a greater role and calculation of cost-benefits was expected.

The defining characteristics of IPM are: (1) *monitoring* to provide sufficient estimates of stage-specific pest densities and forecasts of population trends and expected damage, (2) *estimation of thresholds* as decision points and explicit targets for efficacy, (3) *alternative response options* that reduce resistance and non-target effects, and (4) *evaluation of cost/benefit trade-offs* including costs of development of alternatives and non-target impacts weighed against benefits of greater productivity in competitive markets.

Modern IPM changed pest management from a marriage of entomology and chemistry to one of entomology and socio-economics. But economics is a more fickle partner than chemistry so entomology must pull a heavier load than it did in the past. This is truer in forestry than in agriculture because of their different natures with respect to IPM. In agriculture, crops are diverse assemblages of cultivated, high-value, non- native plants imposed on a simplified, intensely managed ecosystem. Return on investment is short-term and its value relatively predictable. Pests in agricultural systems are similarly non-native and their damage represents a measureable loss in value and so the benefits of further investment in protection are clear. By comparison, in forestry, the crop is an assemblage of relatively few low-value native plant species that nonetheless comprise a complex natural ecosystem. Return on investment is long-term and its already uncertain value must compete with other, often non-market, values. Forest pests are usually native and outbreaks are normative and characteristic of ecosystem dynamics. Investment in protection alternatives is discouraged by uncertain markets and demanding constraints.

The spruce budworm (SBW) illustrates these generalizations. Outbreaks are most common and damaging in homogeneous, mature stands dominated by only two native tree species; balsam fir and white spruce. With few exceptions, these susceptible forests are the legacy of unmanaged processes in the dynamics of forests and represent low investment. Budworm itself is part of those forest dynamics; a northern conifer forest without spruce budworm would not resemble the same forest that we are trying to sustain. Outbreaks create a value dilemma between presumed economic costs and putative ecological benefits. There are few reliable management options other than aerial application of pesticides but even this option is becoming narrower because of multiple social values represented by forest ecosystems on the one hand, and the sporadic and uncertain pesticide market compared to annual crops on the other.

In Canada we add a governance challenge to IPM in forestry because most forest management occurs on crown land; publicly owned but licensed to forest industry for harvest, whereas forest pest management is mostly the responsibility of each provincial and territorial government. Research resides outside all of this in universities and the federal government. This creates rich opportunities for disintegration.

This means that to practise IPM in forestry we must maximize application of our knowledge of pest and forest ecology to address the complexity of forest ecosystems, their diverse values, and the socio-economic constraints associated with their management. Implementing IPM in forestry needs some additional tools.

Risk analysis

About 10 years ago, forest pest managers in Canada were becoming uneasy. In British Columbia, the mountain pine beetle was already beyond control and likely to expand its range eastward and northward into the boreal forest. In eastern Canada, everyone was bracing for the next budworm outbreak. There was increasing pressure for greater vigilance and rapid response to alien species. At the same time, Canada's capacity for forest pest management was shrinking. The national Forest Insect and Disease Survey had been disbanded so that pest monitoring was fragmented into smaller, independent surveys with variable effort and diverging methods. University forestry faculties were closing and federal forestry research labs were shifting priorities away from pest management. This was happening just as forestry itself was experiencing emerging wood-supply problems, competitive markets, constraints on practices, increased investment requirements, and demands to manage for multiple values at a landscape level, which was itself subject to changing land-use patterns and climate.

In 2007, the Canadian Council of Forest Ministers (CCFM) initiated the National Forest Pest Strategy as a venue to harmonize methods, "synergise" resources, and encourage forest ecosystem management. Most in the pest management community felt these objectives were realistic if applied to the problems at hand and in a way that was useful immediately. We proposed a risk analysis approach to selected, emerging problems. Risk analysis had already been adopted for alien species by international regulators. We hoped it would help our balkanized forest pest management community converge on a common lexicon and methods of problem analysis that would be useful when applied to forest pests.

Risk analysis is a multidisciplinary approach to informing policy decisions in the context of threats to individuals, public- and private-sector organizations, and to society and the environment at the local to global scales. Risk analysis includes: (1) *risk assessment*, the use of scientific evidence to estimate the level of risk based on a combination of both the likelihood and consequences of potential harm; (2) *risk response*, the evaluation of control options to reduce that risk; and (3) *risk communication*, an interactive dialogue with stakeholders.

Risk analysis seems like common sense; something we *think* we do all the time. But in fact when pushed to act with little time to analyze the risk, we often resort to a combination of safe social attitudes ("the only good bug is a dead bug!"), forced operational imperatives ("we have do to something!"), and weary habit ("we did this before"). None of these responses are particularly good at keeping up with changing and diverse circumstances, long-term planning, or available budgets. Risk analysis compels us to be more strategic in order to be effective and accountable. If IPM is the goal, then risk analysis is the operational framework that helps quickly break the problem down to focussed objectives and identifies the knowledge required to apply solutions.

The spruce budworm is one of three case studies launched by the CCFM. It is lead by the Ministère des Ressources naturelles du Québec with support from the Canadian Forest Service. Unlike many pest problems, insufficient knowledge is sometimes less of a problem with SBW than knowing what information is most pertinent to specific questions of risk. So, the first step was to invite researchers to assess our knowledge and characterize the nature of the impending SBW risk. As expected, there are many basic aspects that we know uncommonly well; outbreak periodicity, extent, and duration as well as the major risk factors. We know that stand-level risk can be characterized adequately by host basal area and that site characteristics modify that risk.

Knowing something, however, is not the same as applying it effectively. That is where the ambiguities and uncertainties become apparent. So rather than synthesizing our knowledge through the conventional process of having experts present their interpretation of their particular speciality, we used an open, facilitated discussion to identify risk factors with supporting evidence and outstanding uncertainties. This process resulted in a consensus of what constituted a risk factor and a ranking on their importance. A significant management conclusion was that although we characterize and manage forests at the stand level, the processes determining risk actually manifests at the regional level. The implications of this are evident in the early stages of the current outbreak where many stands with variable risk characteristics are becoming equally susceptible because of events elsewhere.

A second workshop focussed on risk response. This was sobering. Many of the hopeful control alternatives reviewed by the Baskerville Task Force in 1976, including biological control and mating disruption, have since been tested and found to have limited effect at outbreak levels. The few remaining registered products are effective but the practical problem is that only a small portion of the area that is likely to be infested can be treated. Priorities need to be set. Where are the forests at greatest risk? What kind of protection tactics would reduce those risk overall? Now the need for effective IPM becomes apparent.

The Spruce Budworm Decision- Support System (SBW DSS), now a suite of tools, assists in the selection of risk response options. It is a forest management-planning tool that incorporates disturbances by the SBW into yield projections. I say 'incorporate' rather than 'integrate' because the SBW DSS requires little to no budworm population knowledge. Budworm impact is an input that modifies expected forest growth. The SBW DSS does a very good job of telling you how yield projections will be affected once you know the risk, *i.e.* likelihood of infested and resulting damage and how much that risk can be reduced by protection, but it begs for better integration with the formidable, but largely unused, knowledge of spruce budworm population ecology. To achieve an integrated *planning* tool, we need better predictions of budworm population behaviour, location, severity and duration of damaging populations. Actual risks could be estimated more accurately and the relative benefits of many different protection tactics, especially early intervention ideas, played out with credible parameters.

Our next workshop looked for the connectors between SBW and forest dynamics. The common currency of both population and decision-support models is defoliation. We know the relationship between budworm population levels and defoliation and we know the relationship between defoliation and impacts. A first exploration of the potential for integration was to use the historical aerial monitoring information on defoliation to construct a set of empirical defoliation scenarios from the spectrum of past patterns. Then, these scenarios were input to the SBW DSS to calculate damage curves associated with each scenario and to identify defoliations (=population) patterns which resulted in significant impacts.

Of all the distinct patterns, four were significant in terms of intolerable loss.

With the defoliation patterns defined, other variables of specific interest including impacts in mixed stands (risk assessment) and alternative protection options (risk response) could be included to see how SBW risk to forest management plans varied with stand characteristics and protection tactics. To attract the interest of operational managers in Quebec (risk communication), an actual forest land-base in Quebec was used as the basis for these scenarios. In fact, this land-base was already infested with budworm and so we had real- time indicators of which defoliation scenarios might be developing and the dubious opportunity to project output in the near future.

This has been a useful first step. It illustrates the extension of a forest management-planning tool to explore how risk varies under natural conditions and how different response options affect cost-benefit trade-offs via monitoring data. But it falls short of a proactive management plan because it relies on historical defoliation patterns; it predicts what will happen if the previous outbreak repeats itself exactly. Greater certainty is denied because we do not know what combination of risk factors that was associated with those observations of defoliation so many years ago. Our spatial inventories were practically non-existent then. We can make educated guesses via a *post-hoc* approach such as hazard rating but realistic predictions require budworm population models aimed at elucidating the conditions that favour the initiation of outbreaks and determine their severity and duration. An empirical model or look-up table analogous to what is used for yield curves might be a good start because both the budworm and forest management components of the IPM solution must be spatial and there is that important distinction between regional disturbance processes and stand-level planning.

In the meantime, we can apply the requirements of IPM to reduce future management uncertainties. If accurate monitoring of annual damage can be maintained and associated stand-level changes in mortality and growth evaluated, perhaps even experimental protection tactics imposed, outputs and observations can be compared to track changes in predictive confidence, or uncertainty, depending on your point of view. Even better, SBW population measures in selected stands would provide badly needed insights into variability in survival and reproduction of SBW populations within a spatial area representative of the dispersal capacity of moths. This information is needed as we target SBW dispersal as fundamental to both the initiation and maintenance of outbreaks and create the highest levels of risk to forest management planning.

Notes

10. Achieving Efficiency in the Direct Protection of Forests by Making Room for Innovation

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Given the current forest context and despite the prevention activities implemented in forests, the aerial spraying of the biological insecticide *Bacillus thuringiensis* var. *kurstaki* (*B.t.k.*) to control spruce budworm (SBW) during outbreak periods seems inevitable. The use of pesticides continues to be mainly a tool of last resort. We will provide an overview of the main components of the methodical approach used by the Société de protection des forêts contre les insects et maladies (SOPFIM) to implement its direct control program. We will look at the entire process as well as the problems and limitations associated with this type of intervention in the areas concerned, and outline the development of this short-term approach.

Main stakeholders

The preparation of control programs requires a variety of information and the collaboration of many stakeholders. Many groups or organizations with roles, responsibilities and concerns specific to their areas of activity are involved in direct control efforts.

Ministère des Ressources naturelles du Québec (MRNQ)

This organization, which manages public forests and is responsible for detecting outbreaks, determines the rules for forest interventions and proposes overall strategies that include preventive and curative treatments. The government draws up forest management plans for industry firms and approves the intervention plans submitted by the SOPFIM. It is also responsible for conducting and funding forest research.

Forest industry

Under the current Forest Regime, forest industry firms actively participate in the protection of forests against SBW. In addition to carrying out silvicultural work stipulated in the forest management plans and salvaging SBW-affected wood, they invest in direct protection and in research.

Privately owned forest organizations

In the case of privately owned forests, regional protection and development plans are prepared by the agencies, while joint management organizations provide advice or carry out required silvicultural work. The unions and wood producers' boards look out for the interests of their members and direct protection is one of the concerns of these stakeholders.

Major private forest owners

The owners of large private forests (800 hectares or more under a single owner) comply with SOPFIM regulations on a voluntary basis.

Société de protection des forêts contre les insectes et maladies (SOPFIM)

This private, non-profit organization is managed by its three lead stakeholders, whose representatives sit on the Board of Directors. Its mission is to provide specialized services to control insects posing a threat to forests, agriculture and human health. In the forestry sector, SOPFIM and its partners work together to develop and implement action plans approved by the Ministère des Ressources naturelles du Québec (MRNQ) out of a concern for efficiency and cost control. In addition to planning and implementing control programs, the organization also has a mandate to (1) compile inventories of infestation level forecasts for areas requiring treatment, (2) carry out mapping and aerial validations of areas eligible for protection, and (3) conduct research and development projects in its field, together with recognized researchers.

Planning of direct control activities

An SBW control campaign is planned in two stages: overall planning and annual planning.

Overall planning

The objectives of the overall plan or 5-year plan is to delimit the areas eligible for protection as well as configure and validate the selected intervention areas. The planning focuses, of course, on the most vulnerable forest stands. In addition, some protected areas, white spruce plantations and areas of precommercial thinning are not yet included in the MRNQ's eligible areas because additional analyses are in progress.

Eligible area selection criteria

- Forest composition ≥ 38% balsam fir + white spruce (volume)
- Forest ≥ 30 years
- Slope < 40%
- Harvest forecast > 5 years
- Area ≥ 150 ha
- Previous defoliation = 1 year, moderate to severe
- Anticipated defoliation ≥ 50% of new foliage

Intervention area configuration criteria

The configuration stage consists in grouping vulnerable stands into 150-ha blocks in which protection measures can be implemented. The blocks are numbered and linked to a history database that is updated every year. Several stakeholders question the relevance of this minimum area because of the parcelling of coniferous forests into both private and public forests. In theory, an intervention area may contain a ratio of 50% non-vulnerable stands, but in practice, we see a breakdown based increasingly on stands dominated by balsam fir owing to the greater accuracy of the available tools.

Validation of intervention areas

The final stage of the overall planning process consists in validating the selected intervention areas in collaboration with regional stakeholders. The results of this work are submitted to the MRNQ and to the industry firms concerned in the form of a map.

Table 1
Distribution of areas qualifying for *B.t.k.* aerial spraying programs
to control spruce budworm in Quebec (updated in 2011)[2]

MRNQ Administrative Region	Area (ha)
Bas-Saint-Laurent (01)	267,724
Saguenay–Lac-Saint-Jean (02)	348,785
Capitale-Nationale (03)	245,151
Mauricie (04)	47,086
Estrie (05)	7,159
Outaouais (07)	9,088
Abitibi–Témiscamingue (08)	38,685
Côte-Nord (09)	400,624
Nord-du-Québec (10)	5,886
Gaspésie–Îles-de-la-Madeleine (11)	317,217
Chaudière–Appalaches (12)	11,914
Lanaudière (14)	14,087
Laurentides (15)	22,305
Centre-du-Québec (17)	360
Total	**1,736,071**

[2]NB: The regional map of eligible areas can be downloaded from the SOPFIM Web portal (http://www.sopfim.qc.ca/en/index.php), under the *Tools for forest managers* tab.

Annual planning

The Forest Protection Directorate of the MRNQ conducts an entomological survey every year within an extensive monitoring network. This is preceded by the compiling of an aerial inventory of annual defoliation. When there are significant signs of SBW, as it currently is the case, the SOPFIM carries out more intensive surveys starting in the fall. The inventory of hibernating larvae (L2) is used to predict anticipated infestation levels for the following year. Using these results as a basis, the MRNQ asks the SOPFIM to prepare an intervention plan, if necessary.

Updating of intervention areas

The objective of this activity is to update the information on target areas by scanning information on recent harvest operations, harvest forecasts (5 years), major disturbances, mortality rates, road network and silvicultural activities. The quality of this update depends on the accuracy of the information provided by various stakeholders. Consequently, the stands scheduled for harvesting within a 5-year period should be excluded from the intervention areas, just like the areas where the mortality rate is higher than 50% of the total volume. However, changes to the 5-year plans and the implementation of special plans during outbreak periods require that an annual validation of the excluded harvest forecasts be carried out. This has a substantial effect on annual planning and leads to last-minute adjustments to the control programs.

Preparation of the control program

Treatment requirements are determined according to the health of stands and anticipated SBW populations.

One insecticide application:
- Healthy forests with moderate to very large populations;
- Affected forests with low to moderate populations.

Two insecticide applications:
- Affected forests with moderate to very large populations;
- Mix of healthy and affected forests with large to very large populations.

Further to the treatment instructions, the blocks to be treated are configured according to the control criteria while leaving out environmentally sensitive areas. The intervention plan is validated with regional stakeholders (industry firms, MRNQ) and submitted to the Minister. Upon approval, the SOPFIM sends a notice to the Ministère du Développement durable, de l'Environnement, de la Faune et des Parcs du Québec.

Preparation of the control program includes several additional activities, including the location of the bases of operations, calls for tenders for aircrafts and *B.t.k.*, preparations for aerial spraying operations, planning of the sample-gathering network, updating of the emergency plan and implementation of a public information program.

Control program implementation

To implement a control program, it is necessary to implement numerous activities before, during and after the spraying operations.

Activities carried out prior to spraying

As soon as the products are received, the SOPFIM carries out quality control of the *B.t.k.* formulations to ensure that they comply with the labels and are free of micro-contaminants. During this same period, bases of operations and field laboratories are set up. Reconnaissance flights are carried out to validate the flight plan and take note of any changes that have occurred since the intervention areas were updated. The development stages of the insects and of balsam fir saplings are determined from selective surveys carried out in the treatment block. The pre-treatment inventory is compiled within a maximum 3-day period before the first round of spraying is done in order to determine larval density and the amount of annual defoliation.

Activities carried out during spraying operations

The effectiveness of the treatments depends on the synchronization of spraying with the timing of balsam fir growth and the development of the insects. Selective surveys combined with the use of an SBW seasonal development forecasting model (BIOSIM; Régnière 2010) make it possible to manage insecticide application over a vast area.

Insecticide application requires a very specific environment: gentle winds, sufficient relative humidity and no precipitation. These requirements are usually met in the early morning or early evening. Continuous weather monitoring and aerial controllers' observations help to ensure that conditions are favourable to spraying.

Throughout the control program, teams criss-cross the intervention areas to make observations, carry out surveys of insecticide application, assess the effectiveness of the treatments, and carry out environmental monitoring and surveillance.

Activities carried out after spraying operations

Surveys carried out on the edges of the spraying operations are analyzed in order to assess larval mortality and foliage protection attributable to the treatments. The protection objective is achieved when annual defoliation is ≤ 50%. At the end of the insect feeding period, the Forest Protection Directorate compiles an aerial inventory of annual defoliation that is used to assess the overall effectiveness of the control program. The MRNQ's success criterion is met when the aforementioned objective is achieved in at least 70% of the treated area. The SOPFIM then compiles the information to produce an annual report. Since the start of direct intervention in 2009, the SOPFIM has achieved nearly 80% of its objective, on average (Figure 1).

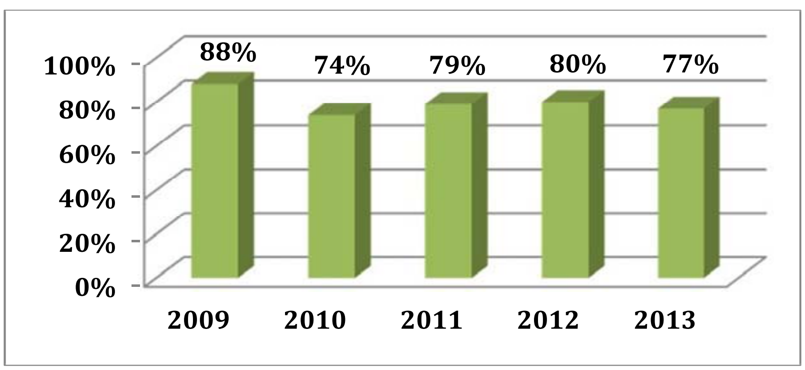

Figure 1 – Annual results of the MRNQ's aerial assessment of SBW control programs carried out by the SOPFIM

Protection activities

Operational *B.t.k.* aerial spraying programs against SBW began in 2009. Given the highly variable impacts of the outbreak anticipated from one location to the next, in addition to the importance of economic considerations, not all forests susceptible to SBW infestation (forests containing relatively high percentages of host species) are treated. For the past five years, the ratio of treated areas to defoliated areas in the North Shore and Saguenay–Lac-Saint-Jean regions has decreased from 20% in 2009 to 8% in 2010, then to 4% from 2011 to 2013. Given the successive "filters" applied in the selection of forests to be protected, it is becoming normal to observe a pronounced decrease in all defoliated areas, in the defoliation measured within forest management units (FMUs), and in qualifying defoliated or treated areas (Figure 2).

