COOPERATIVE FORESTRY RESEARCH UNIT
Research Proposal

Date of Proposal: March 30, 2010

Project Title: Preparing for spruce budworm in Maine: decision support and strategies to reduce impacts

Abstract

Spruce budworm (SBW) is the most widespread and economically important forest insect pest in eastern North America, and periodic outbreaks result in up to 85% mortality in forests containing large quantities of spruces and balsam fir. Both theory and past experience suggest that another spruce budworm outbreak is due across the Northern Forest region. This places Maine's forest, with its high spruce-fir content, in a vulnerable position. Managing that forest in light of an impending budworm outbreak can best be supported if forest managers in Maine (a) understand the magnitude of potential consequences of the next SBW outbreak on their wood supplies, land values, and management plans, (b) implement appropriate harvesting and silviculture in advance of that outbreak to mitigate consequences when it occurs, and (c) have in place a sound decision support system to allocate harvest and protection activities once the outbreak begins. Over two years, this project will implement the Spruce Budworm Decision Support System (originally developed for New Brunswick) and other analytical methods to help equip forest managers in Maine with these capabilities. Specific objectives are to:

1) build SBW defoliation scenarios representative of levels observed in New Brunswick and Maine from available historical data;
2) integrate Forest Inventory and Analysis (FIA) data, the Forest Vegetation Simulator (FVS), and host defoliation-damage relationships to quantify stand volume impacts in Maine stands;
3) customize the Spruce Budworm Decision Support System (DSS) for Maine using those defoliation scenarios and stand impacts to quantify potential impacts and to aid in protection design;
4) produce from the DSS, maps of stand volume impact by outbreak scenario from available CFRU member GIS data and stand yields;
5) develop an aspatial timber supply model for Maine using FIA data, FVS projections, typical silviculture systems, and SBW outbreak and defoliation-impact relationships to help design and quantify the benefits of silviculture portfolios for a wide range of outbreak start dates (2015, 2025, 2035, 2045) and severities.

Name	Organization	Phone	Email
Principle Investigators			
Dr. David A. MacLean	University of New Brunswick	506-458-7552	macleand@unb.ca
Dr. Chris R. Hennigar	University of New Brunswick	506-447-3339	chris.hennigar@unb.ca
Dr. Thom A. Erdle	University of New Brunswick	506-453-4937	erdle@unb.ca

Co-Principle Investigator

Luke Amos-Binks (GIS analyst)	University of New Brunswick

Cooperating CFRU Members or Other Research Organizations

Dr. Jeremy S. Wilson	University of Maine
Dr. Bob Wagner	University of Maine
Greg Adams	J.D. Irving, Limited

Start and Termination Dates of Study

Two-year study; September 1st, 2010 to August 31st, 2012

Statement of Authorization

David A. MacLean
Professor, Faculty of Forestry and Environmental Management
University of New Brunswick

Background

Spruce budworm (SBW) is the most widespread and economically important forest insect pest in eastern North America. Periodic SBW outbreaks typically last about 10 years, and result in up to 90% growth reduction and 40-85% mortality in forests containing high quantities of spruces and balsam fir. As a result, mitigation measures such as insecticide spraying and salvage of impacted stands have been widely used in past outbreaks. Nevertheless, growth and mortality losses wreak havoc with forest management plans and cause major uncertainty about future forest conditions.

During the twentieth century, two budworm outbreaks impacting Maine caused extensive tree mortality (1913-1919 and 1972-1986), while a third in the late 1940s caused defoliation, but was not a major mortality event (Irland et al. 1988; Seymour 1992). The 1970s and 1980s era budworm outbreak stimulated a major insecticide spray program as well as extensive road building to salvage vulnerable, dead, and dying stands. The outbreak and subsequent harvesting regenerated large forest areas in a relatively short time span, and current estimates suggest that 2.4 million acres of Maine forest consist of maturing spruce and fir dominated stands (medium and large diameter). This area supports a standing volume of 3.3 billion cubic feet of fir and spruce in the more vulnerable medium and larger diameter classes (McWilliams et al. 2005). Both theory and past experience suggest that another SBW outbreak is due across the Northern Forest region.

A vulnerable forest combined with a likely recurrence of a budworm outbreak, heightens the need for a systematic approach to mitigating the negative impacts when the outbreak occurs. Such an approach should address three fundamental questions:

[1] What is at stake?

Quantifying the potential consequences of an SBW outbreak on wood supplies, land values, and management plans defines the magnitude of ***what is at stake*** and provides an important basis for deciding upon appropriate management response. Developing this knowledge now is important because the forest management context for the next SBW outbreak will be considerably different than extant the 1970s and 1980s outbreak.

[2] What can be done in advance of the outbreak to mitigate impacts?

