BC JOURNAL OF ECOSYSTEMS AND MANAGEMENT

VOLUME 10 NUMBER 1
— SPRING 2009 —

A Publication of FORREX Forum for Research and Extension in Natural Resources

BC JOURNAL OF ECOSYSTEMS AND MANAGEMENT

—VOLUME 10, NUMBER 1, SPRING 2009—

ABOUT THE COVER PHOTOGRAPH:

A Marbled Murrelet chick sits on a mossy platform of an old western hemlock tree near the Stillaguamish River in Washington State.

—TOM HAMER,
WWW.HAMERENVIRONMENTAL.COM

JEM

BC Journal of Ecosystems and Management

About the Journal

The *BC Journal of Ecosystems and Management* (*JEM*) is a peer-reviewed electronic and print journal published by FORREX Forum for Research and Extension in Natural Resources. Articles in *JEM* inform readers about innovative approaches to sustainable ecosystem management. Aimed at decision makers in the policy, management, and operational realms, as well as practitioners, professionals, researchers, and natural resource users, *JEM* extends research results, management applications, socio-economic analyses, scholarly opinions, and operational and Indigenous knowledge. *JEM* Perspectives are reviewed by one extension specialist; Extension Notes, Discussion Papers, and Research Reports are reviewed by one extension specialist and two external peer reviewers from the natural resource community. Articles first appear in the online "Issue-in-Progress"; when online issues are full, articles are compiled into print issues (available by subscription). Submission Guidelines for authors, and a Print Subscription Form, are included at the back of this issue. To view current and archived issues of *JEM*, see our website at: ***www.forrex.org/jem***

About the Publisher

FORREX is a charitable organization focussed on promoting, supporting, and facilitating co-operative extension, technology development, and research ventures to support innovative and adaptive approaches to sustainable natural resource management. For more information, contact us at:

Suite 702, 235–1st Avenue, Kamloops, BC V2C 3J4
Tel: 250.371.3746 / Fax: 250.371.3997
Email: *society@forrex.org* / Website: *www.forrex.org*

ISSN 1488-4666.

This publication is partly funded by the British Columbia Ministry of Forests and Range through the Forest Investment Account–Forest Science Program.

When is a journal not a journal?

Chris Hollstedt, FORREX Chief Executive Officer and *JEM* Editor-in-Chief

Welcome to another issue of the *BC Journal of Ecosystems and Management*, and to my first formal communication to you as Editor-in-Chief. And it's about time. FORREX is finishing its 11th year of operations, and *JEM* will celebrate 10 years of service in 2010. There is no question that relevant, timely, and trustworthy science-based information is critical to transform our resource sectors into economically, socially, and environmentally sustainable entities. But how do we provide people with high-quality information when time and budgets are constrained? Is *JEM* still relevant and can it meet this need? It seems appropriate to reflect on why FORREX first created *JEM*, who is using the journal, and what we plan to achieve in the coming years.

So why did we create *JEM* as an online, open-access, peer-reviewed journal? In 1999, policy and operational clients indicated that journal articles were their least-preferred information vehicle and were least likely to reach key audiences for science-based information.[1] These clients preferred short summaries and field guides. At the same time, our research clients—the main contributors to our publications—indicated they most preferred journals as a means to publish their research results and to learn about the work of other researchers. Both audiences agreed on the need for high-quality, reliable information and, given funding constraints, would prefer web-based products. This presented FORREX with both a conundrum and an opportunity: We had to publish relevant science-based information in a format useful to our clients and we had to do this in a timely, cost-effective manner, but how could we satisfy the need of our policy and operational clients for expert summaries and also provide the journal format desired by our research community? If using a journal as an information source is perceived as a barrier, when is a journal not a journal?

Our solution? FORREX, with funding support through the BC Ministry of Forests and Range and the Provincial Extension Program, designed a web-based, open-access publishing vehicle that included the types of written products most desired by all audiences (research articles, discussion papers, perspectives, and extension notes and summaries). We linked these published products to a larger provincial extension program strategy. We forged new ground in the journal-publishing world by releasing articles before each issue closed. We established and followed a peer-review process to meet academic standards. So, has the fact that *JEM* is a "journal" affected its reach, accessibility, or use?