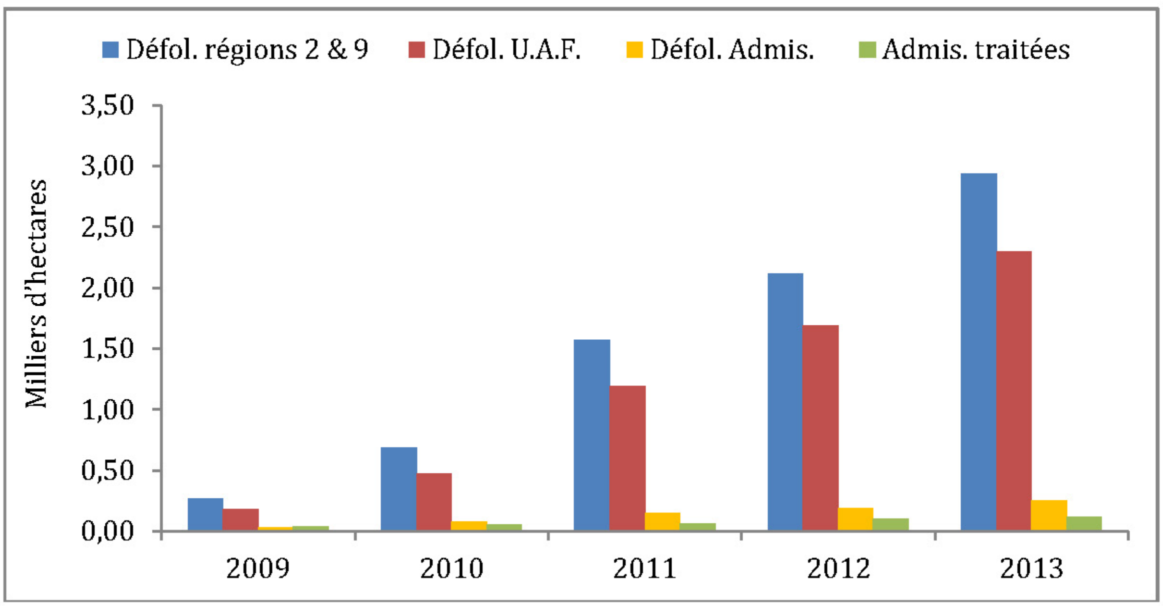

Figure 2 – Protection activities against SBW in the Saguenay–Lac-Saint-Jean and North Shore regions pursuant to the application of protected areas selection criteria

Recurrence of treatments

Because of the annual foliage protection objective of preserving at least 50% of new needles in order to achieve a low level of post-outbreak tree mortality, it often becomes necessary to apply treatments year after year. This high recurrence of treatments assures managers that losses be insignificant after the decline in SBW populations, but also that costs will increase over to time. The latter plays a major part in the cost/benefit analysis used as a rationale for measures taken to control SBW.

Sustained protection means that the same areas are treated on a regular basis. Otherwise, variable or partial protection plans are implemented. In this case, 38,757 hectares of forest were treated for the first time in 2009, whereas only 7,229 hectares (2%) received 5 consecutive years of protection (Table 2). After an analysis was carried out, treatment was withdrawn from these intervention areas and applied instead in proposed parks, new protected areas, biological refuges, salvage cutting areas or areas subject to other government decisions.

Table 2
Annual recurrence of treatments to control SBW in the North Shore and Saguenay–Lac-Saint-Jean regions

	2009	2010	2011	2012	2013	Total	(%)
1 year	**38,757**	34,927	37,410	25,898	42,465	179,457	**48%**
2 years		**20,803**	12,452	42,682	27,524	103,461	**28%**
3 years			**12,691**	17,412	31,851	61,954	**16%**
4 years				**12,052**	11,241	23,292	**6%**
5 years					**7,229**	7,229	**2%**

Cost of programs

Many factors have an impact on the cost of programs, including the number of hectares to be protected, seasonal weather conditions and the number of prescribed insecticide applications.

However, the basic cost factor is still the costs specific to operations, i.e. insecticide purchase, aircraft rental and bases of operations (80% of costs).

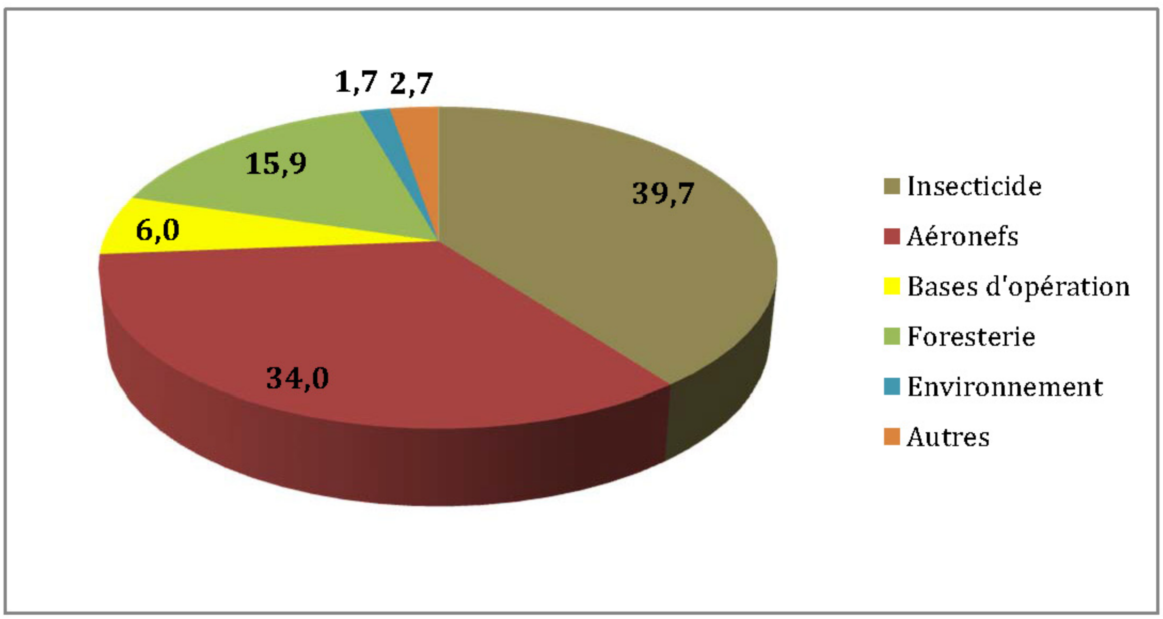

Figure 3 – Breakdown of costs of *B.t.k.* aerial spraying programs to control SBW (2009–2013)

During outbreak periods and when planning the current intervention activities, the SOPFIM makes every effort to reduce the costs of its operations, which can be broken down using two separate methods, i.e. per treated hectare (Figure 4) or per protected hectare (Figure 5).

For the “per treated hectare” calculation, the treated areas receiving single and double applications are added together. This calculation also provides the cost per hectare of a single application. The other method is used to calculate the cost per hectare of protected forest.

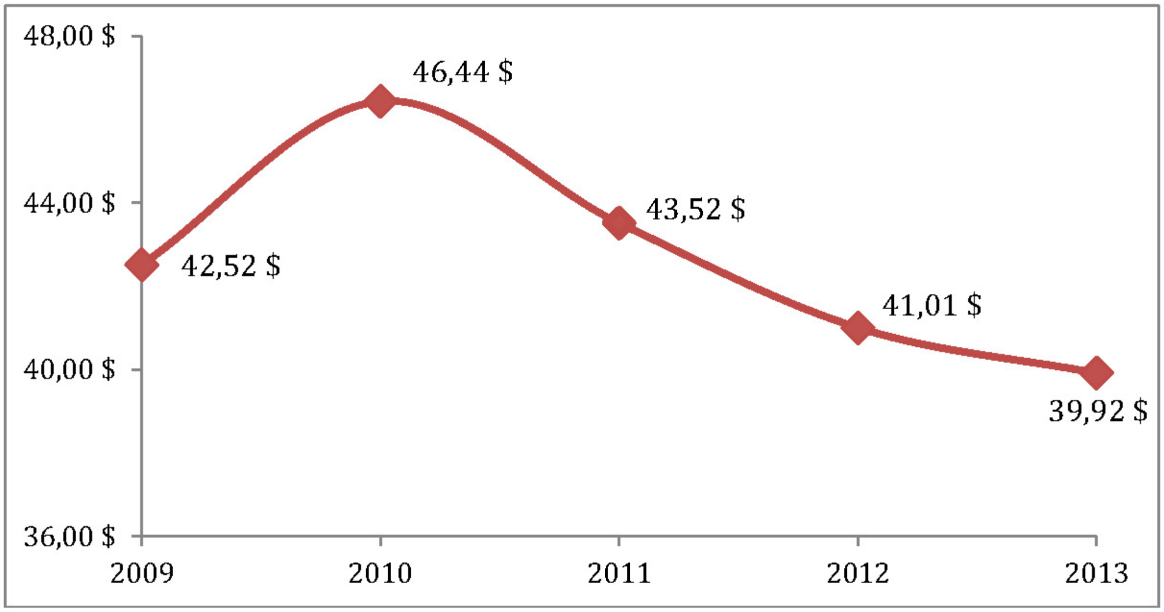

Figure 4 – Cost per treated hectare (total cost / area with 1 application + area with 2 applications)

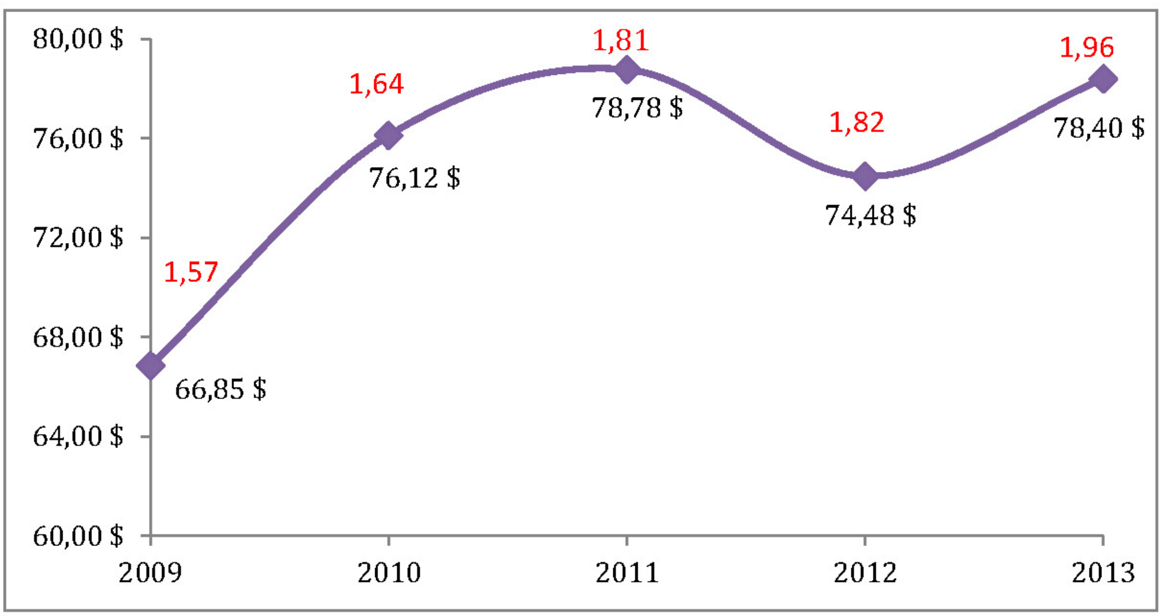

Figure 5 – Cost per hectare of protected forest (total cost / total area to be protected)

Making room for innovation

Access to real-time information

Since its establishment in 1990, the SOPFIM, which will celebrate its 25th anniversary in 2015, has steadily made progress in perfecting its control methods as part of its continuous improvement efforts, while keeping in mind the efficiency of its intervention activities and keeping its costs to a minimum. These efforts have resulted in the gathering of a host of information year after year, either from the research carried out by organizations concerned by SBW, from its own research, or from the data collected during its forest, operations and environmental monitoring activities. This development approach has helped us achieve a level of maturity in our intervention activities and provides us with direction in the selection of options for optimizing the benefits of our programs, and has thus helped us achieve more with the same amount of resources.

Since global information is obtained in real time, the SOPFIM must do likewise. The tools that managers at all levels of the organization use to make decisions must be supplied with information continuously. To make this possible, we are currently developing a Web-operational, geomatics-based system to manage and monitor aerial spraying programs (Figure 6). Despite the province-wide deployment of our operations, the challenge we face is to ensure the two-way circulation of information, i.e. from the managers to the field and from the field to the managers. This one-of-a-kind tool will help to optimize the deployment of all of our resources, and also to maximize the performance of the aircraft fleet assigned to carry out a large number of spraying operations.

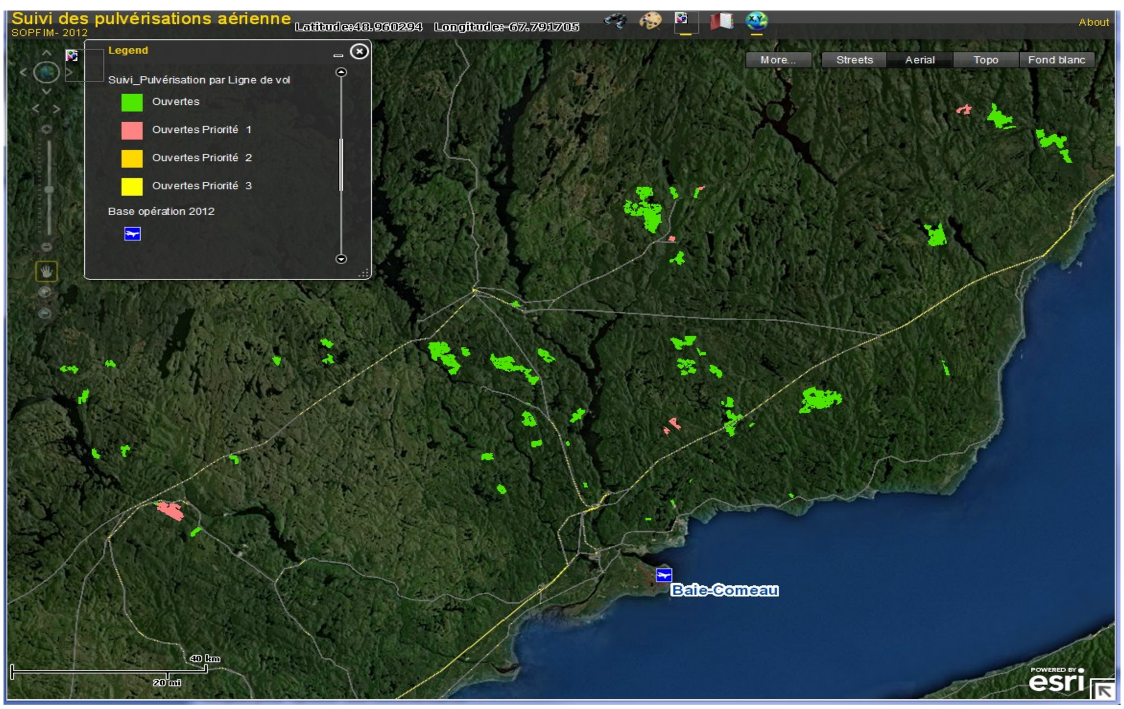

Figure 6 – System for managing and monitoring aerial insecticide spraying programs

Information modelling

We use the statistically proven data collected over the years to create new tools. For example, the collecting of control samples to assess the results of our intervention activities can prove to be of little use when an analysis of the data collected over the years shows us statistically validated patterns. This review of our practices will result in substantial cost reductions in terms of inventories and deserves to be looked at more closely. Why invest effort in inventories that systematically take us to the same foreseeable result?

An intervention approach modified in time and space

The SOPFIM monitors treated areas in order to validate a different direct control approach. Can we modify our intervention activities while refraining from applying treatments on a periodic basis? The rotation of treatments may make it possible to achieve a similar success rate at a lower cost. For example, would it be possible to not apply treatments for one year following two years of a low rate of defoliation without jeopardizing the survival of forests? If the results of this study are positive, substantial savings will clearly be generated, while making optimum use of aerial spraying.

An adapted intervention strategy

For the past five years, the SOPFIM has been carrying out an applied research project. After conducting a thorough comparative analysis, the organization will recommend protection strategies that are adapted to forest resources under threat of an outbreak, to development and production objectives, and to managers' ability to devote their efforts to optimizing the performance of biological insecticide aerial spraying programs to reduce the impact of SBW.

Each of the strategies will be assessed in relation to four main areas: loss of woody material observed (tree mortality and growth), cost of intervention activities, profitability of investments in direct protection, and impact of the outbreak on the forest carbon budget. Depending on the results obtained, it will be possible to determine in which situations the use of each strategy can be given priority, if necessary, while assessing their degree of complementarity in time and space.

The strategies are also being studied to meet various specific objectives, such as the impact of SBW on the production of woody material (quantity and quality) and the acquisition of additional knowledge of the tools used to manage annual direct protection intervention activities.

A direct control approach adapted to the various protection objectives cannot help but result in savings or in an optimization of benefits in areas battling SBW.

Conclusion

The SOPFIM has reached a cruising speed in terms of direct control that enables it to deal with this outbreak. There are certainly major challenges, but the organization's proven capacity to adapt allows it to chart a course to successfully carry out its mission. Since its establishment, the SOPFIM, owing to its continuous improvement philosophy, has continually adjusted its intervention methods and trained its employees. This developmental approach, which has been proven in several fields and organizations, allows the SOPFIM to look confidently towards the future.

Notes

11. The Founding Principles of the Early Intervention Strategy against the Spruce Budworm

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The objective of an early intervention strategy for controlling spruce budworm (SBW) is to alter the course of a new outbreak (stop or slow down the spread of the outbreak). To design such a strategy, it is necessary to obtain a more in-depth understanding of the processes leading to the triggering of a new outbreak. We currently know very little about the dynamics of SBW populations during this period.

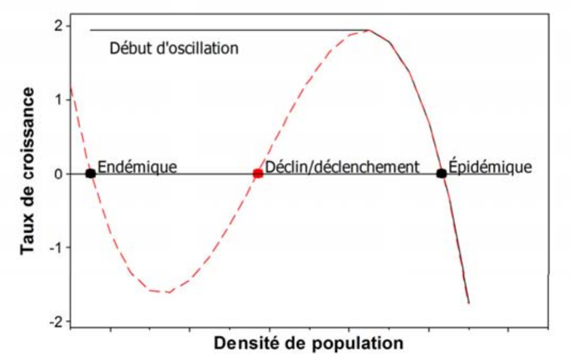

Figure 1 – Theoretical growth rate curves at the start of an outbreak based on the double balance (red line) and oscillating balance (black line) theories.