How the forest is managed from present to time of outbreak will change its character and thus its vulnerability to an SBW outbreak. Harvest and silviculture strategies to be implemented ***in***

advance of the outbreak can be designed to reduce vulnerability of the forest, and thus, magnitude of budworm-induced impacts once an outbreak begins. Such proactive on-the-ground management is consistent with the admonition that "the time to manage budworm damage is between outbreaks…" (Seymour 2009, CFRU Budworm Workshop). Much opportunity exists to systematically explore vulnerability reduction measures, and through quantification of costs and benefits, identify those which are most effective.

[3] What can be done during the outbreak to mitigate impacts?

Judicious design and allocation of salvage harvest and protection measures is critical to limit impacts ***during the outbreak*** itself. Building a fully supportive decision support framework now for use once an outbreak begins is possible and advisable to take advantage of advances in control options, entomological expertise, protection planning and delivery technology; and to account for the numerous changes that have occurred since the outbreak of the 1970s and 1980s, including differences in forest ownership, widespread use of partial harvesting, more extensive road networks, emergence of a forest bio-fuels and bio-products sector, emergence of carbon as a resource value, and differences in political stance and financial resources. Given uncertainties associated with these changes, proactive assessment of vulnerability to, and implications of, a future SBW outbreak is essential to put in place effective policies, response strategies, and appropriate infrastructure before these events unfold.

The Spruce Budworm Decision Support System (SBW DSS), originally developed by the Canadian Forest Service, is available to assist with SBW and forest management planning with respect to these three questions. It quantifies marginal timber supply (m^3/ha) benefits of protecting stands against budworm defoliation (Erdle 1989; MacLean et al. 2001). The DSS allows users to determine effects of different foliage protection (insecticide use) or salvage harvesting strategies on forest development and outputs, and quantifies relative volume benefit of alternative spray or salvage blocks (MacLean et al. 2000a, 2002). The SBW DSS has been implemented for all forest in New Brunswick and for test areas in four other provinces, and used by used by governments and private agencies in New Brunswick, Ontario, and Saskatchewan to quantify budworm defoliation-caused impacts and minimize spruce-fir harvest losses. In recent years, the DSS has evolved in terms of 1) stand-species impact resolution (separation of host species defoliation and volume impact projections; Hennigar et al. 2008), and 2) better integration of stand-impact projections with industrial-scale timber supply models such as Woodstock (Remsoft 2007) to allow optimized re-planning of the harvest schedule and salvage of budworm-killed timber volume (Hennigar et al. 2007). This integrated model framework allows for linear optimization of forest-pest management objectives (e.g., timber supply, habitat, foliage protection, net revenue).

In a CFRU-funded project, Hennigar (2008): 1) developed methods (based on MacLean et al 2001, 2002; Hennigar et al. 2007) to apply the SBW DSS framework on two test forest township datasets in Maine, 2) projected spruce-fir volume reductions from 2010-50 for each township under hypothetical moderate and severe SBW outbreak scenarios beginning in 2010, and 3) demonstrated effects of alternative spatiotemporal protection intensities (0-70% of susceptible forest) and salvage to minimize budworm caused volume loss.

This proposal is to continue implementation of the SBW DSS for all host forest areas in Maine. Hennigar (2008) described the successful test-case implementation. Hennigar (2008) analyzed two Maine townships dissimilar in available forest information and stand types: 1) a 10,500 ha northeastern industrial forest holding operated by J. D. Irving, Limited, having detailed growth and yield projections and an existing Woodstock timber supply model; and 2) a 9,700 ha southeastern forest holding owned by a Real Estate Investment Trust and managed by American Forest Management with relatively coarse growth and yield information (broad stand types and species resolution), no pre-defined timber-supply model or description of forest interventions planned during the next 10-30 years. The two test forest townships contained 78% and 85% of stand types susceptible (≥10% spruce-fir current inventory volume) to SBW.

Project Objectives

In this project, we propose to implement the SBW DSS in Maine to determine: 1) the likely spatial distribution and magnitude of stand volume impacts if a SBW outbreak occurs in the next 5 years on CFRU members' lands; and 2) robust silviculture systems or schedules that consistently reduce SBW impact on long-term harvest, given uncertain timing of outbreak initiation and defoliation severity.

Primary objectives are to:

1. build SBW defoliation scenarios representative of levels observed in New Brunswick and Maine from available historical data;
2. integrate Forest Inventory and Analysis (FIA) data, the Forest Vegetation Simulator (FVS), and host defoliation-damage relationships to quantify stand volume impacts specific to Maine stand types (e.g., what volume loss is expected 15 years post severe defoliation for a mature spruce-fir shade-intolerant hardwood stand type?);
3. map stand volume impact by outbreak scenario from available CFRU member GIS and stand yields; and
4. develop a broad aspatial timber supply model for Maine using FIA plots as inventory, FVS projections, Maine silviculture systems, and SBW outbreak and defoliation-impact relationships to identify universal silviculture and management that consistently reduce future harvest impacts from SBW across a range of outbreak start dates (2015, 2025, 2035, 2045) and severities.