You be the judge. Each time an issue closes, over 15 000 people download articles from the FORREX website and about 400 people receive print copies. Particularly relevant and timely articles can trigger more than 2000 downloads within the month of publication. Recent *JEM* reader surveys[2] and internal and

1 Gregory, R. and T. Satterfield. 1999. Southern Interior Forest Extension and Research Partnership client survey. BC Ministry of Forests and Southern Interior Forest Extension and Research Partnership, Victoria, BC and Kamloops, BC. Working Paper No. 40. ***www.forrex.org/publications/other/jointpubs/wp40.pdf***

2 Schooling, J. 2008. Summary of 2008 *JEM* reader survey results. FORREX Forum for Research and Extension in Natural Resources, Kamloops, BC. Internal report.

external evaluation results[3,4] tell us that readers find *JEM* articles very useful, timely, and relevant to their work. More than 50% of these readers apply what they learn from *JEM* in their decisions. Over the last 9 years, *JEM* has evolved into a tool used by policy and operational practitioners . . . and researchers using *JEM* to share their research know how this information is applied and by whom. However, many British Columbia researchers still prefer to publish their results in other journals perceived as more scholarly. So why is *JEM* considered as a well-received and useful journal by our policy and operational readers, but as less scholarly by researchers? And what should FORREX do about this?

We think the answer lies in providing policy and operational readers with some incentive to help determine what they *need* to know, and then invite the research community to present research results to tackle these priorities. We will still welcome and encourage unsolicited submissions. However, we will now also start to solicit articles that address the following high-priority, emerging natural resource sector issues.

- Managing for changing environments (including climate change), timber value, productivity, markets, and public expectations
- Maintaining functioning forested watersheds, water quality, quantity, and aquatic habitats
- Enabling sustainable resource management and stewardship planning through the adoption of ecosystem management and integrated resource management principles
- Managing landscapes and landscape attributes to mitigate species losses and to maintain viable, reproducing populations of forest- and range-dependent species
- Achieving a balanced social, economic, and environmental portfolio
- Enabling understanding and use of Indigenous knowledge in policy, sustainable forest management, and stewardship planning
- Adapting to the social, economic, and environmental impacts of the mountain pine beetle infestation
- Addressing continuing competency and empowering forestry professionals with timely, relevant, and trustworthy information

So, if you have a pressing information need, research results, an innovative case study, a perspective, or a discussion item that addresses these strategic needs, please contact us and submit your paper to *JEM*. You will have the benefit of knowing that by sharing your knowledge through *JEM*, you will make a difference in the positive and innovative transformation of our resource-based economies and communities.

---

[3] Morford, S. and C. Hollstedt. 2007. Revisiting a forest extension strategy for British Columbia: A survey of natural resource practitioners and information providers. BC Ministry of Forests and Range, Research Branch, Victoria, BC. Technical Report No. 042. ***www.for.gov.bc.ca/hfd/pubs/Docs/Tr/Tr042.htm***

[4] Nexus Consortium Inc. 2007. An evaluation of the Provincial Forest Extension Program. FIA Forest Science Program/BC Ministry of Forests and Range, Victoria, BC Internal Report. ***www.fia-fsp.ca/d-PFEPEvaluationRprt-30May07.pdf***

News from the Editor

Julie Taylor Schooling, *JEM* Project Manager

The articles in *JEM* 10(1) address both biotic and abiotic elements of our ecosystems, explore relationships in both structure and function, and recognize both the influence and reliance of humans on our natural resources.

This issue features two in our series of forest health Stand Establishment Decision Aids (SEDAs) that are designed to summarize information forest managers need to mitigate the impacts of pests and diseases. Descriptions of susceptible stand types, recommended management practices, productivity considerations, and reference lists are provided in this issue for Dothistroma and for White Pine Blister Rust.

Three articles describe survey methods, findings, and recommendations related to Marbled Murrelet habitat with an emphasis on nesting habitat. First, Burger's Extension Note on air photo interpretation and low-level aerial surveys assesses the application of these methods to mapping of small patches or larger polygons. Managers will benefit from this guide to the methods' suitability and limitations as well as references to more detailed resources on testing and applicability. Second, a Research Report by Waterhouse, Burger, Lank, Ott, Krebs, and Parker describes the use of low-level aerial surveys in mapping microhabitat features associated with frequently selected Marbled Murrelet nest sites, and the applicability of ranking habitat using this method as the basis for forest management decisions. Third, Burger and Waterhouse's Discussion Paper synthesizes information on relationships between habitat area, habitat quality, and populations of nesting Marbled Murrelets. They conclude that most, but not all, nests are found in habitat rated as Moderate, High, or Very High according to the classification system they describe.