English Translation
Taux de croissance = **Growth rate**; *Début d'oscillation* = **Start of oscillation**; *Endémique* = **Endemic**; *Déclin/déclenchement* = **Decline/triggering**; *Épidémique* = **Epidemic**; *Densité de population* = **Population density**

There are two schools of thought attempting to explain how SBW outbreaks are triggered. The first was formulated by Clark et al. (1979) in the 1970s as the "double balance" theory. The second, commonly known as the "oscillating" theory, was formulated more recently by Royama (1984). According to the double balance theory, SBW populations are maintained in their lowest state of balance (endemic) by a high mortality rate resulting from a combination of low larval dispersal success rate, high rate of predation and "normal" weather conditions. An outbreak is triggered when the mortality rate drops for one or more of the following reasons: (1) forest ageing, (2) very favourable weather conditions, or (3) the immigration of moths, which in turn causes predator satiation (Figure 1). Using simulation models, Clark (1978) demonstrated that, in this context, migration is a key mechanism in the spread of a new outbreak.

As for the oscillating theory, an outbreak cycle (endemic to epidemic, then back to endemic) is the result of a slow (cyclical) oscillation of "predation" (collective impact of natural enemies, including predators, parasites and diseases). A new outbreak starts when the impact of these natural enemies is at its lowest following depletion after a prolonged period during which preys were very scarce. In response to this decrease in predation, SBW populations start to grow rapidly, most often up to a maximum determined by the quantity of foliage available (Figure 1). Following a period of a few years, the number of natural enemies begins to grow in response to the increase in the number of preys. The outbreak ends when natural enemies take back control over the SBW population (reducing their growth rate to below the replacement level). Then follows a period during which natural enemies overexploit their hosts/preys and exhaust their own resources. According to the oscillating theory, the migration of moths acts as a disturbance in a predator/prey-type system that would otherwise be a "smooth" cycle. The theory also states that immigration does not trigger a new outbreak, but it can accelerate the upsurge of the outbreak or slow its decline. In a relatively vast area, annual fluctuations in the migration of moths can result in a synchronization of the cycles of all the populations (Royama 2005).

Neither of these theories is based on the dynamics of populations at the start of an outbreak because up until now, this information was not available. The double balance theory is based on observations made during and at the end of outbreaks and on a hypothetical increase in the growth rate of populations at very low densities, thus creating an endemic balance. The oscillating theory is based on the parsimony principle: when the information available is not sufficient, the simplest possible explanation should be cited.

The results of studies on the dynamics of populations carried out in Quebec and Ontario since the 1980s have increased our understanding of the outbreak process. First, the gradual change in mortality rates inflicted by natural enemies at the end of an outbreak, which is a central part of the oscillating theory, can be called into question. Observations suggest that in the later stages of outbreaks, the mortality rate increases only after an initial decrease in SBW population that may be caused by a low survival rate during larval dispersal in severely damaged stands, by unfavourable climatic conditions, famine, diseases, massive emigration of moths or even by the application of an insecticide. Following this initial decrease, natural enemies take back control and a new endemic period begins (Régnière and Nealis 2007). Second, studies of two endemic populations (Armagh and Épaule) conducted since the decline of epidemic SBW populations in the mid-1980s have shown that mortality due to natural enemies remains very high for a long period (more than 28 years at the time of writing) despite the complex composition of their natural enemies changing over time (Régnière, unpublished data). In these endemic populations, there is no sign of a gradual release of predation pressure.

Third, it has recently been demonstrated that mating success highly dependent on density in SBW. The females in low-density populations have a very low probability of attracting and mating with a male (Régnière et al. 2012). Low mating success combined with a high mortality rate inflicted in low-density populations by natural enemies constitutes a “demographic Allee effect” (Stephens et al. 1999). Under such an effect, the population growth rate becomes negative at low density (Allee and Bowen 1932). The population level at which the growth rate rises above the replacement level (beyond which a population can grow by itself) is called the Allee threshold.

Consequently, the epidemic process in SBW does not seem to be a simple, synchronized “predator/prey” type of interaction. Instead, it resembles a double balance-type cycle (or even an extinction-invasion cycle). These findings have profound implications for an early intervention strategy. In the context of a simple predator/prey-type oscillation, the growth of a population in the ascendant phase of the cycle is due to the low impact of natural enemies. If a population is regulated in this way, it becomes very difficult to stop its growth, because even after a highly effective control operation, the population will recover rapidly because of its high rate of intrinsic annual growth. Stopping the development of an outbreak becomes even more difficult (if not futile) if all populations are synchronized on a regional scale and if all of them increase simultaneously, exchanging migrating moths between them.

However, in a context where the populations are subject to an Allee threshold, the populations in the early ascending phase may be very localized and scattered (because of previous immigration, for example). Following an effective treatment, they can be brought back to a density level below the Allee threshold, such that their growth rate is too low to allow spontaneous growth. If the sources of high populations are not too numerous or too vast at the landscape scale, it then becomes possible to detect them and reduce their density in order to prevent them from spreading (which they would do by emitting moths).

Since 2011, a research project focusing on these issues has been under way in the Lower St. Lawrence region and the two previously mentioned endemic populations are included in the study (Armagh and Épaule). This project has two main objectives: (1) to observe the dynamics of SBW populations during the ascendant phase of a new outbreak and work with the broadest possible range of densities (from the endemic populations of Armagh and Épaule to the high-density populations on certain sites in the Matapedia Valley)—all of this to try to determine which of the two recruitment curves in Figure 1 is correct; and (2) to carry out tests to determine the effectiveness of *B.t.*, Mimic (Tebufenozide) and pheromone flakes (*Disrupt Bioflakes*). The latter product causes mating disruption in SBW males.

Up until now, we have made three important observations. First, survival between the L_4 stage and adult emergence is dependent upon the density of populations in a growth phase (Figure 2). The form of this density-dependence greatly resembles the prescribed form of the double balance theory (red line, Figure 1).

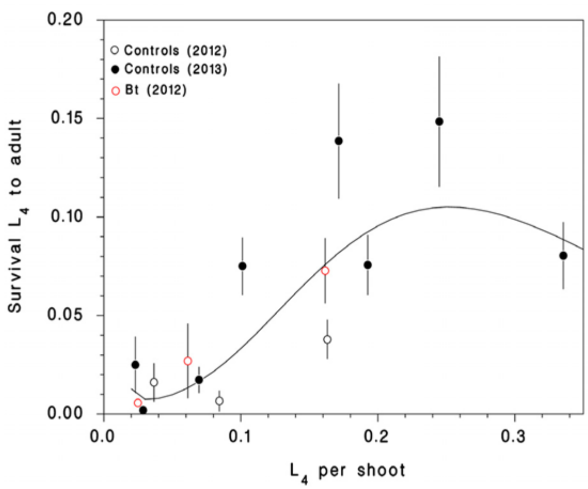

Figure 2 – Relationship between L_4 density and survival up to the adult stage in the control populations treated with *B.t* in the Lower St. Lawrence region (○: *B.t.*; ○: treated in 2012; treated in 2013: ●)

Second, we were able to confirm that the mating success of SBW is dependent on density (Figure 3). This supports the idea that in order for an SBW population to increase to an epidemic density, it must receive a strong impulse to go above the Allee threshold. Immigration from an epidemic population is one of the most plausible ways for this to happen, although other triggering mechanisms cannot be ruled out.

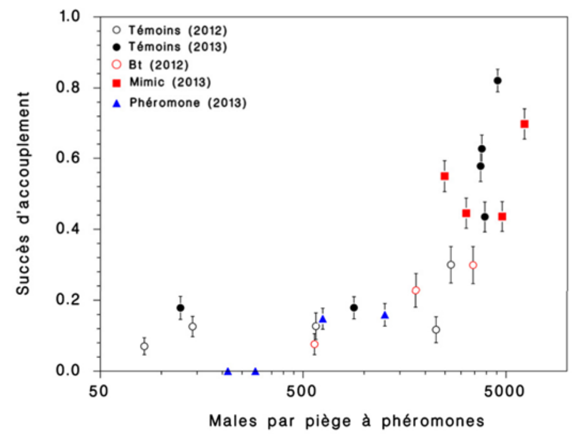

Figure 3 – Relationship between mating success among caged females and total catch per pheromone trap. Plots in the Lower St. Lawrence region, Armagh and Épaule, 2012 and 2013.

<u>English translation</u>:
Témoins: Control
Phéromone: Pheromone

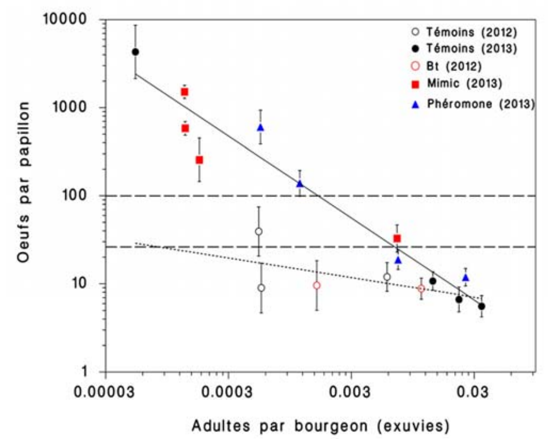

Figure 4 – Relationship between apparent fecundity (eggs per moth) and density of emerged pupae (adults). Lower St. Lawrence region, 2012 and 2013.

<u>English translation</u>:
Témoins: Control
Phéromone: Pheromone

Third, in 2013, we witnessed what was clearly immigration in sites where population densities were lowest, and net emigration in sites where population densities were highest (Figure 4). The data gathered in 2012 show the same trend. We suspect that this density-dependence of the apparent fecundity (egg/moth ratio) is universal in SBW, but that the regional average and gradient vary from year to year in response to factors affecting the moths' migratory behaviour. This process seems to mix the regional populations and homogenize egg densities. The degree of redistribution may be density-dependent on a regional scale (regions with higher average densities would be more easily mixed by migration episodes).

We did not note any foliage protection related to *B.t.* or Mimic following our tests (Figure 5a). However, we demonstrated that Mimic is a very effective insecticide against SBW larvae (Figure 5b).

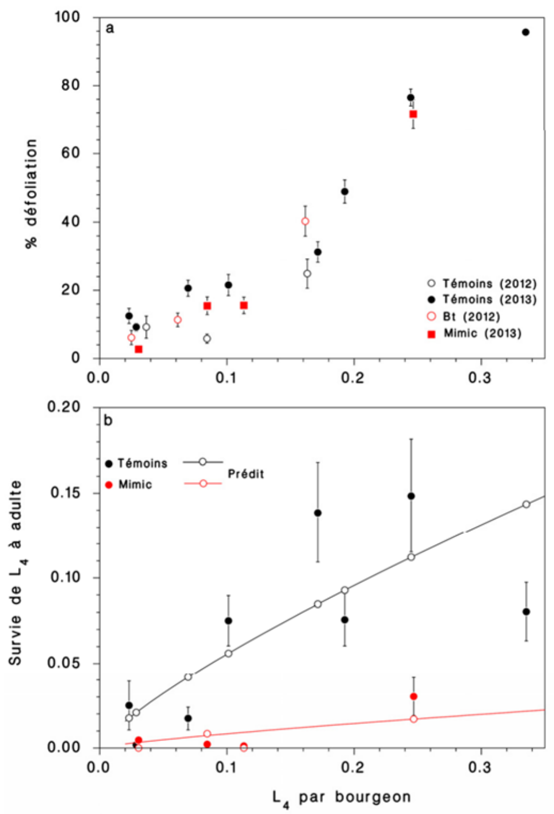

Figure 5(a) – Relationship between L_4 density and late season defoliation, and (b) survival density-dependence between L_4 and adults in control plots treated with Mimic in the Lower St. Lawrence region in 2013.

<u>English translation</u>:
Témoins: Control
% défoliation: % defoliation
Prédit : Forecast
Survie de L_4 adulte : L_4 adult survival
L_4 par bourgeon : L_4 per bud

Disrupt Bioflakes pheromone flakes reduced catches of moths in pheromone traps by about 90% (Figure 6). They also caused a high mating failure rate in caged females (Figure 3). These two observations support the idea that a wild female in a low-density population exposed to flakes impregnated with pheromones would have had little chance of attracting a male and therefore of mating. However, this treatment did not result in any reduction in egg populations or apparent fecundity in the treated populations (Figure 4). In fact, the lowest egg densities were noted in two of the sites treated with Mimic.

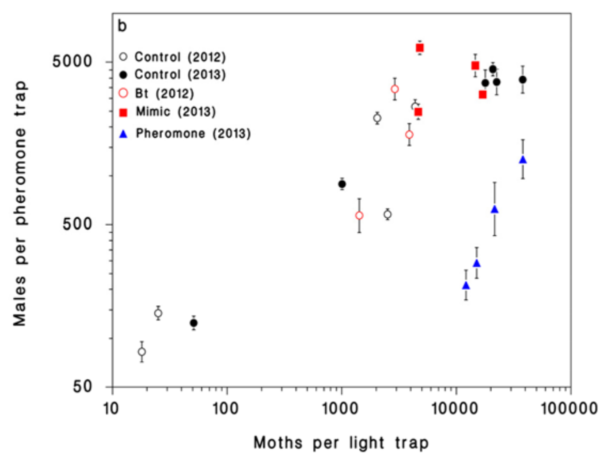

Figure 6 – Relationship between total catch per pheromone trap and total catch per light trap (Lower St. Lawrence region, Armagh and Épaule, 2012 and 2013)

These findings have considerable importance for the development of an early intervention strategy against SBW. First, they imply that it is possible to reduce populations to a density at which mortality due to natural enemies combined with mating failure can then keep these populations under control, provided there is no massive immigration. The fact that a low-density population depends on immigration to go above the Allee threshold implies that if all sources that are fairly likely to produce moths were reduced across the region, it would be possible to curb (prevent) an outbreak. The data we have collected thus far are still insufficient to reliably estimate the density threshold that should be used when making decisions to destroy epicentres. This threshold would be determined by carrying out a series of measurements involving estimates of the following: 1) L_4 density based on a sample of L_2 harvested the previous fall; 2) density of adults based on the relationship between survival and L_4 density (as shown in Figure 2); 3) total seasonal catches in pheromone traps in the absence of immigration; 4) mating success (as shown in Figure 3); and 5) growth rate of the population concerned.

In the summer of 2014, we will continue to work towards our two main objectives. We will return to the 12 sites used in 2013 and complete our observations relative to the survival, recruitment and flight of moths in populations in outbreak growth phase. We will also repeat the *B.t.* spraying experiment in four of these sites. Another team will carry out additional pheromone flake applications in a region of Quebec where SBW are present in sufficient density, but where the risk of massive immigration is low.

Acknowledgements

These projects were carried out with funding from Forest Protection Limited (FPL) and members of SERG International (Newfoundland and Labrador, Nova Scotia, FPL, Quebec, SOPFIM, Ontario, Manitoba, Saskatchewan, Valent Biosciences, and the United States Department of Agriculture's Forest Service [USDA-FS]). The Canadian Forest Service (CFS) contributed funding and considerable support. Special thanks are in order for the owners of the 12 private woodlots where the projects were carried out. Without their knowledgeable input, this research would not have been possible.

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Notes

12. Challenges Associated with the Salvage of Wood and Managing Volumes Affected by the Spruce Budworm

Paul Labbé
Ministère des Ressources naturelles du Québec

Forests have long played a primary role in Quebec's economic development, particularly in regions where the economies of many municipalities are heavily forest-dependent. As owner of public forests, the Quebec government is responsible not only for managing them to maximize their potential for timber production, but also to ensure timber supplies for wood processing plants and to preserve related jobs. At the Ministère des Ressources naturelles du Québec (MRNQ), the Timber Supply Management Directorate has a mandate to manage timber supply and demand, as well as grant forest rights in public forests.

Forest rights during outbreak periods

Under Quebec's *Sustainable Forest Development Act* (chapter A-18.1) (SFDA), the timber from forests in the public domain is allocated in the form of timber supply guarantees (TSGs) or permits to harvest timber to supply a wood processing plant (PRAUs). A portion of this timber is sold through an auction process by the Timber Marketing Board. In addition, the SFDA states that in cases of natural disturbances causing major damage to the forest cover, the Minister may prepare a special forest management plan to salvage damaged timber. The plan may also allow exceeding allowable cuts if the Minister deems it necessary because of the risks of timber loss. Consequently, when a major outbreak occurs, the volume generated each year by harvesting operations may exceed the capacity of the processing plants in a given region.

In cases where the volumes generated by a special plan do not exceed those of a TSG or a PRAU, these volumes replace those of the sectors initially provided for in the annual planning. However, in the event of a large-scale outbreak, that the volumes allocated in the form of a TSG or PRAU may be exceeded should be expected. In such situations, procedures set out in the Act allow for additional volumes to be allocated on a case-by-case basis. Nonetheless, because the processing capacity of local plants is limited, the Timber Supply Management Directorate must sometimes provide other options to ensure that salvaged timber is used.

The case of the North Shore region

Since 2006, the North Shore region's forests have been the most affected by the spruce budworm. Despite the measures implemented by the MRNQ to protect these forests, the size of the outbreak is forcing the MRNQ to increase its timber salvaging efforts. Given the scale of the outbreak that is currently affecting this region and available resources, an outside firm will be awarded a contract shortly to provide support for MRNQ employees involved in forest planning for the region. This firm will have a mandate to draw up a profile of the situation as well as a regional timber salvaging plan covering the next five years. The results will not only help regional teams produce special timber salvaging plans, but they will also provide the Timber Supply Management Directorate with an overview of the flow of timber to be generated in the next few years. These additional volumes could be used to fill numerous additional volume requests or to promote the launch of growth-generating projects creating new products.

Notes

13. Fibre Quality in a Context of Successive Defoliation by the Spruce Budworm in the North Shore Region

Denis Villeneuve
Resolute Forest Products

In a context of harvesting timber affected by the spruce budworm (SBW), Resolute Forest Products wanted to assess the impact on the quality of fibre shipped to the Baie-Comeau pulp and paper mill.

All of the tree species families consisted of stems that had not yet reached the "dry and healthy" stage. The results of measurements of the moisture content in chips taken from each of these species families demonstrated that their quality was satisfactory, although it appeared to be losing moisture content.

The results of basic density measurements were used to supplement the body of knowledge acquired in previous RWRFRU (right wood, right factory, right use) studies and improved the knowledge required for better harvest planning in these sectors. As a follow-up on these studies, it would be appropriate to monitor changes in moisture content loss in the most affected tree species families or to assess the quality of stems whose mortality is deemed recent.

However, it is vitally important that the main players make joint decisions, thus promoting a network approach that facilitates better management of current and future problems arising from the current spruce budworm outbreak in the North Shore region.

Introduction

Since 2010, the North Shore region forest industry has been reviewing its management of fibre supply flow.

This initiative called RWRFRU (right wood, right factory, right use) has resulted in increased productivity in processing plants. One of the basic objectives of this initiative is to reduce variability in the quality of fibre delivered to plants, while taking into consideration that the pillar of the region's forest industry is the Baie-Comeau pulp and paper mill. The method of supplying plants has shifted from a production-driven "push" approach to a market-driven "pull" approach.

The pull approach ensures that only fibre with a processing value meeting the defined criteria of the receiving plant is delivered to that plant. As part of this approach, a fibre management framework has been developed and is being meticulously monitored.