The primary objectives of this project relate to the three general questions stated in the project's background above and answering specific questions as follows:

[1] What is at stake?

What is the likely spatial distribution and magnitude of stand volume impacts one could expect if a SBW outbreak was to occur sometime in the next 5 years on CFRU members' lands?

[2] What can be done to mitigate impact in advance of an outbreak?

Can robust silviculture systems or schedules be identified that consistently reduce SBW outbreak impact on long-term harvest given uncertain timing of outbreak initiation and defoliation severity?

[3] What can be done to mitigate impacts during an outbreak?

How much harvest impact resulting from SBW can be avoided by implementing various levels of salvage and foliage protection (bio-insecticide application)?

Methods

The current proposed project will expand the approach used by Hennigar (2008).

1. Quantify forest and spatially explicit volume impacts for CFRU members' lands.

a) Define state-wide balsam-fir defoliation scenarios based on existing historical Maine defoliation data and compare with New Brunswick 'moderate' and 'severe' SBW outbreak scenarios defined in MacLean et al. (2001; 2002) and used in Hennigar (2008).
b) Modify balsam fir outbreak scenarios to reflect lower spruce defoliation (Hennigar et al. 2008) and explore effects of this specific assumption on volume impact.
c) Simulate outbreak and foliage protection scenarios, including base (no defoliation), moderate, severe, and historic Maine outbreak patterns (beginning in 2012), combined with foliage protection scenarios using biological insecticide (*Bacillus thuringiensis; Bt*) application on 10, 20, 40, or 70% of susceptible area, when fir defoliation >40%.
d) Explore modified *Bt* efficacy projected using relationships from population-defoliation process models (Régnière and Cooke 1998), and explore effects on stand volume impact.
e) Develop a stand-alone SBW extension for FVS, to allow simulation of SBW defoliation effects on tree growth and mortality using existing defoliation-growth and defoliation-survival relationships (Erdle and MacLean 1999). In Hennigar (2008), the STAMAN stand growth model from New Brunswick was used to estimate relative stand impacts from SBW, which were applied to Maine stands. This project will extend defoliation modeling capabilities of STAMAN to FVS by developing software to automatically build FVS keyword files that instruct FVS to reduce tree survival and growth for a given level of defoliation during runtime.
f) Calculate a Maine SBW stand impact matrix (SIMPACT), which specifies marginal changes to stand volume for each defoliation scenario by stand type and size class, using Maine FIA susceptible plots (>10% host composition), the FVS-SBW extension, and SIMPACT calculation methods described in Hennigar (2008).
g) Apply the SBW DSS framework to each CFRU member lands, using: i) area of stand types (GIS), ii) classification of current landbase stand types by budworm stand impact type (volume composition and size class), and iii) host species volume projections for each stand type. This provides all necessary data to link to relative volume impacts in the SIMPACT by defoliation scenario. Relative time-dependant volume impacts will be multiplied against base yield volumes for each area record, to calculate absolute volume impact across space and time, and produce spatially explicit (GIS) estimates of stand volume impacts.
h) Apply a series of GIS select and action queries for each township database to link future stand conditions (time and/or age, host species yield) with the SIMPACT to quantify volume losses over time for outbreak and protection scenarios.

<u>To develop stand impact maps for specific CFRU member landbases, we will need:</u>

- GIS shapefiles and respective coordinate projection systems with associated meta-data describing table columns and data contained within, such as:
  - species names and % compositional attributes (e.g., % by volume, % by cover);
  - stand age, development stage (e.g., young, mature, old), height class, or size class (e.g., sapling, pole)
- Yields of merchantable volume by species over age or time for each stand type.

2. Determine silviculture and management strategies and treatment schedules to minimize SBW negative effects on harvest, regardless of outbreak timing or severity.

a) Develop an aspatial timber supply model (Woodstock; Remsoft 2007) for Maine forests with i) broad stand types defined from, and area proportional to, i) Maine FIA inventory, ii) silviculture systems defined through consultation with CFRU members, and iii) stand type yields defined from mean FVS projections of FIA-derived tree lists (i.e., stand tables) and silviculture systems.
b) Explore possibilities of using data from the Wilson et al. Maine NSRC/SSI project, which is developing i) satellite change detection maps for northern Maine (since the 1970s; in combination with a current type map allows determination of softwood stands < and >40 yrs old); and ii) a process to identify proportions of budworm host species in current stands based on FIA plot locations (with known proportions) and timed images showing differences in phenology. The result would be a map of host proportions and maturity.
c) Represent SBW outbreak and defoliation-impact relationships developed above, as well as foliage protection and salvage treatments, into the timber supply model, using methods from Hennigar et al. (2007) and Hennigar (2008).
d) Identify base-case (no defoliation) treatment schedules to maximize non-declining spruce-fir harvest discounted at 5% over 100 years.
e) Simulate a range of SBW outbreak start dates (2015, 2025, 2035, 2045) and severities (moderate, severe, historical Maine), and determine effects on harvest levels.
f) Using re-optimization of the harvest schedule and simulated deterministic outbreak effects, identify differences in amount, type, and/or timing of management or silviculture treatments that minimize SBW impacts on harvest.
g) Determine effects of area foliage protected or salvaged on results, and their interaction with pre-outbreak silviculture scheduling, to minimize SBW-caused harvest reductions.
h) Make recommendations from steps *e* and *f* above regarding management strategies that should be avoided or used to minimize harvest risk to SBW.