As described in the Research Report by Wulder, White, Grills, Nelson, Coops, and Ebata, the authors examined data from 1999 to 2005 to determine the effectiveness of aerial overview surveys in capturing the increasing area, severity, and spatial variability of British Columbia's mountain pine beetle infestation. They recommend reporting of both severity and cumulative impacts of the infestation over time.

Lodgepole pine plantations in British Columbia's Central Interior are the focus of Opio, Fredj, and Wang in their Extension Note on profitability of manual brushing in young stands. The results and economic framework they present in this synthesis will help forest practitioners to analyze the value of brushing in terms of return on investment.

Interest in management and harvest of a non-timber forest product motivated Kranabetter, Williams, and Morin to prepare their Extension Note describing the ecology, habitat, and extent of the Pacific golden chanterelle in Haida Gwaii.

Soils and drainage, key features in chanterelle habitat, tie in to the Discussion Paper by Smerdon, Redding, and Becker on the topic of forest management effects on groundwater hydrology. They introduce the role of groundwater in watersheds, present an overview of our province's groundwater resources, and describe the influence of various management activities and natural disturbances on these resources.

It is the behaviour of surface water, on the other hand, that concerns Green and Westbrook in their Research Report on observed changes in structure of riparian areas, stream channel hydraulics, and sediment yield following the removal of beaver dams from Sandown Creek in the East Kootenays. Their results confirm common assumptions about beaver ponds' roles in trapping sediment and reducing flow velocities.

We trust that this collection of articles provides natural resource practitioners with a combination of useful context and readily applicable guidance as the basis for informed decision making. We encourage readers of *JEM*'s print issues to visit our website which now allows us to highlight topically themed articles and issues along with the newest content posted in the issue-in-progress. We will be launching our reader survey early in the new fiscal year, and look forward to your responses!

Adding Value . . .

Marbled Murrelet Web Module

As a result of the collaboration among a group of experts on Marbled Murrelet habitat identification including consultants, academia, and provincial government representatives, and with funding by the FIA Forest Science Program, FORREX is developing a web module to illustrate the different habitat classifications currently used to identify Marbled Murrelet nesting habitat. The web module references air photograph and aerial survey techniques showing examples of the end products that can be obtained, and provides links to experts and further information on this topic. This web module will be available soon at: ***www.forrex.org/marbledmurrelet***

Relevant References: Marbled Murrelets

Birds of North America species account for Marbled Murrelet (Nelson 1997): ***bna.birds.cornell.edu/bna/species/276/articles/introduction***

Simon Fraser University Marbled Murrelet nest site photos and information: ***www.sfu.ca/biology/wildberg/mamuweb/welcome.htm***

Alan Burger (UVic) Marbled Murrelet research site: ***web.uvic.ca/~mamu/***

Clayoquot Sound Marbled Murrelet Studies in 1990s (book online): ***wlapwww.gov.bc.ca/wld/documents/techpub/mamuwebs.pdf***

Sustainable Ecosystems Institute (US): ***www.sei.org/murrelet.html***

Canadian Marbled Murrelet Recovery Team and links to publications of the Marbled Murrelet Conservation Assessment: ***www.sfu.ca/biology/wildberg/bertram/mamurt/links.htm***

Status review of Marbled Murrelet in Alaska and British Columbia (Piatt et al. 2006): ***pubs.usgs.gov/of/2006/1387***

BC Identified Wildlife Management Strategy account and measures for Marbled Murrelet: ***www.env.gov.bc.ca/wld/frpa/iwms/documents/Birds/b_marbledmurrelet.pdf***

BC Standards for Marbled Murrelet inventory and habitat assessment:

- Air photo interpretation and low-level aerial surveys: ***wlapwww.gov.bc.ca/wld/documents/fia_docs/mamu_standard.pdf***
- Radar surveys: ***ilmbwww.gov.bc.ca/risc/pubs/tebiodiv/murrelet2k6/mamu_radarsurv.pdf***
- Audiovisual, vegetation (habitat), and at-sea surveys: ***ilmbwww.gov.bc.ca/risc/pubs/tebiodiv/murrelet2k1/mamu%20ml20.pdf***

Strengthening Marine and Freshwater Conservation in British Columbia

On November 21, 2008, the Marine Conservation Caucus (MCC) hosted a one-day workshop to discuss a variety of opportunities and challenges facing organizations involved in marine and freshwater conservation in British Columbia, and to explore ways to strengthen collaboration among the marine and freshwater conservation community. See the Workshop Summary Report and some key presentations at: ***www.mccpacific.org/mccworkshop2008.htm***

Newly Published From FORREX

Greig, M. and G. Bull. 2008. Carbon management in British Columbia's forests: Opportunities and challenges. FORREX Series 24. *www.forrex.org/publications/forrexseries/fs24.pdf*

This report consolidates forest carbon management information currently available for British Columbia in the policy, research, and operational communities. The material presented is intended to increase awareness and facilitate a constructive dialogue among those interested in forest carbon management in the province.