Industry firms are implementing this approach with the assistance of experts from the Centre de recherche industrielle du Québec (CRIQ) and with coaching provided by employees of the Ministère des Ressources naturelles du Québec (MRNQ) and the Ministère des Finances et de l'Économie (MFE). Since 2010, more than $1 million has been invested in acquiring a body of knowledge on fibre quality, the impact of fibre quality on processes and the implementation of a reinvented approach.

In the context of the current SBW outbreak affecting the North Shore region since about 2006, because SBW-affected fibre can vary considerably in terms of its properties and because a significant percentage of this fibre is shipped to the Baie-Comeau pulp and paper mill, Resolute Forest Products wanted to learn more about the properties of this fibre in order to predict potential impacts.

The CRIQ had already carried out significant studies of the properties of wood chips as part of the RWRFRU project. To acquire additional knowledge of fibre properties, Resolute Forest Products asked the CRIQ to study the issue of SBW-affected fibre. The objective of the project, carried out jointly with Resolute Forest Products, was to analyze the properties of chips produced from SBW-affected timber and to incorporate the data obtained from the analysis into the data already compiled in previous studies.

The primary objective of this study was to set harvesting priorities and establish a harvesting sequence in various sectors without compromising the strict quality requirements of the Baie-Comeau pulp and paper mill clientele. By using this body of data and the knowledge acquired in the RWRFRU project as a basis, Resolute Forest Products will be able to better predict the impact of using this fibre on pulp and paper manufacturing and on the manufacturing of sawn softwood lumber.

More specifically, the objectives of this project are the following:

- Document the properties of fibre obtained from SBW-affected areas by identifying the main differences between:
    - the level of damage sustained in the various so-called "affected level" categories that will be established in the harvest protocol;
    - parts of damaged stems (sections from the crowns versus logs usually intended for sawn lumber);
    - the impact on the quality of various levels of damage sustained by the two main species: balsam fir and black spruce.
- Implement this approach by merging the results obtained with the results obtained in the RWRFRU analyses.

As with the previous analyses, the characterization of chips was carried out in the analysis laboratories of Resolute Forest Products' plant in the Laurentians.

We did not gather measurements of some of the properties deemed to be less critical, such as fibre length and the percentage of extractable substances. However, we gathered balsam fir and spruce bark samples for each attack level as well as samples of bark from both species that had not been attacked by SBW. These samples are being kept at the CRIQ for possible studies of forest extractives. They were shipped to the CRIQ by the Conférence régionale des élus de la Côte-Nord, a funding partner for this study.

In addition, although SBW may have an effect on the quality of sawn lumber products, there were no measures implemented in the study to demonstrate this. However, visual observations of the presence of decay and coloration were documented based on a longitudinal profile of the sample stems.

It should be pointed out that this study does not cover the operational aspects of harvesting SBW-affected stems, nor does it quantify effects related to the various processing methods or to the methods used to manage this affected fibre.

Resolute Forest Products wanted to know the condition of SBW-affected stems at the time when stems were normally harvested in accordance with current practices.

Stages in the Approach

Preliminary analysis of North Shore region budworm outbreak issue and challenges

Early on in the project, it was vitally important to carry out a preliminary analysis of the issue arising from the presence of SBW in the North Shore region. During this stage, we constructed a more descriptive profile of the effects of the outbreak.

The entire body of knowledge acquired thus far in the RWRFRU project was used to carry out this study, from the definition of the mandate to the analysis of the results.

Implementation of the project was affected by several hypothetical questions and areas of uncertainty.

- What are the damage levels in the various harvest sectors throughout the timber supply area?
- Do mature and over-mature stands have greater vulnerability and higher damage

levels than younger stands? How do black spruce trees behave in a sector greatly affected by SBW?

- Since young and mature stands do not usually have harvest priority, what is the quality of this wood when it comes from SBW-affected areas?
- SBW is present in areas where Resolute Forest Products has no recent harvest history. What are the properties of this fibre?

Definition of the methodology, taking into account established issues

Using the main findings of the analysis of Resolute Forest Products' SBW issue, we developed a methodology for harvesting sample trees. Based on the area involved (Table 1) and the degree of defoliation (Table 2), a total of six tree families were identified, based on the questions initially asked. Resolute Forest Products then identified sectors (and then plots) affected by SBW where it was possible to find trees belonging to the families identified.

Table 1 – Defoliation levels

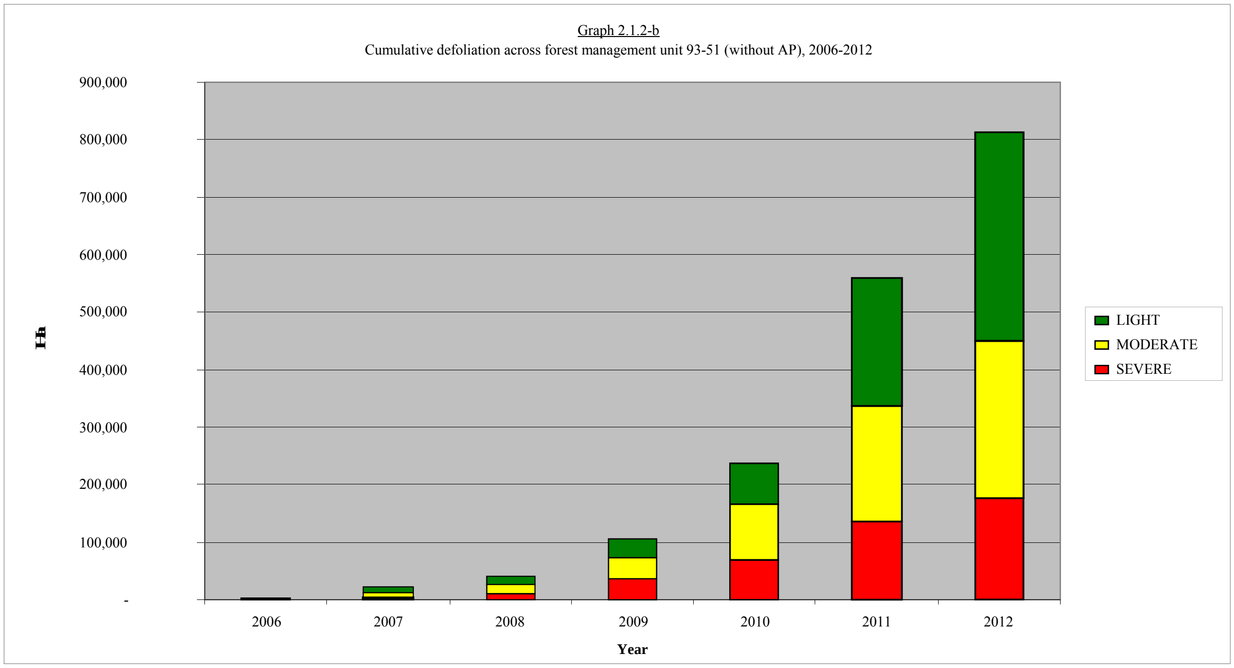

Table 2 – Breakdown of areas with mature and over-mature stands by defoliation category

COVER TYPE	R						
Successive defoliation	**1-2-3**	**4-5-6-7**	**8-9-10**	**11-12-13**	**14-15-16-17**	**18-19-20-21**	
Total of hectares	**Phase**						
Stage	**Initial**	**Attacked**	**Progressive**	**Affected**	**Advanced**	**Terminal**	**Total**
Mature	68,45	25,208	5,206	2,967	1,317	169	103,327
Over-mature	46,45	38,913	8,615	3,836	2,761	723	101,305
Total	**114,91**	**64,120**	**13,821**	**6,802**	**4,079**	**892**	**204,632**

Anticipated Impacts	**Growth Loss**	**Growth Loss and Tree Mortality**	**Growth Loss Tree Mortality Stand Mortality**

The successive defoliation rating is obtained by placing geomatic overlays on top of the annual mapping surveys conducted by the MRNQ and by adding ratings. A "light" defoliation level is assigned a value of 1, while "moderate" is assigned a value of 2, and "severe" is assigned a value of 3. For example, 6 years of "severe" defoliation in the same location is assigned a rating of 18.

Table 3 shows the families identified. Because this level is characteristic of the number of years of successive defoliation and the severity of this defoliation, a total of six families were identified, ranging from F1 to F6. Each family has two sub-families. For example, F1S corresponds to "sawn", meaning wood intended for sawn lumber purposes, and F1T corresponds to "top", meaning top of trees.

The percentages indicated characterize the degree of stem defoliation at the time of harvesting.

Thus, Family F1 includes stems from plots whose rating for the number of years of successive defoliation was at a maximum, while Family F2 comes from sectors where the SBW outbreak is more recent. Families F3 and F4 come from sectors whose rating is intermediate. Family F5 consists of black spruce stands greatly affected by SBW, and Family F6 consists of and is located in an environment of both young and mature balsam fir forests.

Table 3
Definition of harvested families

Level of defoliation Species	Initial	Attacked	Progressive	Affected	Advanced	Terminal
Balsam fir	F2S 0%–30%	F2T 0%–30%	F3S 30 30%– 60%	F3T 30 30%– 60%	F1S 60% +	F1T 60% +
Black spruce	F6S 0%–30%	F6T 0%–30%	F4S 0%–30%	F4T 0%–30%	F5S	F5T
Intermediate balsam fir						

For each family, 12 plots were identified and samples were collected according to the usual methods. One stem was taken from each plot for a total of 72 plots. The characteristics of the collected stems more or less reflected the average characteristics of the plots from which they were taken, particularly in terms of average stand age, average diameter breast height (dbh), average height and Hunter classes. The harvested stems were all in Hunter classes 1, 2 and 3.

For each family, two sub-families were created, one being the family producing logs taken from the merchantable part of stems (up to a diameter of 14 cm) and the other being logs taken from the "top" of stems, as shown in Figure 1 in which the log removal instructions are defined. The "top" part is defined as the non-merchantable part and is removed when stems have a diameter (large end) greater than 14 cm.

Creation of chip batches and measurements obtained

The logs removed had non-standard lengths to ensure safety during the sawing and chipping operations. A mobile chipper was brought to the mill to process the previously debarked logs.

The chips produced were not screened, as chips manufactured in sawn lumber processes normally are, and therefore they did not have a particle-size distribution meeting the usual requirements of pulp and paper mills.

A quantity of chips from which eight measurements per family could be obtained was shipped to the analysis laboratory of the Laurentian mill in leakproof bags after being mixed as uniformly as possible.

Analysis of the measurements obtained

Figure 1 is a histogram of average moisture content in the collected batches. The blue bars show the results for balsam fir families from mature and over-mature stands. The red bar represents the black spruce family while the yellow bar represents the balsam fir family from non-mature stands. Starting from the left, the balsam fir families are placed in ascending order based on the extent to which they were affected by SBW.

The graph in Figure 1 gives rise to the following observations.

- There is a slight loss of moisture content based on the severity of the infestation, which is beyond the degree of uncertainty caused by standard variations. This trend can be seen both in families comprising "sawn" parts and in families comprising "top" parts.
- The moisture content values for the families comprising "top" parts are all higher than those for the corresponding families comprising "sawn" parts. This observation corroborates the results obtained in other studies.

Without underestimating the fact that the timber was harvested and then immediately analysed, all of the families continued to comply with the values required by the pulp and paper mill, i.e. minimum values of 40% for black spruce and of 45% for balsam fir. The values for non-mature black spruce and balsam fir families were also in compliance.

Lastly, since the standard variations of the averages that were obtained were relatively low, these confirm that the chips had been well mixed in the bags sent for analysis.

It is important to note that the harvested logs were completely processed into chips. Under normal sawing conditions, the chips produced would come from the sapwood and would have higher moisture content.

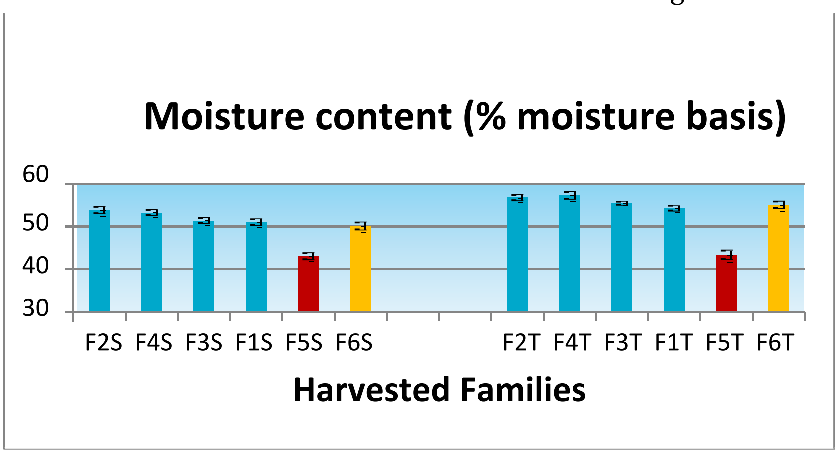

Figure 1 – Average moisture content obtained for each sample batch or family. Vertical error bars represent standard variations. Blue = balsam fir family; red = spruce family; yellow = balsam fir family in a non-mature sector.

As for the densities obtained, the following observations can be drawn from Figure 2.

- The balsam fir families have average densities that are all close to the values normally observed in timber from this species when it is delivered to the pulp and paper mill, i.e. an average of about 335 kg/m^3.
- The F6 family has quite interesting density values (F6S: 351.7 kg/m^3; F6T: 333.4 kg/m^3), despite the fact that this family comprises stems from "potential" areas, i.e. not having harvest priority.

- The density values for families producing timber from tree “tops” are not necessarily higher than the values from their corresponding family producing timber from “sawn” logs, except in the case of the black spruce family.

Although the F5 family consists solely of black spruce stems, the average density measurement for the F5 family is surprising. The value obtained for the “sawn” part is 372.6 kg/m³, while the value for the “top” part is 399.1 kg/m³. The measurements obtained at the Baie-Comeau pulp and paper mill are generally in the range of 410 kg/m³.

Lastly, as was the case for the moisture content values, because the standard variations for the averages obtained were relatively low, they also confirm that the chips were well mixed in the bags sent for analysis.

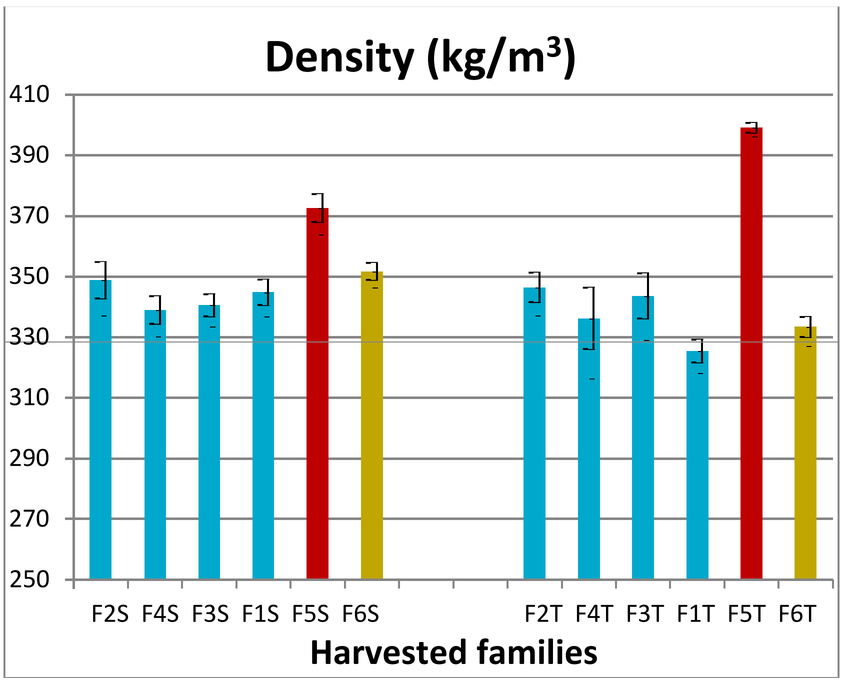

Figure 2 – Average density obtained for each sample batch or family. Vertical error bars represent standard variations. Blue = balsam fir family; red = spruce family; yellow = balsam fir family in a non-mature sector.

The main conclusions are the following:

- As long as mortality is very recent (Hunter 3), it can be assumed that the fibre is not yet degraded;
- Because of their lower density values, some batches of timber harvested in these areas may cause problems at the pulp and paper mill if the mixture is not well managed or if it is unknown.

In order to implement an initiative to introduce new rules for the management of fibre obtained from SBW-affected areas, it is imperative that the following aspects be taken into consideration:

- The mortality rate of trees may increase significantly and therefore solutions relative to harvest methods may need to be implemened;
- The rate of decay may increase as the mortality rate increases, and consideration must be given to signs of coloration (revealing the start of decay) in logs, which affects both the quality of sawn timber and that of paper. Should there be new instructions for harvesting? Should there be new timber measurement methods?
- Further along in the chain, SBW-affected timber inventories should be better managed, which involves implementing methodological or technological solutions as well as quality measurement points upon receipt of deliveries at the pulp and paper mill.

With respect to pulp and paper mill concerns, it is important, for these and other reasons, that all of the decision-makers in the processing chain incorporate all of the quality aspects of chip mixing. They must also take into consideration all of the data gathered thus far in RWRFRU studies.

Figure 3 shows the results of visual observations of the longitudinal profile inside the sample stems. An area measuring 4 in x 4 in within each 1-m section along the length of the stem was studied.

We can see a strong presence of coloration in the F1 family. Brown coloration predominates in the base of the stems and is also very present in the crowns of stems of this family. The other families that were studied also had coloration and decay profiles, but to a lesser extent. It will be interesting to see the development of this problem as the outbreak progresses.

Additional analyses are under way at the Des Outardes sawmill to assess the impact of this coloration on the sawmill’s range of products.

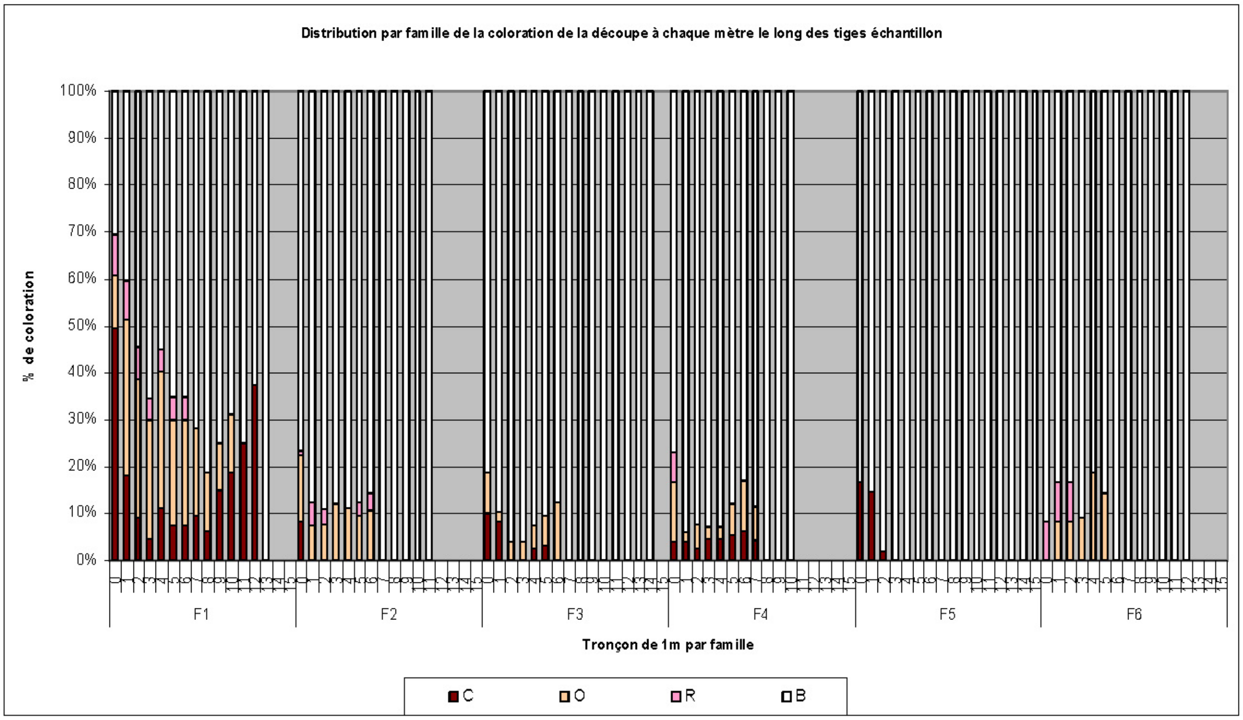

Figure 3 – Distribution of the coloration at each metre along the sample stems by family

Conclusion and recommendations

The results of this study have contributed to a better understanding of changes in wood chip moisture content and density based on the severity of SBW infestation. For the time being, the quality of the fibre taken from the stems of SBW-defoliated trees that falls into the first three Hunter classes complies with the pulp and paper mill's recommended values when the fibre is processed immediately after it is harvested. It is important to consider here that the results were obtained using stems that had been harvested in optimal conditions and that they **had not sustained losses of freshness and ageing** due to storage in the forest or in plant yards.