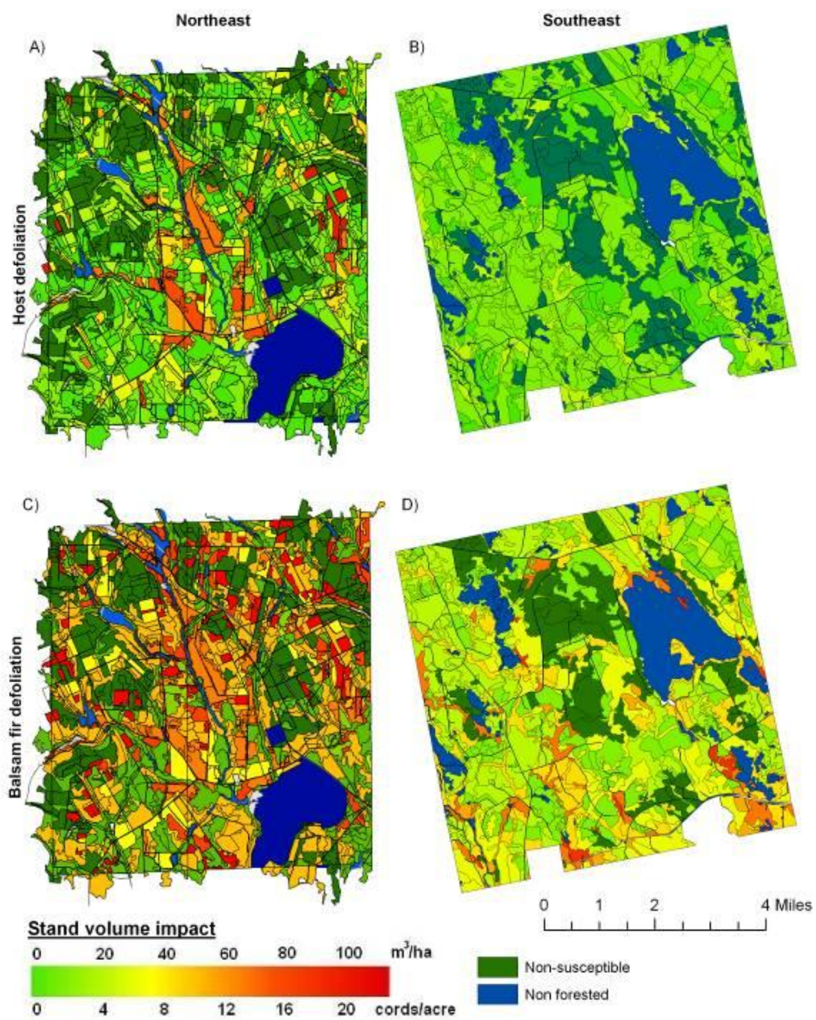
Anticipated Benefits to the CFRU

SBW outbreaks and management decisions put at risk over 3 billion cubic feet of fir and spruce timber in Maine. This study will provide a rigorous basis to quantify potential losses spatially, to determine sensitivity of particular landowners to a SBW outbreak and management decisions, and to assemble data that can be used to help determine policy responses to the next outbreak.

The earlier CFRU test study (Hennigar 2008) on two (northeast and southeast) townships demonstrated that the SBW DSS can be applied throughout Maine, despite seemingly large differences among landowner forest inventory and GIS data resolutions and formats. It also showed the degree of SBW impact differences that may be expected across Maine, from high impact in the north to low in the south, as a function of differences in host content in stands. Potential spruce-fir inventory reduction forecast for 2025-29 as a result of moderate and severe SBW outbreak scenarios were 13-28% in southeast and 23-47% for northeast townships (Hennigar 2008). This project will provide land managers with a customized database tool to forecast potential losses and help develop pre-outbreak management strategies to reduce impact. These mitigation strategies could include targeted removal of dying trees within stands, use of targeted applications of insecticide on high-impact stands, and use of harvest re-scheduling or salvage to reduce losses.