Relevant References: Hydrology

Redding, T., R. Winkler, P. Teti, D. Spittlehouse, S. Boon, J. Rex, S. Dubé, R.D. Moore, A. Wei, M. Carver, M. Schnorbus, L. Reese-Hansen, and S. Chatwin. 2008. Mountain pine beetle and watershed hydrology. *In* Mountain Pine Beetle: From Lessons Learned to Community-based Solutions Conference Proceedings, June 10–11, 2008. *BC Journal of Ecosystems and Management* 9(3):33–50. ***www.forrex.org/publications/jem/ISS49/vol9_no3_MPBconference.pdf***

Smerdon,B., T. Redding, and J. Beckers. 2009. Forest management effects on groundwater: Large knowledge gaps persist. *Streamline Watershed Management Bulletin* 12(2):17–22. ***www.forrex.org/publications/streamline/ISS40/Streamline_Vol12_No2_art4.pdf***

Submissions for this page are welcome.
Please forward to the Managing Editor at: jem@forrex.org

Tables of Contents

LINK Newsletter
— Volume 10, Number 3, Fall 2008 —

Download this issue of* LINK *at:
www.forrex.org/link

Streamline Watershed Management Bulletin
— Volume 12, Number 2, Spring 2009 —

Download this issue of* Streamline Watershed Management Bulletin *at:
www.forrex.org/streamline

Extension Note

British Columbia's Northern Interior Forests

Dothistroma Stand Establishment Decision Aid

Larry McCulloch[1] and Alex Woods[2]

Introduction

Dothistroma needle blight, also known as red band needle blight, is caused by the fungus *Dothistroma septosporum*. It affects over 60 species of pine in 45 countries and is considered the most destructive pine needle disease in the world. All pine species native to British Columbia are susceptible and the fungus is widely distributed wherever host species can be found. Infection is caused by rain splash and air dispersal of the spores. In the southern hemisphere, it has been a major problem for decades. In British Columbia, however, damage levels from this pathogen have historically been low. Recent widespread defoliation, mortality (including mature tree mortality), and plantation failure caused by Dothistroma in the northwest portion of the province may be a result of changing climatic conditions that allow the fungus to develop in a way that was not previously possible.

The Stand Establishment Decision Aid (SEDA) format has been used to extend information on a variety of vegetation and forest health concerns in British Columbia. The two-page SEDA presented in this extension note was developed to summarize information that provincial forest managers will need to mitigate the impacts of Dothistroma needle blight. The first page provides information on susceptible stand types, disease biology, hazard ratings, and appropriate management practices. The second page outlines forest productivity considerations and risks to human health. A resource and reference list that readers can use to find more detailed information is also included. Most reference material that is not available online can be ordered through libraries or the Queen's Printer at: ***www.qp.gov.bc.ca***

? *Test Your Knowledge* *Questions on page 113*

Acknowledgements

The preparation and publication of this decision aid was supported by the British Columbia Ministry of Forests and Range through the Forest Investment Account–Forest Science Program.

KEYWORDS: *climate change, Dothistroma needle blight,* Dothistroma septosporum*, forest health, red band needle disease, tree species deployment.*

Contact Information

1 Principal, LM Forest Resource Solutions Ltd. PO Box 880, Smithers, BC V0J 2N0. Email: larry.mcculloch@lmfms.ca

2 Forest Pathologist, BC Ministry of Forests and Range, Northern Interior Region, Regional Service Centre, Bag 6000, 3333 Tatlow Road, Smithers, BC V0J 2N0. Email: alex.woods@gov.bc.ca

ARTICLE RECEIVED: **June 26, 2007**
ARTICLE ACCEPTED: **October 3, 2008**

McCulloch, L. and A. Woods. 2009. British Columbia's northern interior forests: Dothistroma Stand Establishment Decision Aid. *BC Journal of Ecosystems and Management* 10(1):1–3.