It was found in the density measurements analysis that the black spruce family had values well below those normally observed in the shipments of North Shore supplies of pure species timber. One of the possible causes appears to be related to growth conditions fostering above-average growth for the harvested stems of this family.

The observations that were made of the longitudinal profile of the stems raise major concerns as to the value of the range of sawn lumber products.

To continue with this initiative, it would be useful to be able to predict the time when deterioration resulting in substantial production losses can no longer be tolerated. Deteriorating trees should be more fully characterized on the basis of widely recognized factors that cause heavy losses.

Some of the key factors for consideration in the value chain are dry, healthy trees, decay, and the pronounced presence of areas of coloration indicating the onset of decay.

Visual indicators of deterioration in trees should be identified in order to verify whether or not there is a possible correlation with the internal characteristics of stems. However, in order to continue with this initiative, it is vitally important to incorporate all of the knowledge acquired thus far in the RWRFRU projects.

This analysis cannot be used to interpret all of the aspects linked to the impacts of SBW. The issue of harvesting costs associated with volumes of dead wood and additional processing work resulting from defects in the wood is a major challenge.

Similarly, in order to be able to determine optimal strategies focusing on the main issues (forest management, harvesting, quality, impact management, etc.), it is essential to bring together the main players in the forest resource processing chain to increase the potential impact of any decisions they make.

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Notes

14. Resistance of Managed Stands and White Spruce to Spruce Budworm

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Conifers' resistance to or tolerance of forest pests, including spruce budworm (*Choristoneura fumiferana* Clemens) (SBW), can be improved or increased through the use of various procedures, such as good silvicultural practices and the selection of trees with greater resistance. These various approaches can be quickly and easily incorporated into our current forestry practices and can thus help to reduce the negative impact of SBW on the forest ecosystem.

Thinning is a silvicultural practice used to increase the diameter of residual trees, shorten the rotation age, and increase the value and quality of the residual stand (Pothier 2002). In the past, thinning was also recommended to reduce SBW-caused damage (Crook et al. 1979; Bauce 1996). However, the reported findings of many studies on thinning are contradictory. Indeed, some studies have demonstrated that the resistance of stands to SBW could increase (Batzer 1967; Bauce 1996; Bauce et al. 2001; D'Amato et al. 2011), decrease (Piene 1989; MacLean and Piene 1995) or remain unchanged (Crook et al. 1979) after thinning is performed. A better understanding of the effects of thinning on the resistance of trees and on SBW performance may help to reduce the negative impact of this pest, while respecting the ecological integrity of forests.

Our study assesses the effects over time of commercial thinning as well as of the drainage class of the forest station on the resistance to SBW of balsam fir (*Abies balsamea* [L.] Mill.), white spruce (*Picea glauca* [Moench] Voss) and black spruce (*Picea mariana* [Mill.] B.S.P.). Therefore, the objective of this study is to determine whether or not it is possible to use this silvicultural practice as a preventive measure to control SBW.

To achieve this objective, 40 experimental plots, each comprising an area of two hectares, were established in the Forêt Montmorency in order to assess the effects of thinning and drainage class on the biological performance of SBW, as well as the response of various host species. SBW were raised and biochemical analyses of the foliage of host species were carried out along a thinning intensity gradient (salvaging was done on 0%, 25% and 40% of the land surface) as well as along the station's drainage class gradient (drainage classes 2, 3, 4 and 5) in the balsam fir–white birch domain. The selected stands were 50 years old and covered an area varying between 27 and 44 m^2/ha. In order to monitor the responses of the various host species as well as SBW performance over time, larval bagging was done 1 year, 3 years, 4 years and 6 years after implementation of the silvicultural treatment.

In each experimental plot and for each forest species present (balsam fir, white spruce or black spruce), two dominant or co-dominant trees were selected randomly each year. On each tree, two 75-cm branches were selected in the north/northwest part of the central portion of the tree crown. On each branch, 20 Stage-2 SBW larvae were placed in muslin bags measuring 75 x 100 cm. In order to simulate normal emergence in the field, the Stage-2 larvae were placed into bags 2 to 3 weeks before balsam fir budbreak by using degree-days as a model. During the bagging activities in the field, all of the experimental plots were free of local SBW population.

The branches on which the bags were installed were then cut down and brought to the laboratory once the larvae reached the pupa stage. In the laboratory, the quantity of foliage consumed by the spruce budworm larvae, the quantity of faeces produced, the quantity of foliage remaining and the total foliage produced were calculated for each branch in order to calculate a resistance indicator (Bauce 1996). In addition, larval mortality, pupa weight and the gender of individuals were determined in the laboratory. For the biochemical analyses of the foliage, a branch from each tree selected during the bagging of the larvae was cut down in late June and in late July. The first harvest of branches was carried out 15 days after the start of the bagging operation, while the second harvest was carried out during the final harvesting of the bagged branches. During the biochemical analyses, concentrations of proteins, nutrients (P, K, Ca and Mg), soluble sugars, total tannins, hydrolysable substances, condensates and phenols were quantified.

In the short term (1 year), the results indicate that balsam fir resistance to budworm following thinning operations is significantly reduced (Fuentealba and Bauce 2012a). This is the result of an increase in defoliation that is directly related to a reduction in concentration of certain monoterpenes (the plant's defence compound) and a reduction in the quantity of foliage produced by balsam fir trees. This change in the foliage biochemistry has positive effects on insect performance, including a reduction in development time, an increase in pupa weight, and greater foliage consumption by the insect (Bauce 1996; Fuentealba and Bauce 2012a). What is interesting to note is that thinning causes increased balsam fir resistance on sites located in drainage class 5 areas and this response is more pronounced when maximum thinning (40%) is carried out (Fuentealba and Bauce 2012a). In the case of the other two forest species (white spruce and black spruce), thinning does not have a significant effect in the short term on foliage production and foliage chemical composition.

In the medium term (3–4 years), balsam fir resistance in thinned stands increases for all drainage class categories. This increased resistance is linked mainly to an increase in the quantity of foliage produced (Fuentealba and Bauce 2012b). Following SBW larvae feeding, this increase in foliage production is accompanied by an increase in the quantity of remaining foliage, which makes the tree more tolerant of the defoliator. Furthermore, in the case of balsam fir and white spruce, the highest intensity thinning (40% of the land area) increases the quantity of foliage in the current year as well as the quantity of foliage remaining after budworm-caused defoliation (Fuentealba and Bauce 2012b). This increase makes trees more tolerant compared with intermediate thinning (25% of the land area). The results also show that thinning increases SBW performance in terms of increased pupa weight, particularly when they are on balsam fir trees (Fuentealba and Bauce 2012b). The main explanation for this result is a large increase in nitrogen and phosphorus in balsam fir foliage. A high concentration of nitrogen in foliage helps to increase the speed of SBW development (Mattson et al. 1991; Carisey and Bauce. 1997), whereas phosphorus is positively correlated with an increase in pupa size (Schmitt et al. 1983; Fuentealba and Bauce 2012a).

Six years after silvicultural treatment (long term), balsam fir resistance to budworm in thinned stands is greater for all of the drainage class categories, and this increased resistance is linked mainly to an increase in the quantity of foliage produced (Bauce and Fuentealba 2013). This increase in foliage production is accompanied by an increase in the quantity of remaining foliage, which makes the tree more tolerant of the defoliator (Bauce and Fuentealba 2013). However, the balsam fir resistance indicator (Bauce 1996; Bauce and Fuentealba 2013), when compared with this same indicator obtained for the medium term (4 years), is lower for sites located in drainage class 3 areas, whereas it is comparable for sites located in drainage class 4 and 5 areas. These observations show that the positive effect of thinning on balsam fir trees is produced more quickly on drainage class 3 sites compared with drainage class 4 and 5 sites, where the effects of the silvicultural treatment are maintained for a longer time period .

All of the results obtained over the long-term (6 years) period suggest that thinning can be used as a preventive measure to increase the resistance of trees and thus lower the susceptibility of trees and stands to SBW (Bauce and Fuentealba 2013). However, it is necessary to take into account thinning intensity, forest station quality (drainage) and the host species, because the resistance indicator for each species under consideration varies over time (Bauce and Fuentealba 2013). It has been demonstrated that this silvicultural method is effective in increasing tree resistance at the stand scale. However, it is impossible at this time to know what the impact of this method will be at the landscape scale, or whether or not this method can alter the course of a spruce budworm outbreak.

In addition to using silvicultural methods such as thinning to increase tree resistance, it is possible to select individuals with interesting characteristics that intuitively give them a degree of protection against defoliators such as SBW. Thus, for the past several years, white spruce trees in a plantation in the Drummondville area have attracted attention because they sustained practically no defoliation (<10%) while the majority of individuals in the same plantation sustained a considerable amount (>50%) of SBW-related defoliation.

After some verifications were made (insect's presence on the plant, female egg-laying on the trees, etc.), one of the most probable explanations for this phenomenon was the presence of certain molecules in the white spruce foliage. To verify this hypothesis, leaf extracts from trees with substantial defoliation and from trees with little defoliation were collected for laboratory analysis. Because phenolic compounds comprise one of the biggest classes of secondary defence compounds in conifers and because they are often involved in plant defence responses to herbivores and pathogens (Schopf 1989; Bennett and Wallsgrove 1994), we put forward the hypothesis that some of these molecules could be partly responsible for this lack of defoliation in some white spruce trees. Following a series of biochemical analyses using leaf extracts from various white spruce trees (Delvas et al. 2011), the biochemical profile of the trees with little defoliation contained two molecules that were different from those of other trees exhibiting a high defoliation rate. The two molecules identified in trees exhibiting little defoliation are piceol and pungenol (Delvas et al. 2011).

The molecules identified were then incorporated into an artificial diet with various concentrations (0.5, 1 and 2 times the concentrations observed in the field) in order to quantify the effects of the identified molecules on budworm development and biological performance. The results show that piceol and pungenol slow down larval development, reduce pupa weight and increase mortality in SBW larvae (Delvas et al. 2011). Moreover, when the molecules are used together in the same artificial diet, there is a synergy (amplification) in terms of the effects on budworm development, performance and food utilization.

All of this research demonstrates that it is possible to increase the resistance or tolerance of various conifer species and thus reduce the potential negative impact of SBW on the forest ecosystem. Additionally, these various approaches can be incorporated into our current forestry practices and can thus help in the short and long terms to reduce the negative effects of SBW and other forest pests.

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Notes

15. Impact of Spruce Budworm on Landscapes and Effects of Landscape Structure on Outbreaks

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Both the theory and empirical data suggest that forest structure (composition and configuration) may affect the dynamics of insect populations and therefore modulate the risk of outbreaks. With respect to spruce budworm (SBW), several observations at the stand scale appear to demonstrate that forest structure and composition have an impact on damage severity. On a broader scale, the silvicultural hypothesis is that the increased severity of outbreaks in the last century is the result of forest conditions created by forest management activities (Blais 1983). In other words, forestry methods, such as cutting with protection of regeneration and soil (CPRS), tend to increase the percentage of balsam fir, the main host species, on managed lands. Despite this finding, several authors question this increased frequency and severity at the regional scale (Boulanger et al. 2012; Bouchard et al. 2006), because a definitive test of the hypothesis maintaining that changes to forest composition and structure have an impact on outbreaks has not yet been carried out (Miller and Rusnock 1993).

Although there are persistent doubts about the silvicultural hypothesis, the relationships observed at the stand level have been sufficient to allow them to be used to reduce balsam fir (*Abies balsamea* (L.) Mill.) abundance and age as well as increase the abundance of spruce (*Picea* spp.) and deciduous trees since the last outbreak. However, the effects of these measures on the timber supply remain uncertain. Intuitively, structural modifications would have a direct impact on outbreaks, such as increased or decreased host continuity, in addition to an indirect impact, such as the influence of the diversity of communities on parasitoids and their mobility. Although some authors suggest that a reduction in forested areas dominated by the host species will reduce the severity of outbreaks, research done on other insects, such as forest tent caterpillars and winter moths (*Operophtera brumata* L.) (Roland 1993; Roland et al. 1998; Wesolowski and Rowinski 2006), suggests that subdivision of the forest into small plots of host species results in longer outbreaks of greater severity.

To assess the effect of forest management at the landscape scale, we constructed models and used historical data and a field sample gathered over an area of several thousand km^2. Using dendrochronological methods, we assessed the effects of various types of forest management on the synchronicity, duration and severity of outbreaks in three landscapes that had undergone various types of forest management (conservation area, large-scale forest management area [100 ha] and small-scale forest management area [10–20 ha]) in Ontario and Minnesota. We also assessed the impact of changes in forest composition and structure on potential timber losses in a 2,500-km^2 area in the Gaspé area. In addition, we modelled the effects of interaction between disturbances on available timber in a large area of mixed balsam fir forest in the Mauricie region. Lastly, we used genetic markers to test the dispersal of spruce budworms and their parasitoids (e.g. *Glypta*) in forest landscapes. All of these methods will be used to test the silvicultural and natural enemies hypotheses for their control of the severity of large-scale spruce budworm outbreaks.

Our results from the dendro-chronological studies of the Ontario and Minnesota forest landscapes suggest significant differences in the dynamics of outbreaks between forest management areas. By using group analyses for a temporal series as well as a partition of the variance on satellite data of forest and climate structure, we identified a significant temporal variation in insect outbreaks between areas with different forest management histories. Spruce budworm outbreaks inside the conservation area were less frequent, had greater synchronicity and had a higher percentage of affected trees than in the small-scale forest management area. Outbreak characteristics in the large-scale forest management area consisted of a mix of those of the conservation area and of those of the small-scale forest management area. Although our analysis of the variance partition showed that there was a slight climate effect, the dynamics of the outbreaks were more affected by the configuration of the host species and by forest age and composition. Our study therefore supports the silvicultural hypothesis and demonstrates that the observable effects of forest heritage on the dynamics of outbreaks occur at both the local and a landscape scales.

In parallel, we also assessed the effect of forest condition on forest tent caterpillar outbreaks in forests. We observed that the characteristics of these outbreaks are closely associated with current forest composition and with forest legacies (forest management). Outbreaks on sites located in the conservation area are partly desynchronized because of a small abundance of host species in this area. In fact, trembling aspen dominates managed landscapes because its numbers increase following logging, which may explain the more severe and synchronous outbreaks in managed areas, and thus the contrast with SBW.

This study clearly demonstrates that the effects of anthropogenic changes associated with forest management at the landscape scale are real and that it is important to measure these effects in a variety of forest conditions. Based on our findings, it can be established that changes in the distribution of host species in the landscape have an impact on outbreak cycles and that changes at the landscape scale help to moderate outbreak cycles. In addition, all of our findings highlight the importance of considering the impact of forest management on many types of insects, because conditions unfavourable to one insect pest may become favourable to another.

From 1985 to 2004, we also assessed the characteristics and history of disturbances and the supply of conifers in intensively managed forests in Eastern Quebec (in the Gaspé area) during a major spruce budworm outbreak. We estimated the vulnerability of the forests based on reductions in conifer volumes determined in outbreak simulations of varying degrees of severity (low, moderate, severe), while taking into consideration the effect of deciduous trees in reducing the defoliation of balsam fir and spruce (continuous throughout the outbreak; only at the beginning or at the end of the outbreak; or no effect). There seemed to be similar reductions in timber volumes for the outbreak simulations beginning in 1985 or in 2004. In the case of light and severe outbreaks, the reduction in timber volumes varied from about 15%−46% (where deciduous trees had no effect) to 13%−39% (where deciduous trees had a maximum effect). Given the difficulty of increasing the abundance of spruce and the relatively low impact of deciduous trees in reducing volume decreases, we question the silvicultural method used to reduce SBW-related losses.

In order to estimate the long-term potential impact of composition changes on SBW-caused damage, a stochastic landscape simulation model (LANDIS-II) was set up on a 3,600-km^2 area located in a mixed boreal forest of the Mauricie region in central Quebec. We specifically monitored changes in forest composition and volumes for each species group based on combinations of silvicultural treatments (clear-cutting, precommercial thinning and plantations) and successive SBW outbreaks of varying severity over 200 years. The results demonstrated that the protection provided by deciduous trees had a maximum impact in the unmanaged forest scenario with conifer cover, suggesting a clear loss of conifer volume in forests with a mixed cover. In addition to SBW-related damage, our results suggest that in order to increase conifer volumes in forests, additional efforts must be made to limit conversion into deciduous forest in the aftermath of tree-cutting activities.

During a similar modelling exercise using the SELES-Vermillion platform, we assessed the impact of three interacting disturbances, i.e. spruce budworm outbreaks, fires and logging, on forest vulnerability to future outbreaks (James et al. 2011).

Our findings suggest that an increase in the fire cycle as well as an increase in tree-cutting activities reduce the severity of outbreaks. These findings seem to contradict other findings suggesting that tree-cutting activities increase the percentage of host species. However, these findings underscore the importance of taking into consideration the interaction between factors affecting the severity of outbreaks, given that rejuvenation of the age structure through forest normalization reduces forest vulnerability by transforming old-growth stands of balsam fir into immature stands (Hennigar et al. 2008).

We are beginning a new research to describe the spatial variation of parasitoid communities in an area subject to an SBW outbreak. We will then study how forest landscapes affect the dispersal of SBW and of a major SBW parasitoid, *Glypta fumiferanae*, by using new genetic markers. Our objective is to assess the importance of epicentres versus the Moran effect. In the short term, we observed moths coming from sites further north and going towards sites where this life stage had ended in the local population a few weeks before. Our findings will be used to make recommendations for the creation of landscapes that will help us to increase the control that parasitoids exercise.

We also observed an increase in warblers, which are known to feed on SBW in areas where the outbreak is emerging. These birds can therefore serve as sentinels for detecting the distribution of outbreaks.