Development of a stand-alone SBW defoliation-impact tool will allow users to 1) translate historical or projective annual defoliation levels into periodic defoliation estimates, 2) link periodic defoliation to expected tree growth and survival loss estimates from Erdle and MacLean (1999), and 3) build required FVS 'keyword files' to adjust tree growth and survival by host species during the FVS simulation. Because this software tool will be stand-alone, it will be compatible with newer versions of FVS currently under development by Dr. Weiskettel. Given extensive FVS users across North America, this effort will likely foster increased collaborative efforts in other organizations (Univ. Maine, USDA Forest Service) to further improve the software, and at the very least, provide Maine land managers capability to model SBW disturbance using Maine models.

Timber supply analyses at the state level will permit evaluation of harvest sensitivity to SBW outbreak timing, severity, and effect of management responses. More importantly, this project will explore new questions that explicitly investigate how management strategies today could be altered to minimize potential harvest losses for unpredictable timing and severity of SBW disturbance events.



Example results from Hennigar (2008) implementation on two test townships in Maine. Projected 2025-29 merchantable inventory reduction for Northeast (a, c) and Southeast (b, d) Townships caused by a severe spruce budworm outbreak initiating in 2010 using i) reduced defoliation on spruce relative to balsam fir (a, b) and ii) spruce species defoliation equal to balsam fir levels (c, d). Future forest condition does not consider harvesting.

Deliverables

This project will produce a progress report, a final project presentation to the CFRU, a peer-reviewed journal article, and a final report. The final report will include:

- i. the likely spatial distribution and magnitude of stand volume impacts one could expect if a SBW outbreak was to occur sometime in the next 5 years on CFRU members' lands;
- ii. Maine-specific SBW defoliation patterns, developed from historical population/defoliation data;
- iii. SBW FVS keyword file builder executable, documentation, and examples;
- iv. models/databases used to implement the SBW DSS on CFRU lands;
- v. maps and databases of SBW impacts for outbreak scenarios on CFRU member landbases; and
- vi. recommendations for management to reduce future impacts of SBW disturbance on harvest:
    - a. what silviculture systems or schedules can mitigate impact on long-term harvest in advance of an outbreak, given uncertain timing of outbreak initiation and defoliation severity?
    - b. what levels of salvage and foliage protection (bio-insecticide application) can be done to mitigate harvest impacts during an outbreak?

Communications Schedule

- i. Oral progress reports at CFRU meetings
- ii. Written progress report by August 1st, 2011 (prior to year 2 renewal)
- iii. Written annual report; October 1st, 2012
- iv. SBW FVS keyword file builder extension documentation and examples.
- v. One-half to one-day workshop to present preliminary models and results to CFRU members and acquire input on specific silviculture systems, objectives, and constraints that will be used in the timber supply analysis; to be scheduled in October 2011
- vi. Summary report with SBW impact maps and data summary, specific to each CFRU landowner landbase, as well as FVS keyword files to model SBW impacts; October 1st, 2011
- vii. Final report within 6 months of project termination; February 28th, 2012
- viii. Data deposited into the CFRU databank according to required specifications

Literature Cited

Blackman, M.W. 1919. Report on the spruce budworm. Maine Forestry Department and Maine Agriculture Experiment Station. 10p.

Erdle, T.A. 1989. Concept and practice of integrated harvest and protection design in the management of eastern spruce fir forests. PhD Thesis. University of New Brunswick, Fredericton, NB, Canada. 161 p.

Erdle, T.A., and MacLean, D.A. 1999. Stand growth model calibration for use in forest pest impact assessment. Forestry Chronicle 75:141–152.

Hennigar, C.R. 2008. Spruce Budworm DSS application and projected spruce-fir volume impacts for two forest Townships in Maine from 2010 to 2050. Report submitted to Cooperative Forest Research Unit, University of Maine.

Hennigar, C.R., MacLean, D.A., Porter, K.B., and Quiring, D.T. 2007. Optimized harvest planning under alternative foliage-protection scenarios to reduce volume losses to spruce budworm. Can. J. For. Res. 37: 1755-1769.

Hennigar, C.R., MacLean, D.A., and Quiring, D.T., Kershaw J.A. Jr. 2008. Differences in spruce budworm defoliation among balsam fir and white, red, and black spruce. For. Sci. 54: 158-166.

Irland, L.C., Dimond, J.B., Stone, J.L., Falk, J., and Baum, E., 1988. The spruce budworm outbreak in Maine in the 1970’s - assessment and directions for the future. Maine Agriculture Experiment Station, University of Maine, Orono, Bulletin 819. 119 p.

MacLean, D.A., Porter, K.B., MacKinnon, W.E., and Beaton, K.P. 2000. Spruce budworm decision support system: lessons learned in development and implementation. Comp. Electr. Agric. 27**:** 293-314.

MacLean, D.A., Erdle, T.A., MacKinnon, W.E., Porter, K.B., Beaton, K.P., Cormier, G., Morehouse, S., and Budd, M. 2001. The spruce budworm decision support system: forest protection planning to sustain long-term wood supply. Can. J. For. Res. 31: 1742-1757.