Dothistroma Needle Blight – Northern Interior Forest Region

Dave Weaver

Dothistroma-infected lodgepole pine needles with characteristic red bands

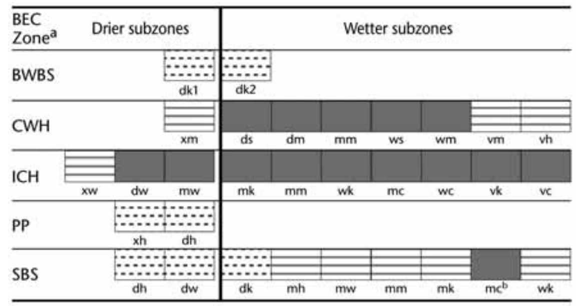
Characteristics of susceptible stands

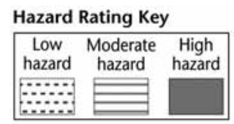
- All pine species native to British Columbia are susceptible.
- Non-native pine species established in the province (e.g., Monterey pine and bishop pine) are highly susceptible.
- The most severe infections have occurred in northwest British Columbia in managed plantations of lodgepole pine (up to 30 years old). Mortality has also been observed in mature lodgepole pine in this area.
- Cold air ponding sites and areas along major watercourses are typically the areas worst affected.

Description and biology

- Crowns tend to be thin and tufted in appearance. The lower crown is often most severely affected.
- In severely affected stands, crowns are thin with extensive red foliage making it appear as though a fire has been through the stand.
- Needles of all ages are susceptible.
- Spots and bands appear on the needles and turn reddish brown (see the left side of the photo above), although the base of the needles often remains green.
- The best time of year to identify the disease is in the spring when needles that were affected the previous year show up most clearly. Needles that have been killed 1–2 years earlier are best for positive identification (dark red bands on straw-coloured needles – see right side of photo above).

Hazard ratings[1]





[a] See Meidinger and Pojar (1991) for an explanation of Biogeoclimatic Ecosystem Classification (BEC) zone, subzone, and variant abbreviations.
[b] In areas adjacent to the ICH.

[1] Ratings represent expert opinion based on known biology and current climatic conditions. Climate change will affect these rankings (see Hamann and Wang 2006). If a biogeoclimatic unit is not listed, Dothistroma is not considered to be a significant hazard.

- Spores are released from previously infected needles and infections can occur throughout the growing season provided temperatures are above 5°C and moisture is present. Temperatures between 15 and 20°C during extended periods of moisture are optimal for infection.
- Spores can be transported long distances in moisture-saturated air (e.g., mist or cloud). If spores land on host material during periods of high humidity, these can germinate and penetrate the unaffected needles.
- The fungus goes through a period of vegetative growth within the needle. This growth produces a toxin that causes the red pigmentation in diseased needles. Fruiting bodies (pseudothecia) form on dead needles and appear as small, dark structures that break through the epidermis (see right side of photo above).
- During periods of high humidity, mature fruiting bodies release new spores to complete the life cycle. Depending on climatic conditions and other factors, this can take 1–2 years.
- Recent research indicates that a strong correlation exists between infection levels and the frequency of warm rain events (i.e., daily high temperatures exceeding 18°C for 3 or more consecutive days in July or August). In north-central British Columbia, the frequency of such events is increasing.

Management considerations

Until recently, the damage caused to pine species in British Columbia by Dothistroma needle blight was of little concern. With changing climate and the potential for Dothistroma to spread into drier areas such as the Sub-Boreal Spruce (SBS) zone, more effort will be needed to prevent and control this disease if management for lodgepole pine continues to be a priority. Some treatment options are described below by stage of management intervention.

Harvesting

- Ensure silviculture prescriptions for moderate- and high-hazard areas require establishment of a species mix; pine should not be favoured in high-hazard areas.
- If the intention is to re-establish pine, avoid clearcutting in potential cold air ponding sites in high-hazard areas.

Stand establishment

- Regeneration with a tree species mix is imperative. The proportion of regenerated pine should not exceed 20% in high-hazard areas. By the year 2025, the northern portion of the SBS zone is predicted to experience a shift in climatic conditions that will more closely resemble the Interior Cedar–Hemlock (ICH) zone (see Hamann and Wang 2006). Such a shift will make these areas a high hazard for Dothistroma in the future.
- Consider establishing Douglas-fir as a replacement for pine even in some of the warmer BEC subzones where it is not currently listed as an acceptable species. Subzones in which Douglas-fir might be acceptable must be chosen carefully with consideration given to both anticipated changes in climate and root disease hazard.
- Consider establishing a breeding program in which Dothistroma-resistant provenances of lodgepole pine are identified and developed. In other locations, host-resistance trials with ponderosa, radiata, and Austrian pine have shown promise. The Dothistroma fungus itself shows some genetic diversity; further genetic research may help managers identify and create conditions to minimize infection and spread.