To sum up, our work conducted at the landscape scale demonstrates that forest management involving changes to forest structure configuration as well as forest composition have an impact on the characteristics of outbreaks (duration, frequency, synchronicity and severity), but that the established rules for stands cannot simply be transposed onto a broader scale. Our work also calls into question the usefulness of increasing the percentage of deciduous trees if the objective is to produce conifers. Foresters should therefore clearly assess their objectives. Additional studies are needed to obtain a better understanding of the impact of landscape-scale changes (or of the impact of forest management units); however, our findings suggest that the impact of changes to landscapes may be different than the impact of changes to stands.

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Notes

16. Wood Degradation Caused by Bark Beetles and Woodborers Following Spruce Budworm Outbreaks

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Salvage cutting in forests affected by natural disturbances is one way of maintaining the timber supply required for forest industry operations, particularly in a context of successive decreases in allowable cut. For the past 15 to 20 years, salvage cutting has been carried out where fires have destroyed large expanses of forest and will be used increasingly in the context of the continually expanding spruce budworm (SBW) outbreak.

The knowledge obtained from the study of fires cannot simply be transferred to the issue of post-SBW stands. In fact, when a forest fire occurs, the trees in stands die very quickly (within a few hours at most), whereas during a spruce budworm outbreak, tree mortality increases gradually and not uniformly. In fact, tree mortality occurs over several years in a given stand. Fire is not very selective in regard to the trees it destroys, while a spruce budworm outbreak does not affect all trees. For example, the first trees likely to die are suppressed trees and intermediate ones (Baskerville and MacLean 1979) that have developed crowns and are therefore vulnerable to defoliation. Burnt trees are rapidly colonized by woodborers, while the abundance of bark beetles in burnt trees is small (St-Germain et al. 2004a, b, c; Boulanger and Sirois 2007; Boulanger et al. 2010, 2013; Azeria et al. 2012a, b; Boucher et al. 2012). During an SBW outbreak, bark beetles are the first to colonize affected trees (Belya 1952a, b; Basham 1986). It is probably the quality of the subcortical tissues that determines the type of insects that colonize dying or dead trees.

After a fire, salvage cutting must be done as soon as possible because woodborers colonize trees quickly and in massive numbers in the following weeks. The tunnels (galleries) they dig a few months later will reduce the timber value, particularly for the production of sawn lumber. The optimum time to begin salvage cutting during a spruce budworm outbreak still remains to be determined.

Most studies of the deterioration of trees killed by SBW have been conducted outside Quebec, particularly studies by Belyea (1952a, b), Basham and Belyea (1960), Stillwell and Kelly (1964) and Basham (1984, 1986). They report that several insects attack trees killed by SBW, the most numerous being balsam fir bark beetles, *Pityokteines sparsus*, followed by whitespotted sawyers, *Monochamus scutellatus scutellatus* (Basham 1986). Immediately following the death of a tree, a sapwood-discolouring fungus, *Amylostereum chailletii*, quickly establishes itself (Basham 1984). This fungus is carried by Siricidae that are more abundant in the Atlantic provinces than in Ontario, which explains why sapwood discoloration is more frequent in Eastern Canada. Basham (1986) reports that sapwood decay, *Trichaptum abietinum*, develops more quickly when balsam fir bark beetle populations are abundant, although no direct link between bark beetles and the fungus has been made. This decay becomes established one year after the tree dies, but reaches a peak after four or five years.

In Quebec, the Forest Protection Directorate carried out a major study of balsam fir deterioration during the 1980s. It was found that bark beetles were the first colonizers of dying trees, but that they were no longer present in dead trees after more than two years. Bark beetles then follow in recently dead trees, although they may be found in dying trees up until two years after the trees have died. These insects do not damage the wood, because their presence is limited to the bark and to the wood surface. Two other families of species, Melandryidae and Siricidae, appear at the same time as bark beetles. These insects are found up to three years after the death of the trees. Woodborers are sometimes present in dying trees, but they mostly colonize trees during the first year of mortality. Starting in the second year of mortality, the insects cause a fairly sharp depreciation in the value of sawn lumber because of the twisting, longitudinal galleries they dig, often into the core of the tree, in order to feed themselves.

Conceptual model for determining the best salvage cutting period

The best period for harvesting trees for sawn lumber is determined according to the extent of damage caused by woodborers, which can begin by attacking dying trees, but are mainly present after the death of trees. In addition, in the case of trees intended for pulp and paper mills, the available time for harvesting dead trees can vary considerably, depending on the processing methods and market requirements. There are many studies on the use of dead trees in various processes, and several of them demonstrate the feasibility of using dead wood. About 80% of the timber volume is still healthy between two and three years after tree death. An important variable that must be taken into consideration in some processes is wood moisture content. However, we know that deterioration primarily affects sapwood because its moisture content is higher in the beginning. This is also the part of the tree where the moisture content decreases the most.

There are three separate periods for harvesting vulnerable stands. Preventive harvesting means that the most vulnerable stands are harvested before the end of the first year of the outbreak. Preliminary salvage (pre-salvage) cutting is carried out during the first five years of the outbreak, because only a small percentage of the timber volume consists of dead trees. As for salvage cutting, it is carried out starting in the sixth year of the outbreak because the percentage of the volume consisting of dead trees begins to be substantial (about 10%). Special salvage cutting plans must then be drawn up quickly to limit timber deterioration and reduce losses.

Research in progress

Research is under way to identify indicators to be used to assess tree mortality risks at least one year in advance. Forest managers will use this information to review their annual forest intervention plans and include a pre-salvage cutting or salvage cutting plan in them.

In a project involving researchers at the Université du Québec à Montréal (UQAM) and the Canadian Forest Service (CFS), participants are taking a detailed look at the issue at the tree level. They plan to measure the colonization of SBW-defoliated trees (balsam fir and black spruce) by wood-boring insects based on the accumulated amount of tree defoliation (MacLean et al. 2001). Cages were installed around the trunks of trees that had been defoliated to a moderate or severe degree in the previous three to six years in the North Shore region. This non-destructive approach will help to determine the degree of accumulated defoliation of trees that is necessary to result in colonization by wood-boring insects. In addition, crossvane traps were attached to trees that had undergone each stage of defoliation in order to estimate, based on the accumulated defoliation, the average number of tree visits made by the two species. This method was used to test a less costly method that may provide a rapid indication of the state of vulnerability of the trees. The relationship between the average number of tree visits by wood-boring insects during year "n" and the actual colonization recorded during the year "n + 1" measured in the emergence cages will help to provide a better understanding of the process for selecting the hosts for wood-boring insects. Very few whitespotted sawyers were caught in 2013, which was the first year of the study. However, many bark beetles and weevils were caught. Some species may be indicators of mortality risks in the short term. The research will continue for at least the next two years.

The issue is also being addressed at the MRNQ, but on a broader scale that is better suited to operations management. The two projects are complementary and researchers involved are working together to ensure that the research findings can be quickly incorporated into the management tools developed by the MRNQ. In fact, the protection of forests against forest pests is the responsibility of the Ministère des Ressources naturelles du Québec. During outbreak periods, such as the current SBW outbreak, guidelines are developed and actions are taken to reduce the negative impact of the outbreak and prevent timber losses.

Despite the effort made to control the outbreak, its vast extent results in gradual tree mortality in forest stands affected by serious SBW defoliation over several consecutive years. In the past few years, parts of the North Shore and Saguenay–Lac-Saint-Jean regions have been particularly affected by defoliation, i.e. 2,465,721 and 470,215 hectares, respectively, in 2013. In areas where tree mortality is beginning to occur, salvage cutting must be carried out quickly to limit timber deterioration and reduce timber losses.

It is therefore vitally important to have information on the health of stands in order to provide direction for regional salvage cutting operations in areas affected by the SBW outbreak. In 2012, a method for assessing the health of stands and for monitoring mortality was developed in order to identify stands with a high mortality risk.

Aerial and land-based assessments of stand health

The assessment method focuses on the areas most seriously affected by SBW damage in recent years, i.e. areas with the greatest probability of tree mortality. By superimposing severe annual defoliation mapping data (one to seven consecutive years of defoliation), it is possible through aerial surveys to identify the most damaged areas in the North Shore and Saguenay–Lac-Saint-Jean regions in order to assess stand health and mortality risk. Helicopters then fly over these areas to conduct surveys. In addition, aerial observers used a grid made up of 300-m x 600-m (14-hectare) tesserae (squares) to produce digital maps for assessing total defoliation. They associated a total defoliation category with each tessera in order to determine stand health and the mortality risk associated with each of these categories. In 2012, aerial surveys were conducted over a total area of 62,500 hectares and these included less than 1% of stands with a high mortality risk in the short term (i.e. with more than 90% of total defoliation); in 2013, this risk was 3.7% over the 92,328 hectares where aerial surveys were conducted.

In order to validate the results of aerial assessments of stand health, a land inventory in the Baie-Comeau and Forestville areas of the North Shore region was compiled. In 2012 and 2013, 120 and 138 plots were established, respectively, in accessible areas that had accumulated more than three consecutive years of serious defoliation. The total amount of defoliation of trees susceptible to SBW was assessed in these plots. In 75% of all cases, the results obtained from either the aerial or the land-based method of assessing defoliation were similar.

Mortality monitoring

Given the continuous annual progression of the spruce budworm outbreak, tree mortality in some stands is expected to gradually rise and spread over larger areas in the near future. Consequently, a tree mortality inventory began to be compiled in the fall of 2012 with the establishment of 66 monitoring plots in the Baie-Comeau area. Information on tree health and total defoliation of trees identified in the plots is gathered every year in order to quantify mortality, and also to determine a cumulative defoliation limit associated with the occurrence of tree mortality in the stands. The first analyses indicated that mortality was not spreading on a large scale, but that it had nonetheless spread between 2012 and 2013. In 2013, crossvane traps were installed on tree trunks in the plots in order to monitor changes in insect communities, such as whitespotted sawyers, associated with dying or recently dead trees. No whitespotted sawyers were found in the traps. However, many specimens of bark beetles and weevils were collected, and some species may be indicators of mortality risks in the short term. The link with the UQAM–CFS project will provide valuable information in that regard.

Assessments of stand health and tree monitoring will continue to be carried out in the next few years in areas showing mortality risks. These activities will help to improve and validate the assessment method, but above all, they will provide an updated profile of SBW-caused tree mortality in the region that will be very useful for forest managers. It is vitally important that this information be taken into account in forest planning (for example, to provide a new direction for harvesting) in order to limit economic losses and contribute to sound management of the spruce budworm outbreak.

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Notes

17. Profitability of Spraying for Spruce Budworm and Market Opportunities for Damaged Wood

Jean-François Côté and Jean-Philippe Brunet
Consultants forestiers DGR inc.

With the introduction of a new government timber production strategy at a time when a spruce budworm (SBW) outbreak is taking on such proportions as to be deemed out of control, it is appropriate for forest engineers to provide some insight as to the best use of public funds in this context. From an economic perspective and for the well-being of society, is it more worthwhile to establish high-yield plantations, set up commercial thinning workshops, bring unproductive sites back into production, protect recent silvicultural investments or implement a spraying program to minimize conifer losses in SBW-infested areas?

And when the wood damaged by the outbreak is no longer suitable for processing into sawn lumber and pulp and paper products, is it viable, as foresters in British Columbia did with the pine forests decimated by mountain pine beetles, to harvest the dead wood and use it, for example, to produce energy?

As part of their duties and obligations to the public, forest engineers must support any measures that they feel will help to improve the forest heritage and the well-being of society. Forest engineers must also inform the public or notify the Ordre des ingénieurs forestiers du Québec when they find that a forest policy, measure or provision may be harmful to the forest heritage. The issues associated with protecting forests against SBW and stepping up efforts to implement more forest management, and to salvage and find new uses for damaged wood are of direct concern for forest engineers because they require that the use of their skills in the areas of forest economics, forest heritage protection and finding new uses for wood. To deal with these three issues, forest engineers must use their expertise to inform society about making the best possible choices. In a context where public funds are limited and where other required public services are competing for those funds, it is necessary to provide a rationale relative to the cost-effectiveness of activities funded by taxpayer dollars.

In 2008, the Ministère des Ressources naturelles du Québec hired Consultants forestiers DGR to carry out a study to assess the profitability of an insecticide spraying program to control SBW. The objective of this spraying program, beginning possibly in 2009, was to limit the damage and foreseeable timber losses in order to maintain the level of harvesting over time, as determined in allowable cut calculations. The spraying program would include the spraying of managed and unmanaged young and growing stands as well as the spraying of managed and unmanaged mature or nearly mature stands, using an insecticide mixture based on the scale and severity of the outbreak, available budgets, and with other possible options taken into consideration, such as salvage cutting (harvesting) of the affected quantities of timber. It should be noted that in a situation of overabundance of mature forests, as is the case in many forest management units of the boreal forest, there is no doubt that sustained-yield harvesting by itself cannot be enough to prevent losses of SBW-affected timber. Consequently, the spraying strategies will have to include old-growth stands.

"One dollar invested in spraying equals two dollars for society"

This statement needs to be backed up by well-documented arguments and a sensitivity analysis in order to provide an understanding of the effects of multiple inputs in a model used to assess the profitability of a SBW control program, because there is some degree of variability in the potential behaviour of the insect outbreak, in the vulnerability of stands, and in the relative effectiveness of insecticide spraying.

The following parameters were assessed in DGR's 2008 study: (1) discount rate; (2) anticipated period of time before the benefits are achieved or the period of time elapsed before harvesting; (3) cost of the strategy in today's dollars; (4) avoided losses measured in merchantable volumes associated with the spraying protection strategy; and 5) economic benefits derived from each cubic metre harvested and processed. A simple analysis tool in Excel format was developed in order to assess the net present value (NPV) or the cost/benefit ratios of various scenarios.

In practice, the stands selected for spraying protection will be large expanses of forest that are not yet mature for harvesting. Mature forests that are likely to sustain SBW-caused damage will be given priority for salvage cutting by the forest industry over the next few years, based on the industry's capacity to harvest quantities of timber at risk of being lost. Figure 1, prepared using data gathered by Alain Dupont's team at the SOPFIM, shows the merchantable volume of **living** conifers measured 14 years after the most recent outbreak, based on the age category of the stands prior to the outbreak. It shows a loss of 40 m^3/ha to 60 m^3/ha for the 36-to-45 and the 46-to-55 age categories, respectively. That is why, in an assessment of the impact of spraying as a protection measure for stands dominated by balsam fir and white spruce, it is appropriate to use an average value of **50 m^3/ha** to serve as the net gain effect or **avoided loss in terms of tree mortality and reduced growth** relative to a non-spraying scenario.

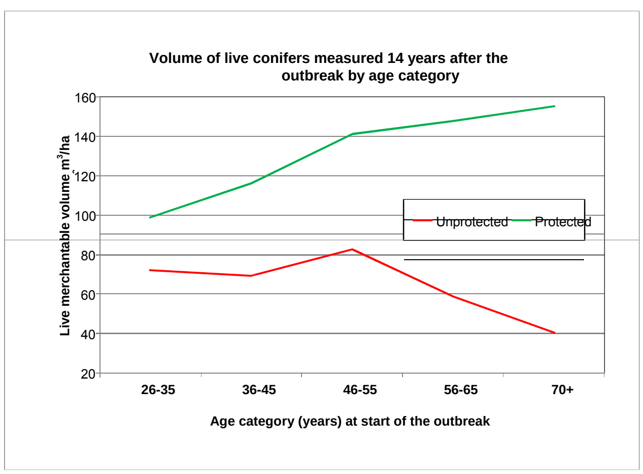

Figure 1 – Merchantable volume of live conifers

The following chart is a summary of the sensitivity analysis on which the report's main conclusion was based. Assuming a net social discount rate for inflation of 4%, a 20-year waiting period between the start of spraying and harvesting, and an income of $35/m^3$ (total of the merchantable value of standing timber, employee salaries and earnings for businesses), a spraying sequence that would cost $400/ha in today's dollars and make it possible to save 50 m^3/ha would result in a return of 2.0 times the investment cost.

Profitability of *B.t.* spraying based on treatment cost and anticipated benefits
(i.e. product of the saved volume multiplied by the benefits associated with that volume)

Chart of cost/benefit ratios

Relative difference or avoided loss in SEPM volume (m^3/ha) in a scenario of spruce budworm infestation without spraying*

Updated cost ($/ha) of the spraying sequence spread over the next few years

Cost ($/ha)	5	10	15	20	25	30	35	40	45	50	55	60
240	0.3	0.7	1.0	1.3	1.7	2.0	2.3	2.7	3.0	3.3	3.7	4.0
260	0.3	0.6	0.9	1.2	1.5	1.8	2.2	2.5	2.8	3.1	3.4	3.7
280	0.3	0.6	0.9	1.1	1.4	1.7	2.0	2.3	2.6	2.9	3.1	3.4
300	0.3	0.5	0.8	1.1	1.3	1.6	1.9	2.1	2.4	2.7	2.9	3.2
320	0.2	0.5	0.7	1.0	1.2	1.5	1.7	2.0	2.2	2.5	2.7	3.0
340	0.2	0.5	0.7	0.9	1.2	1.4	1.6	1.9	2.1	2.3	2.6	2.8
360	0.2	0.4	0.7	0.9	1.1	1.3	1.6	1.8	2.0	2.2	2.4	2.7
380	0.2	0.4	0.6	0.8	1.1	1.3	1.5	1.7	1.9	2.1	2.3	2.5
400	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0	2.2	2.4
420	0.2	0.4	0.6	0.8	1.0	1.1	1.3	1.5	1.7	1.9	2.1	2.3
440	0.2	0.4	0.5	0.7	0.9	1.1	1.3	1.5	1.6	1.8	2.0	2.2
460	0.2	0.3	0.5	0.7	0.9	1.0	1.2	1.4	1.6	1.7	1.9	2.1
480	0.2	0.3	0.5	0.7	0.8	1.0	1.2	1.3	1.5	1.7	1.8	2.0
500	0.2	0.3	0.5	0.6	0.8	1.0	1.1	1.3	1.4	1.6	1.8	1.9
520	0.2	0.3	0.5	0.6	0.8	0.9	1.1	1.2	1.4	1.5	1.7	1.8
540	0.1	0.3	0.4	0.6	0.7	0.9	1.0	1.2	1.3	1.5	1.6	1.8
560	0.1	0.3	0.4	0.6	0.7	0.9	1.0	1.1	1.3	1.4	1.6	1.7
580	0.1	0.3	0.4	0.6	0.7	0.8	1.0	1.1	1.2	1.4	1.5	1.7
600	0.1	0.3	0.4	0.5	0.7	0.8	0.9	1.1	1.2	1.3	1.5	1.6

*Volume of balsam fir, spruce, jack pine and tamarack

A ratio equal to 1.0 means that the activity has an actual yield rate equivalent to 4%.
Value of income per cubic metre of conifers: $35/m^3$
Number of years before harvesting can take place: 20 years

What will the future timber production strategy be?

Investments in intensive silviculture must be assessed on the same basis and according to the same criteria as investments to protect forests against SBW, i.e. with the dual objective of maximizing future stand yield while protecting existing timber capital. Profitability appears less evident in the case of silvicultural investment projects involving very young trees, such as tree planting, land clearing or precommercial thinning, when the benefits are obtained half a century later.

The economic assessment model that was developed by the Timber Marketing Board (TMB) and recently made available can be used to carry out simulations of intensive forest management tasks. However, a comparative economic assessment with natural forest development reference scenarios suggests that intensive scenarios rarelu are cost effective. Properly cultivated plantations consisting of 2,000 stems per hectare in a fertile area that require two to three intervention activities to maintain tree growth are costly and are not free from the risks related to natural disturbances that could reduce the high yields anticipated in 60 years, for example. The presumed benefits of producing larger-diameter stems are still difficult to take into account in the models given the current uses made of softwood lumber.