MacLean, D.A., Beaton, K.P., Porter, K.B., MacKinnon, W.E., and Budd, M. 2002. Potential wood supply losses to spruce budworm in New Brunswick estimated using the Spruce Budworm Decision Support System. For. Chron. 78:739-750.

McWilliams, W.H., et al. 2005. The forests of Maine, 2003. Resour. Bull. NE-164. Newtown Square, PA: U.S. Dept. Agriculture, Forest Service, Northeastern Research Station. 188 p.

Régnière, J., and Cooke, B. 1998. Validation of a process-orientated model of *Bacillus thuringiensis* Variety *kurstaki* efficacy against spruce budworm (Lepidoptera: Tortricidae). Environ. Entomol. 27: 801-811.

Remsoft. 2007. Spatial Woodstock 2009.9 User guide. Remsoft Inc., Fredericton, NB, Canada.

Seymour, R.S. 1992. The red spruce-balsam fir forest of Maine: Evolution of silvicultural practice in response to stand development patterns and disturbances. p. 217-244 in The ecology and silviculture of mixed-species forests: a festschrift for David M. Smith. Kelty, M.J., B.C. Larson, and C.D. Oliver eds. Kluwer Academic Publishers. Boston. 287 p.

Resume of Principal Investigator:

David A. MacLean

Professor, Faculty of Forestry and Environmental Management, UNB

Dr. David MacLean is Professor in the Faculty of Forestry and Environmental Management at the University of New Brunswick, where he was Dean from 1999-2009. Prior to joining UNB in 1999, he researched effects of natural disturbance (insect outbreaks and fire) on forest ecology and management with the Canadian Forest Service. Through the 1990s, Dr. MacLean coordinated two Canada-wide research networks to (1) develop GIS-based decision support systems (DSS) for four of Canada's major insect pests, and (2) determine silvicultural approaches to integrated insect management. He led development of the Spruce Budworm DSS, which has been implemented, in partnership and with funding from provincial governments and industry, for all 7.4 million hectares of forest in New Brunswick and on test landbases in Quebec, Ontario, Alberta, and Saskatchewan. Current research projects deal with analysis of TRIAD (zoning) management, the role of natural disturbance (fire, insects, wind), and causes of natural decline of forest stands in NB, and the use of forest management and pest management to sequester carbon by forests. Dr. MacLean currently supervises or co-supervises 8 graduate students. He has published over 140 papers and 75 technology transfer publications and given numerous presentations at scientific and technical conferences. He also led the successful 8-university TRANSFOR (*Transatlantic Education for Global Sustainable Forest Sector Development*) international academic mobility project under the Canada-EU Program for Cooperation in Higher Education.

INSTITUTION: Faculty of Forestry and Environmental Management, University of New Brunswick, PO Box 4400, 28 Dineen Drive, Fredericton, NB E3B 5A3 CANADA Email: macleand@unb.ca

Current positions

Chair of Canadian Model Forest Network
President of the Fundy Model Forest
Chair of J.D. Irving, Limited Scientific Advisory Committee
Board of Directors of NCE Sustainable Forest Management Network
Canada alternate representative, Intern. Union of Forest Research Organizations (IUFRO), 2006-2010

Education and Awards

BSc with Honors in Biology UNB 1973. PhD in Forest Ecology UNB 1978. Natural Science and Engineering Research Council (NSERC) of Canada Post-doctoral Fellowship and Killam Post-doctoral Fellowship, University of British Columbia.
Canadian Forestry Scientific Achievement Award, 2008; Canadian Forest Service Merit Award for Innovation and Creativity and Collaboration and Partnership (2001); Forestry Canada Merit Award, 1992.

Past positions

Research Area Leader for Intensive Forest Mgmt. for NCE Sustainable Forest Management Network

President, Association of University Forestry Schools of Canada

Board of Directors, Forest Engineering Research Institute of Canada (FERIC)

Associate Editor, Canadian Journal of Forest Research and Northern Journal of Applied Forestry

Recent publications

Dick, A.R., J.A. Kershaw Jr., and D.A. MacLean. 2010. Spatial tree mapping using photography. North. J. Appl. For. (in press; accepted Jan. 13 ‘10).

Slaney, G.L., V.A. Lantz, and D.A. MacLean. 2010. Assessing costs and benefits of pest management on forested landbases in eastern and western Canada. J. For. Econ. 16: 19-34.

Wilson , J.J., V.A. Lantz , and D.A. MacLean. 2010. A benefit-cost analysis of protected natural areas in New Brunswick, Canada. Forest Policy Economics. 12: 94-103.