Presentations on the results of various simulations were given during the symposium to show the profitability of silvicultural investments in a context where huge sums of money are required to implement more intensive forest management on 5% of the area concerned and, at the same time, to show that a considerable amount of funding will be required from the government and other contributors to the SOPFIM to control the new SBW outbreak.

What to do with dead wood?

The wood from trees killed by SBW will deteriorate fairly quickly owing to the activities of fungi and secondary insects. The wood will quickly become unsuitable for sawn lumber and, eventually, its fibre will no longer be desirable for manufacturing paper products. Over time, the harvesting of damaged wood will become increasingly difficult, costly and hazardous because of stem breakage during handling operations.

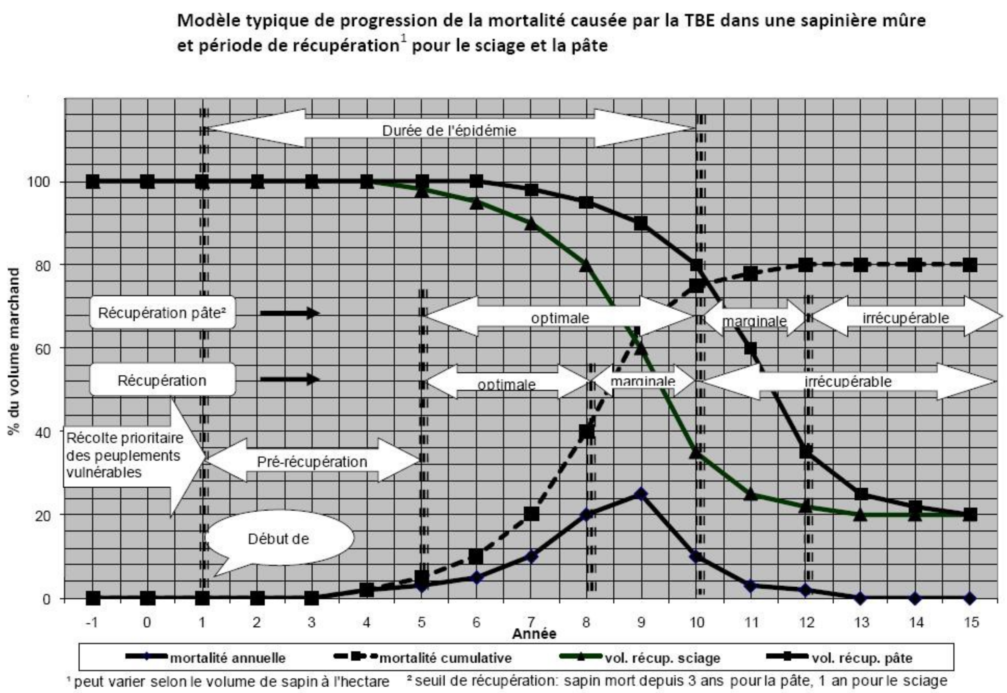

Figure 2 – Standard model of the progression of SBW-caused mortality

English Translation

Modèle typique de progression de la mortalité causée par la TBE dans une sapinière mûre et période de récupération[1] pour le sciage et la pâte		**Standard model of the progression of SBW-caused mortality in a mature balsam fir forest, and salvage harvesting period for dead wood intended for sawn lumber and pulp**	
		optimale =	**optimal**
Durée de l'outbreak =	**Outbreak duration**	*marginale =*	**marginal**
% du volume marchand =	**% of merchantable volume**	*irrécupérable =*	**unsalvageable**
Récupération pâte[2] =	**Salvage harvesting for pulp**	*Année =*	**Year**
Récupération	**Salvage Harvesting**	*mortalité annuelle =*	**Annual mortality**
Récolte prioritaire des peuplements vulnérables =	**Priority harvesting of vulnerable stands**	*mortalité cumulative =*	**Cumulative mortality**
Pré-récupération =	**Preliminary salvage harvesting**	*vol. récup. sciage =*	**Volume of wood salvaged for sawn lumber**
Début de =	**Starting from**	*vol. récup. pâte =*	**Volume of wood salvaged for pulp**
[1]peut varier selon le volume de sapin à l'hectare =	**[1]May vary according to the balsam fir volume per hectare**	*[2]seuil de recuperation: sapin mort depuis 3 ans pour la pâte, 1 an pour le sciage =*	**[2]Salvage limit: balsam fir dead for 3 years for pulp dead for 1 year for sawn lumber**

It is said that the most recent outbreak destroyed the equivalent of 10 years of forest harvesting in Quebec. At the current rate at which the outbreak is spreading, and given the extent of the sprayed areas and of areas harvested by the logging industry, there is bound to be a loss of timber that could have been used to meet human needs.

In that regard, it is already necessary to acknowledge what is currently happening in Western Canada with the mountain pine beetle outbreak. There are opportunities in Western Canada to promote the energy potential of wood by setting up wood pellet manufacturing plants and biomass-fuelled electricity cogeneration plants. Starting in 2007, efforts were already being made to develop new wood-concrete products using wood fibre from trees killed by the mountain pine beetle: http://www.unbc.ca/wood-concrete.

On December 30, 2013, the USDA (United States Department of Agriculture) announced the allocation of $10 million in funding to a research consortium overseen by Colorado State University for the purposes of exploring new options for the *in situ* thermo-chemical conversion of pine timber killed by the mountain pine beetle in order to produce liquid biofuels and other by-products.

With the growing world demand for renewable energy with a small ecological footprint, the annual production of wood pellets is expected to increase by 20 million tonnes in 10 years, reaching 35 million metric tonnes per year in 2020. For comparative purposes, one hectare of coniferous forest, which contains an average of 100 m^3/ha, could produce nearly 50 metric tonnes of pellets from fibre salvaged for energy purposes. All that would be needed to supply a pellet-manufacturing plant producing 50,000 tonnes per year is 10 km^2 or 1,000 hectares of damaged forest.

To put everything into perspective, it was estimated, based on the 2013 aerial survey of SBW-caused damage, that more than 32,060 km^2 of forest are affected to varying degrees. Half of the infested areas have been seriously defoliated. During the most recent SBW outbreak, the infested areas in Quebec **expanded at an exponential rate** during the first 10 years. At the peak of the outbreak, 350,000 km^2 or 35,000,000 hectares showed signs of defoliation. When the “light” defoliation category is excluded, the SBW infestation affected slightly more than **31 million hectares**.

Emerging biomass energy markets are creating a new range of opportunities to make use of SBW-damaged wood. This is a promising option for creating wealth from the dead wood found in vast expanses of forest that cannot be salvaged in time or protected through a spraying program.

Notes

18. Spruce Budworm Management Approach

Paul Lamirande
Ministère des Ressources naturelles du Québec

Because forests are essential to the well-being of Quebecers, the government is serious about developing and protecting them, and especially about limiting the negative impact of natural disturbances. As manager of public lands, the Ministère des Ressources naturelles du Québec (MRNQ) must implement management methods to maintain healthy stands and reduce timber losses. Given that spruce budworm (SBW) populations have reached epidemic proportions in several regions of Quebec, the MRNQ is proposing an integrated management approach to minimize the negative impacts of SBW outbreaks. The Forest Protection Directorate is co-ordinating this departmental approach with the support and collaboration of several MRNQ directorates.

Because the protection of forests against insects and diseases is closely linked to forest management, it can only be effective when it is incorporated into an overall approach based on an in-depth knowledge of the forest environment that takes into account the role of tree insects and diseases in forest dynamics. To ensure that this approach is consistent with the ecosystem management principles set out in Quebec's *Sustainable Forest Development Act*, it is important to keep in mind the following specific objectives:

1. Reduce timber volume losses that may result from tree mortality caused by the SBW outbreak;
2. Promote maximum harvesting of timber in SBW-disturbed forests over the medium and long terms;
3. Maintain or restore the natural attributes of stands that are disturbed by SBW and in which forest management is practised;
4. Ensure that age structure targets are achieved and prevent the depletion of stands capable of exercising the ecological roles of old-growth forests.

To achieve these four objectives, the MRNQ is implementing a series of measures that take the development of the outbreak into account and that are based on an understanding of the outbreak's actual and probable effects. To bring this about, the MRNQ is making use of the lessons learned from the last SBW outbreak as well as extensive knowledge of the insect and its effects on the environment. The MRNQ also has various tools for gathering information on the health of stands as the outbreak progresses. The main measures under consideration during an outbreak period are preventive harvesting, preliminary salvage cutting, salvage cutting and direct control measures.

To be able to more effectively respond to the economic and environmental issues arising from the current SBW outbreak, the MRNQ has gathered information on knowledge gaps within the MRNQ directorates concerned. These gaps were classified under six headings: population dynamics and epidemiology; detection; control measures; impact; biodiversity and ecosystems; and forest dynamics. Research and collaborative projects are currently in progress, including several funded directly or indirectly by the MRNQ, and they encompass some of the knowledge gaps identified.

It is necessary for SBW outbreak management that adjustments be made to the Department's planning activities. There are numerous issues that add to the complexity inherent to integrated public forest management, the objective of which is to reconcile the many uses made of public forests. Since 2006, the North Shore region has been the region most affected by SBW and measures have been implemented to effectively deal with the main negative effects of the outbreak. The SBW management approach contains some elements developed for the North Shore region and proposes new potential solutions. To support the implementation of these new solutions, technical guides will be prepared, particularly for forest planning purposes, that can be used by MRNQ professionals working in the region.

Notes

19. Spruce Budworm: After a Century of Observation, Conjecture and Insight, What Can We Predict?

Barry Cooke
Northern Forestry Centre, Natural Resources Canada

The current rise in spruce budworm populations is likely to continue, and develop into a large-scale outbreak. The precise level and extent of damage will depend on several factors that are not well understood or are beyond our control.

Introduction

There are two basic ways of predicting the future: (1) statistical modeling of patterns of the past, assuming the future is a stochastic realization of a previously sampled ensemble; (2) process modeling of those processes which are thought to be most critical to system behaviour, and which are likely to change as we transition out of the past and into the future. Both approaches have been used in the case of the budworm system through data modeling efforts going back more than five decades.

The next outbreak cycle is now upon us (Figure 1), more or less as predicted by Gray et al. (2000), so now is a good time to evaluate the robustness of our science and the degree to which our forecasting ability is constrained by unresolved and/or irreducible uncertainties. Here, we briefly summarize the history of budworm modeling efforts with a view to developing a synthetic understanding and appreciation for what is likely to come next.

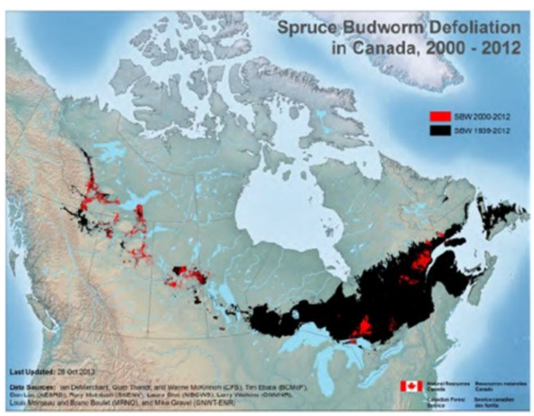

Figure 1. Distribution of spruce budworm defoliation across Canada, historically (black) and over the last 13 years (red). Note (1) the northerly distribution of defoliation in Quebec, and (2) the failure of spruce budworm to cause much damage at higher elevations in the northwest.

The data supporting these modeling efforts come in a variety of forms, which has evolved over the decades (Figure 2). In this paper we discuss models of tree-ring (dendrochronology) data, aerial survey defoliation data, and population survey data.

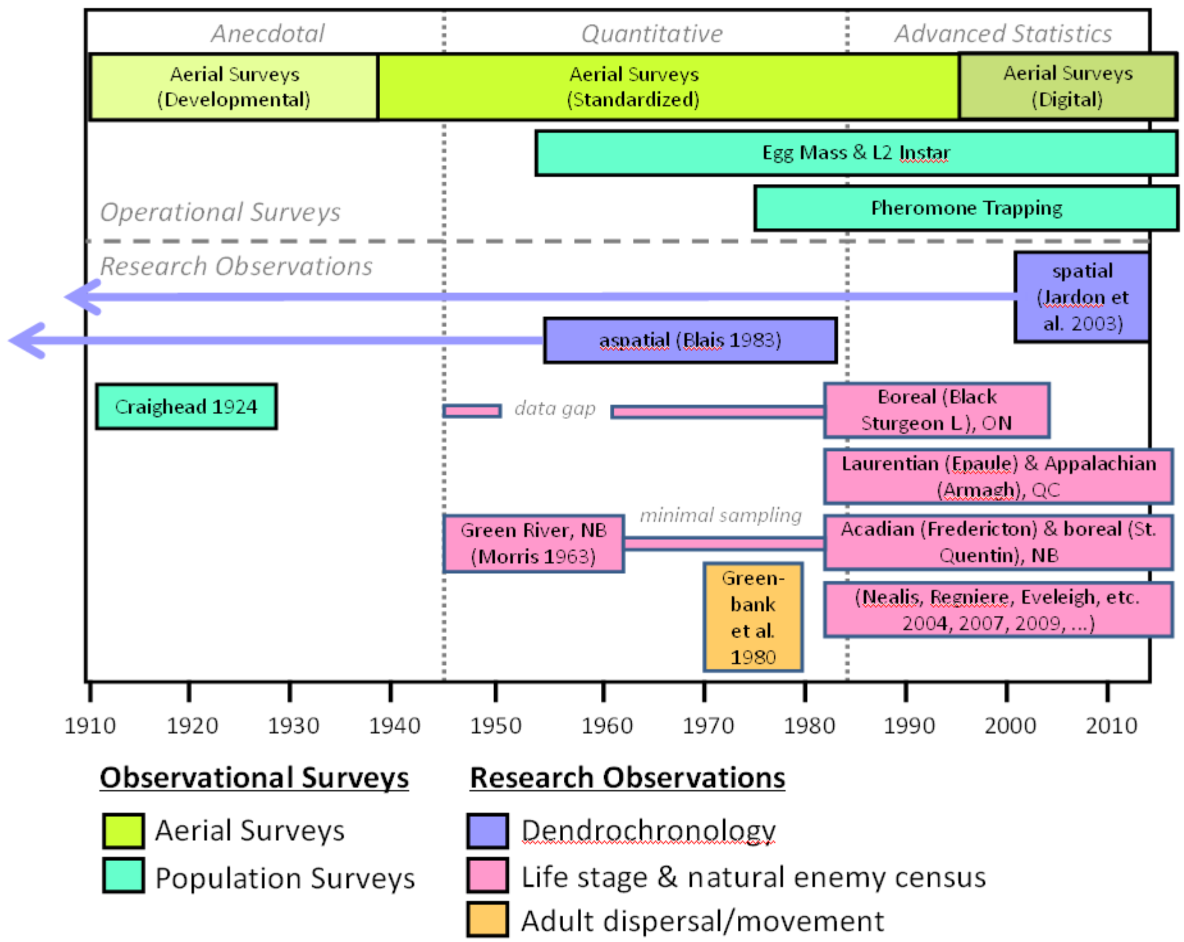

Figure 2. Evolution of data sources describing spruce budworm system behaviour. From small-scale studies at the start of the 20th century to systematic monitoring and large-scale integrated research programs at the end of the 20th century. Scientific advances have followed concurrent methodological improvements in data collection, data analysis, and simulation modeling.

Historical pattern analysis

The longest-term records of budworm activity come from studies of tree-ring data which reveal that the budworm is remarkably periodic in its recurrence in Quebec (Jardon et al. 2003, Boulanger et al. 2012), Ontario (Robert. et al. 2012), and as far west as British Columbia (Burleigh et al. 2002). Figure 3, shows that the budworm may cycle with different frequencies in different parts of its range in eastern North America. More importantly, the amplitude of the oscillation appears to vary in a systematic manner; when it is high in the north it is low in the south, and vice versa.

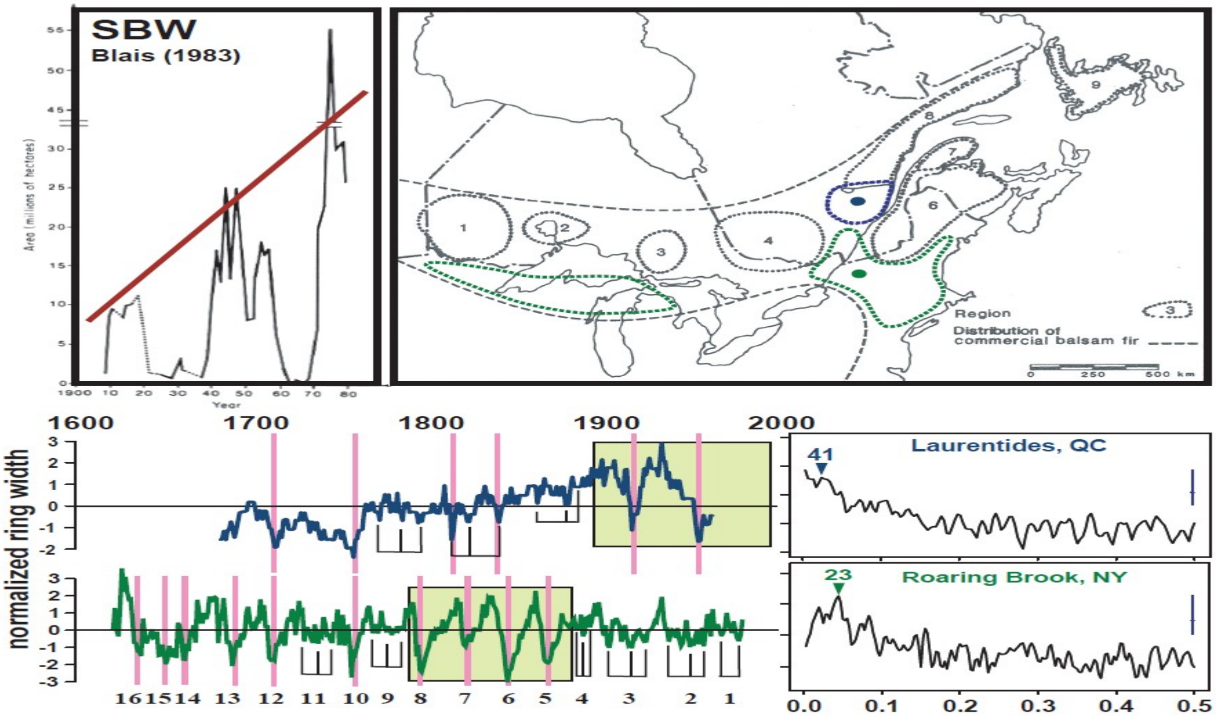

Figure 3. Importance of scale in historical budworm dendroentomological epidemiology. Studying tree-ring records in nine regions of eastern North America (b), Blais (1983) described a 30-year outbreak cycle that, overall, was increasing in intensity over time (a). Although the dominant periodicity in the Laurentian region 5 is 41 years (c), the dominant periodicity in New York–a region Blais did not sample–is 23 years (d). More important is the disappearance of the cycle in the 20th century in New York (f), and its concomitant emergence in Quebec (e). The tree-ring data, as a point-wise estimator, are a good proxy for local population density, unlike the defoliation data in (a), which are more indicative of large-scale outbreak dynamics.

Cluster analyses of defoliation data from Quebec over the 20th century reveal a similar pattern (Figure 4), with two dominant features: (1) an increasing trend through much of the northeast in the intensity of the second outbreak over the first, with the opposite declining trend in the southwest; (2) a 24-year cycle in parts of the Ottawa valley (black box).

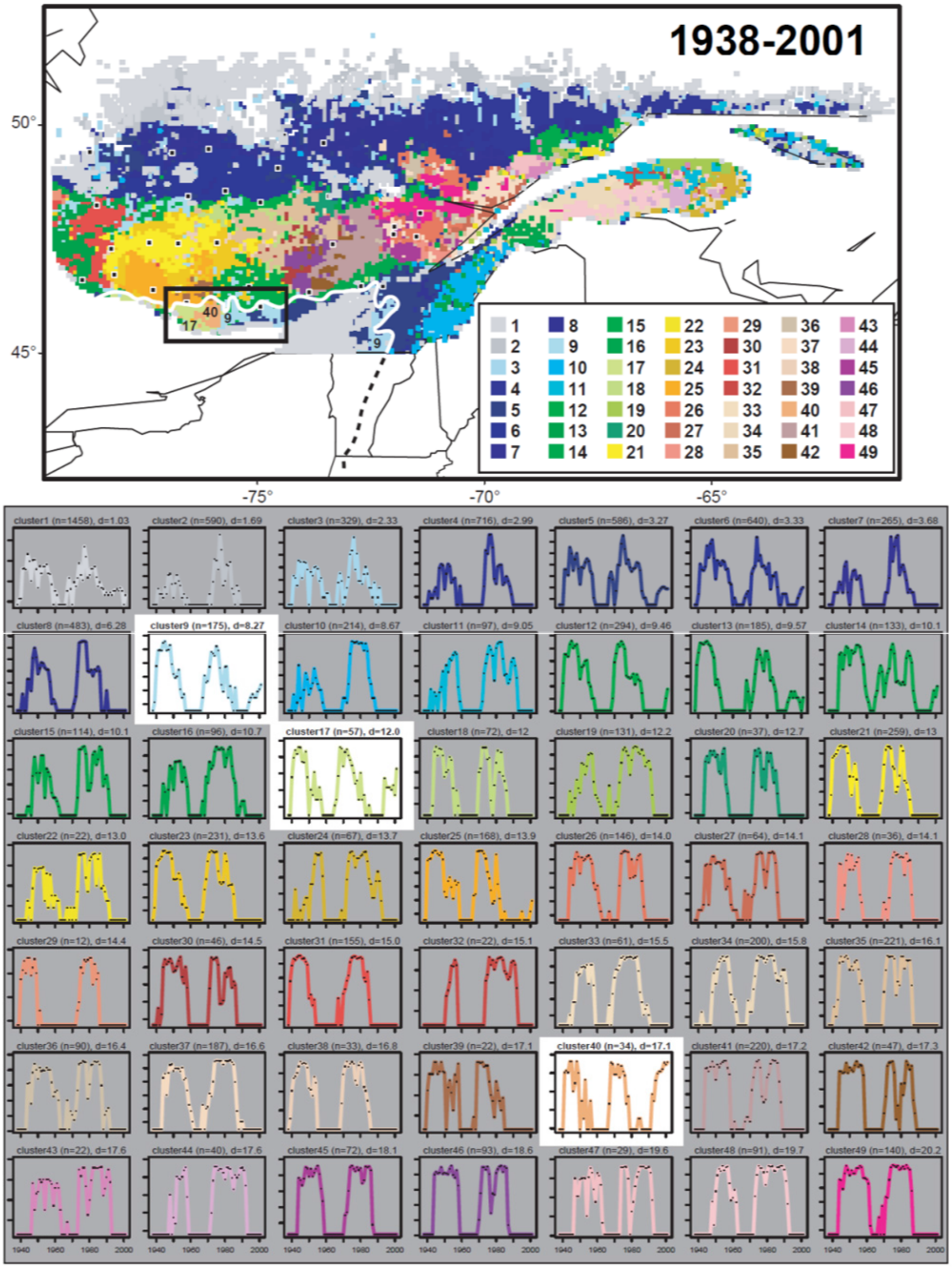

Figure 4. Spatial history of spruce budworm area defoliated in Quebec, 1938-2001. Cluster analysis reveals several important variations, including (1) opposing trends in northern versus southern Quebec, and (2) a substantial anomaly in cycle frequency in the Ottawa Valley (clusters 9, 17, 40), with a 24-year cycle rather than the 30-year cycle of the provincial average.

Insights and forecasting

Although the spruce budworm clearly cycles, the patterns in the Quebec tree-ring data and defoliation data appear to be "noisy" or "rough". In fact, this roughness is a characteristic feature of budworm fluctuation across its range, and the pattern is evident in finely resolved population data as well (Figure 5).

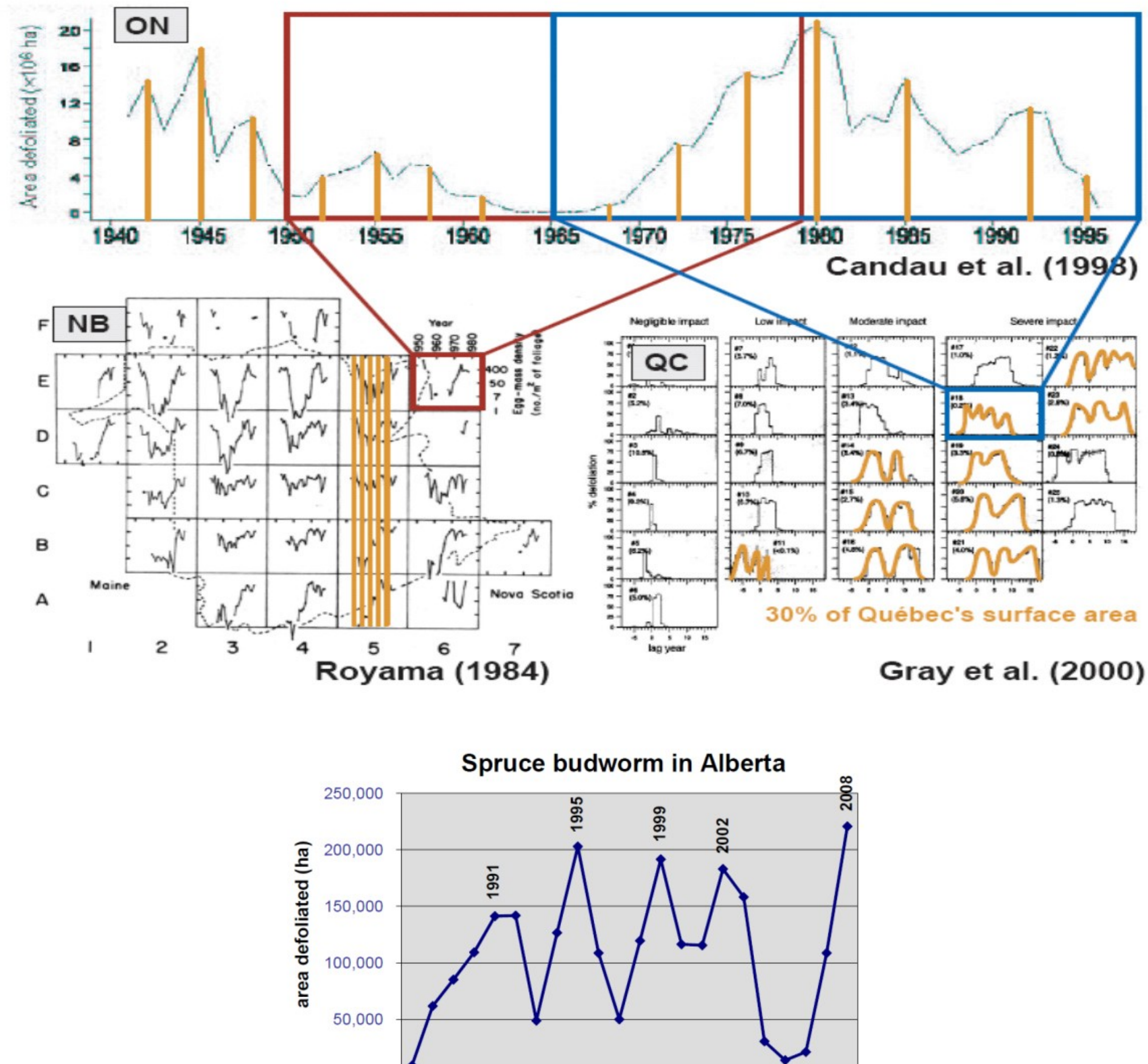

Figure 5. Published data from Ontario, Quebec and New Brunswick and unpublished data from Alberta all indicate high-frequency 3-7 year fluctuations that overlie the primary multi-decadal outbreak cycle.

We now know that these high-frequency fluctuations are attributable to migratory dynamics resulting from a reciprocal herbivory feedback loop (Nealis & Regniere 2004b). These "sawtooth "oscillations" (Royama 1984) can mislead forecasters who do not appreciate the determinacy of periodic rebound. A severe outbreak that lasts 16 years will tend to come in four distinct pulses. The existence of high-frequency fluctuations in budworm numbers and impact may occasionally obscure the low- frequency cycle, as can be seen in central New Brunswick and Alberta. Spatially, it is not entirely clear what leads to the belt-shaped distribution of defoliation in eastern North America, although the model time-series analysis of Régnière et al. (2012), and the spatial analyses of Gray (2008, 2013) and Candau & Fleming (2011), and the mechanistic reasoning of Fleming (1996) all point to a climatic limitation–budworm being limited by cold in the North and by heat in the South. The opposing trends in the tree-ring data (Figure 3) lead to the interesting possibility that the belt-shaped distribution of budworm activity is modulated by natural and anthropogenically forced variations in climate, represented in the schematic of Figure 6.

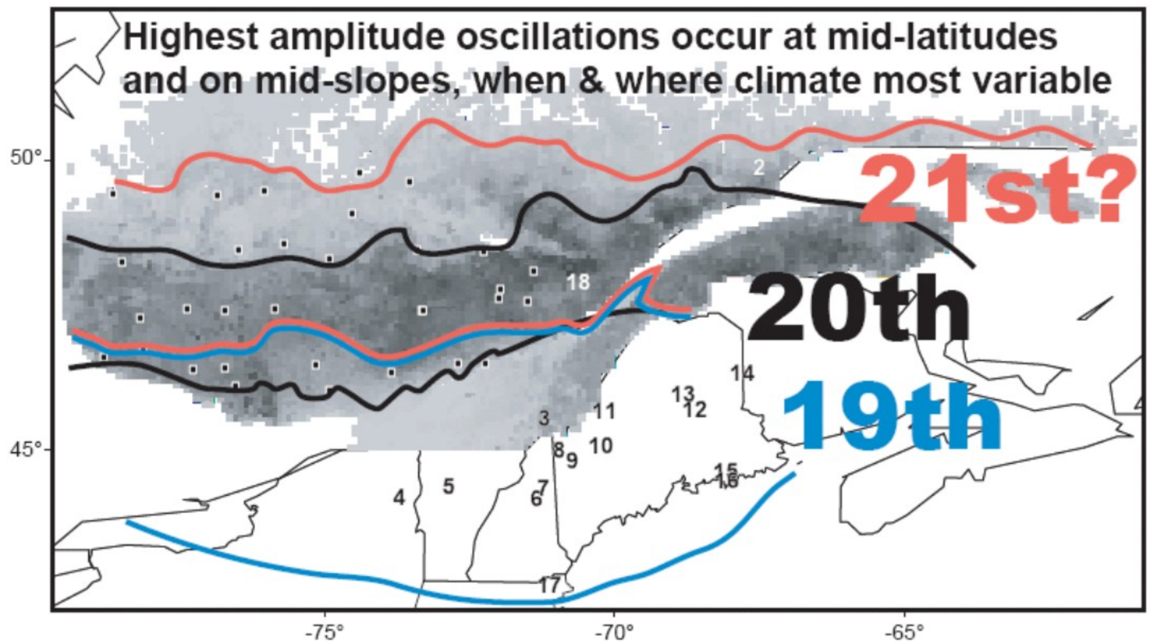

Figure 6. Northward shift in the distribution of intense spruce budworm activity from the 19th century to the 20th century, potentially extending into the 21st century under a deterministic trend in anthropogenic climate warming.

The consequences of this "belt shift" hypothesis are somewhat clear, but not clear enough to support specific client needs in the area currently under attack by budworm. It is clear that a warming future might lead to less intense budworm outbreaks in the southern part of its range. But what specifically might this imply for southern New Brunswick and Maine? What are the 30-year (long-term, climatic-scale) expectations? How might observations deviate from expectation in the short run (the scale at which weather anomalies occur)?

There are a number of key uncertainties that prevent us from formulating a definitive reply to this question. The sources of the uncertainties are twofold: (1) a lack of necessary data on rate processes that we know are key; (2) a lack of appropriate models for interpreting historical data. The first constraint is always going to be a challenge. The second constraint is one that can be resolved imminently. Figure 7 shows a simple way in which the epidemiological models of the past may be reformulated to accommodate our current understanding based on mechanistic process ecology.

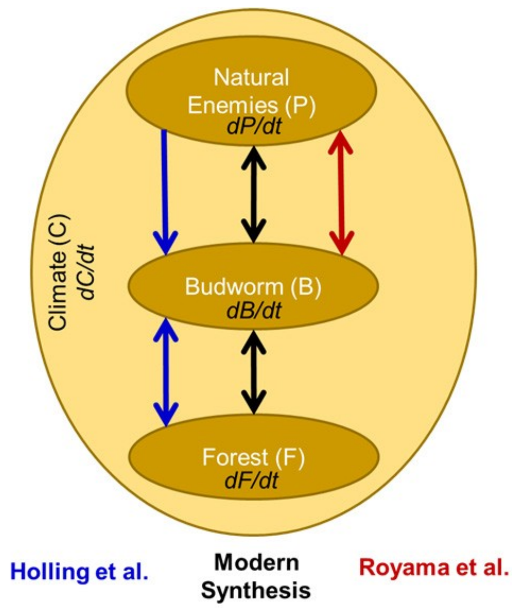

Figure 7. Minimal model of spruce budworm population dynamics might include both reciprocal feedback loops that exist in any tritrophic (enemy-budworm-forest) system. The original models of Holling et al. (left) did not close the top (budworm-natural enemies) feedback loop. The later models advocated by Royama et al. (right) downplayed the bottom (budworm-forest) feedback loop. A modern synthesis (centre) would consider both levels jointly and would include both the potential for both eruptive behaviour and cyclic behaviour.

With this model as a template it is perhaps clearer now how it will always be a challenge to correctly parameterize the four rate functions and the two sets of transfer functions on the reciprocal feedback loops. More specifically, information on the status of natural enemy communities is probably always going to be limiting in this system, as operational monitoring costs of diverse natural enemies are exceedingly high (Eveleigh et al. 2007). This means there will always be, as in meteorological modeling, a certain level of irreducible uncertainty that will always constrain our ability to forecast future budworm impacts.

Conclusion

The foregoing analysis was developed largely in 2003-04. It is heartening to see that patterns since that time have evolved in accordance with those early expectations in terms of the development of large-scale defoliation in the North Shore region of Quebec. What happens next depends on some critical processes that are currently the subject of investigation, especially budworm aggregation (Régnière et al. 2013), dispersal (Royama 1980; Régnière and Lysyk 1995; Sturtevant et al. 2013), and the multiple reciprocal effects of host forest structure (Nealis and Régnière 2004a, 2009; Bouchard et al. 2005; Campbell et al. 2008).

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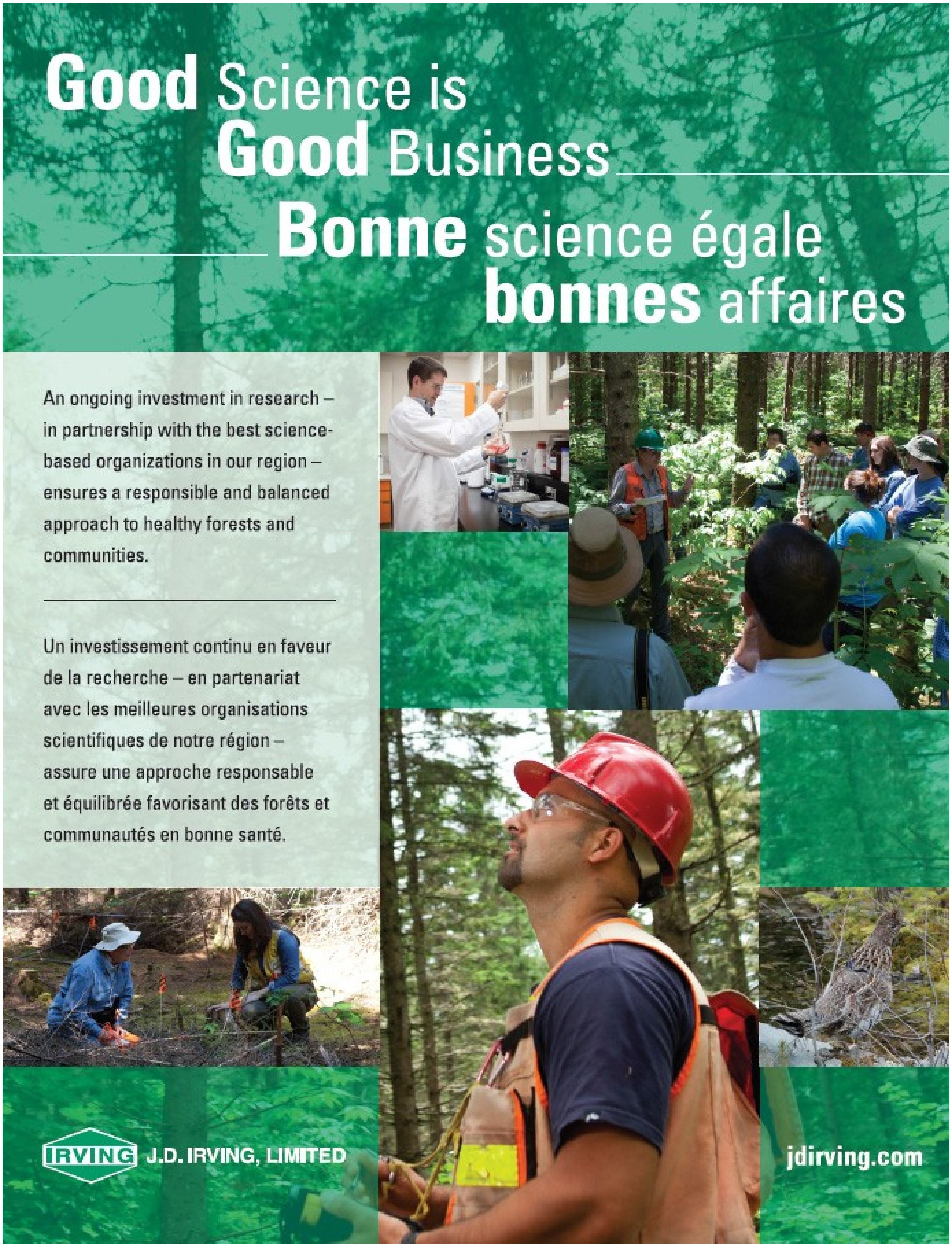
Notes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