Amos-Binks, L.J., D.A. MacLean, J.S. Wilson, and R.G. Wagner. 2010. Temporal changes in species composition of mixedwood stands in northwest New Brunswick: 1946-2008. Can. J. For. Res. 40: 1-

12.
Spence, J.R., D.A. MacLean, and 12 others. 2010. The TRANSFOR Success Story: International Forestry Education Through Exchange. For. Chron. 86: 57-62.
Iqbal, J. and D.A. MacLean. 2010. Estimating cumulative defoliation of balsam fir from hemlock looper and balsam fir sawfly using aerial defoliation survey in western Newfoundland, Canada. For. Ecol. Manage. 259: 591–597.
Slaney, G.L., V.A. Lantz, and D.A. MacLean. 2009. The economics of carbon sequestration through pest management: application to forested landbases in New Brunswick and Saskatchewan, Canada. Forest Policy and Economics 11: 525-534.
Chang, W-Y., V.A. Lantz, and D.A. MacLean. 2009. Public attitudes about forest pest outbreaks and control options: Case studies in two Canadian provinces. For. Ecol. Manage. 257: 1333-1343.
Taylor, S.L. and D.A. MacLean. 2009. Legacy of insect defoliators: increased wind-related mortality two decades after a spruce budworm outbreak. Forest Science 55: 256-267.
MacLean, D.A., R.S. Seymour, M.K. Montigny and C. Messier. 2009. Allocation of conservation efforts over the landscape: the TRIAD approach. *In:* Setting Conservation Targets for Managed Forest Landscapes. *Edited by* M-A. Villard and B-G. Jonsson. Cambridge University Press, Cambridge, UK. Pp. 283-303.
Arseneault, J.E., J.A. Kershaw, Jr., J.B. McCarter, and D.A. MacLean. 2008. Forest Vegetation Simulator Ingrowth Tool: Incorporating ingrowth tree lists into Forest Vegetation Simulator growth projections. North. J. Appl. For. 25: 158-160.
Campbell, E.M., D.A. MacLean, and Y. Bergeron. 2008. The severity of budworm-caused growth reductions in balsam fir/spruce stands varies with the hardwood content of surrounding forest landscapes. For. Sci. 54: 195-205.
Hennigar, C.R., D.A. MacLean, D.T. Quiring, and J.A. Kershaw Jr. 2008. Differences in spruce budworm defoliation among balsam fir and white, red, and black spruce. For. Sci. 54: 150-166.
Hennigar, C.R., D.A. MacLean, and L.J. Amos-Binks. 2008. A novel approach to optimize management strategies for carbon stored in both forests and wood products. For. Ecol. Manage. 256: 786-797.
MacLean, D.A. and A.R. Andersen. 2008. Impact of a spruce budworm outbreak in balsam fir and subsequent stand development over a 40-year period. For. Chron. 84: 60-69.
Neilson, E.T., D.A. MacLean, F.-R. Meng, C.R. Hennigar and P.A. Arp. 2008. Optimal on- and off-site forest carbon sequestration under existing timber supply constraints in northern New Brunswick. Can. J. For. Res. 38: 2784-2796.
Taylor, S.L. and D.A. MacLean. 2008. Validation of spruce budworm outbreak history developed from aerial sketch-mapping of defoliation in New Brunswick. North. J. Appl. For. 25: 139-145.
Abbott, K.N., B. Leblon, G.C. Staples, D.A. MacLean, and M.E. Alexander. 2007. Fire danger monitoring using RADARSAT-1 over northern boreal forests. Inter. J. Remote Sens. 28: 1317-1338.
Hennigar, C.R., D.A. MacLean, K.B. Porter, and D.T. Quiring. 2007. Optimized harvest planning under alternative foliage-protection scenarios to reduce volume losses to spruce budworm. Can. J. For. Res. 37: 1755-1769.
Hennigar, C.R., MacLean, D.A., and Norfolk, C.J. 2007. Effects of gypsy moth defoliation on softwood and hardwood growth and mortality in New Brunswick, Canada. North. J. Appl. For. 24: 138-145.
Kennedy, M.I.L., V.A. Lantz, and D.A. MacLean. 2007. Forest and economic impacts of alternative management strategies on Crown land in New Brunswick. Can. J. For. Res. 37: 2624-2636.
MacLean, D.A. 2007. Does the Canadian forest sector have a viable future? Is current forest management acceptable to the general public? Would you advise your kids to take forestry? For. Chron. 83: 54-60.
Neilson, E.T., D.A. MacLean, F.-R. Meng, and P.A. Arp. 2007. Spatial distribution of carbon in natural and managed stands in an industrial forest in New Brunswick, Canada. For. Ecol. Manage. 253: 148-160.
Taylor, S.L. and D.A. MacLean. 2007. Deadwood dynamics in declining balsam fir and spruce stands in New Brunswick, Canada. Can. J. For. Res. 37: 750-762.
Taylor, S.L. and D.A. MacLean. 2007. Spatiotemporal patterns of mortality in declining balsam fir and spruce stands. For. Ecol. Manage. 253: 188-201.
Etheridge, D.A., D.A. MacLean, R.G. Wagner and J.S. Wilson. 2006. Effects of intensive forest management on stand and landscape characteristics in northern New Brunswick, Canada (1945-

2027). Landscape Ecology 21: 509-524.

Higdon, J.W., D.A. MacLean, J.M. Hagan and J.M. Reed. 2006. Effects of forest management on vertebrate species risk in northwestern New Brunswick, Canada: 1945, 2002, and 2027. Can. J. For. Res. 36: 467-481.

Montigny, M.K., and D.A. MacLean. 2006. Triad forest management: scenario analysis of effects of forest zoning on timber and non-timber values in northwestern New Brunswick, Canada. For. Chron. 82: 496-511.

Neilson, E., MacLean, D.A., Arp, P.A., Meng, F-R., Bourque, C.P., Bhatti, J.S. 2006. Modeling carbon sequestration with CO2Fix and a timber supply model for use in forest management planning. Can. J. Soil Sci. 86: 219-233.

Erdle, T., and D.A. MacLean. 2005. Forest management in New Brunswick: the Jaakko Pöyry study, the Legislative Select Committee on Wood Supply, & where do we go from here? For. Chron. 81: 92-96.

Etheridge, D.A., D.A. MacLean, R.G. Wagner and J.S. Wilson. 2005. Changes in landscape composition and stand structure from 1945-2002 on an industrial forest in New Brunswick, Canada. Can. J. For. Res. 35: 1965-1977.

Higdon, J.W., D.A. MacLean, J.M. Hagan and J.M. Reed. 2005. Evaluating vertebrate species risk on an industrial forest landscape. Forest Ecology Manage. 204: 279-296.

Montigny, M.K., and D.A. MacLean. 2005. Using heterogeneity and representation of ecosite criteria to select forest reserves in an intensively managed industrial forest. Biological Conserv. 125: 237-248.

Taylor, S.L., and D.A. MacLean. 2005. Rate of decline of mature and overmature softwood stands by ecological region in New Brunswick. Can. J. For. Res. 35: 2479-2490.

MacKinnon, W.E., and D.A. MacLean. 2004. Effects of surrounding forest and stand conditions on growth reduction caused by spruce budworm defoliation. Can. J. For. Res. 34: 2351-2362.

Krause, C., F. Gionest, H. Morin, and D.A. MacLean. 2003. Temporal relations between defoliation caused by spruce budworm and growth of balsam fir. Dendrochronologia 21(1): 23-31.

Piene, H., D.A. MacLean, and M. Landry. 2003. Spruce budworm defoliation and growth loss in young balsam fir: relation-ships between volume growth and foliage production in defoliated and protected stands. For. Ecol Manage. 179: 37-53.

MacKinnon, W.E., and D.A. MacLean. 2003. The influence of surrounding forest landscape and stand conditions on spruce budworm defoliation in New Brunswick. Forest Science 49: 657-667.

MacLean, D.A., K.P. Beaton, K.B. Porter, W.E. MacKinnon, and M. Budd. 2002. Potential wood supply losses to spruce budworm in New Brunswick estimated using the Spruce Budworm Decision Support System. For. Chron. 78: 739-750.

MacLean, D.A., T.A. Erdle, W.E. MacKinnon, K.B. Porter, K.P. Beaton, G. Cormier, S. Morehouse, and M. Budd. 2001. The Spruce Budworm Decision Support System: forest protection planning to sustain long-term wood supplies. Can. J. For. Res. 31: 1742-1757.

MacLean, D.A., W.E. MacKinnon, K.B. Porter, K.P. Beaton, G. Cormier, and S. Morehouse. 2000. Use of forest inventory and monitoring data in the Spruce Budworm Decision Support System. Computers & Electronics in Agric. 28: 101-118.

MacLean, D.A., K.B. Porter, W.E. MacKinnon, and K.P. Beaton. 2000. Spruce Budworm Decision Support System: lessons learned in development and implementation. Comp. Electr. in Agric. 27: 293-314.

Piene, H., and D.A. MacLean. 1999. Spruce budworm defoliation and growth loss in young balsam fir: patterns of shoot, needle and foliage weight production over a 9 year outbreak cycle. Forest Ecol. Manage. 123: 115-133.

MacLean, D.A., and P. Ebert. 1999. The impact of hemlock looper (*Lambdina fiscellaria fiscellaria* (Guen.)) on balsam fir and spruce in New Brunswick, Canada. Forest Ecol. Manage. 120: 77-87.

Erdle, T.A. and D.A. MacLean. 1999. Stand growth model calibration for use in forest pest impact assessment. For. Chron. 75: 141-152.

Needham, T., J. Kershaw, D.A. MacLean, and Q. Su. 1999. Effects of mixed stand management to reduce impacts of spruce budworm defoliation on balsam fir stand-level growth and yield. North. J. Appl. For. 16: 19-24.