Dothistroma Needle Blight – Northern Interior Forest Region

Management considerations (continued)

Plantation maintenance

- Although broad spectrum copper fungicides have been used to control Dothistroma on radiata pine in the southern hemisphere since the early 1960s, this treatment is not recommended in British Columbia. Unlike radiata pine, which is susceptible to age 15, lodgepole pine remains susceptible throughout its life, which would require a spray program for most (or all) of the rotation. Other non-timber resources, such as the wild mushrooms common in high-hazard areas, could also be damaged by such treatments. In British Columbia, most high-hazard areas are capable of supporting numerous acceptable crop species; resource managers should ensure that sites are not managed for a single species.
- If conducting spacing or brushing treatments, favour non-susceptible species as leave trees. In high-hazard areas, pine trees should not be felled, but their presence should not preclude leaving other trees (i.e., treat the pine as ghost trees).
- No existing biological controls have been proven effective with Dothistroma. Although research continues, new measures are unlikely to be available in the near future.

Damage and impact on productivity

- Dothistroma infects pine needles of all ages resulting in premature leaf mortality and reduced photosynthetic capacity.
- Wood yield loss is proportional to the volume of needles affected.
- Outbreaks vary greatly from year to year depending on weather conditions, which affect spore production, release, and germination.
- Repeated severe attacks lead to growth loss and mortality.
- In northwest British Columbia, extensive plantations of lodgepole pine along with a marked increase in the frequency of weather events favourable to the disease have resulted in unprecedented levels of Dothistroma infection.
- Reconnaissance flights over approximately 40 000 ha of pine plantations in province's northwest, revealed that 92% show some signs of Dothistroma infection (varying from low levels to almost 100% mortality). Nine percent of the plantations are so severely defoliated that recovery seems unlikely. In monitored stands, mortality of individual trees is close to 7%.

Risk to human health

- Dothistroma needle blight produces a toxin, dothistromin, that is closely related to the potent carcinogen, aflatoxin. Studies have shown that dothistromin is a weak mutagen and clastogen and is, therefore, a potential carcinogen. Despite this, the risk to forest workers is considered to be very low because the toxin must be ingested. It is prudent for forest workers to wash their hands before eating if working in Dothistroma-infected stands.

Resource and reference list

Allen, E., D. Morrison, and G. Wallis. 1996. Common tree diseases of British Columbia. Natural Resources Canada, Canadian Forest Service, Victoria BC. ***www.pfc.cfs.nrcan.gc.ca/diseases/ctd/index_e.html*** (Accessed February 2009).

Bradshaw, R.E. 2004. Dothistroma (red band) needle blight of pines and the dothistromin toxin: A review. Forest Pathology 34:163–185.

Hamann, A. and T. Wang. 2006. Potential effects of climate change on ecosystem and tree species distribution in British Columbia. Ecology 87:2773–2786.

Meidinger, D. and J. Pojar. 1991. Ecosystems of British Columbia. BC Ministry of Forests, Victoria, BC. Special Report Series No. 6. ***www.for.gov.bc.ca/hfd/pubs/Docs/Srs/SRseries.htm*** (Accessed February 2009).

Peterson, G.W. 1967. Dothistroma needle blight of Austrian and ponderosa pines: Epidemiology and control. Phytopathology 57:437–441.

_______. 1982. Dothistroma needle blight of pines. US Department of Agriculture Forest Service, Lincoln, Nebr. Forest Insect and Disease Leaflet No. 143. ***www.na.fs.fed.us/spfo/pubs/fidls/doth-istroma/doth.htm*** (Accessed February 2009).

Rehfeldt, G.E., C.C. Ying, D.L. Spittlehouse, and D.A. Hamilton, Jr. 1999. Genetic responses to climate in *Pinus contorta*: Niche breadth, climate change, and reforestation. Ecological Monographs 69(3):375–407.

Woods, A. 2003. Species diversity and forest health in northwest British Columbia. Forestry Chronicle 79:892–897.

Woods, A., K.D. Coates, and A. Hamann. 2005. Is an unprecedented Dothistroma needle blight epidemic related to climate change? BioScience 55(9):761–769. ***www.for.gov.bc.ca/hfp/fft/scientific-articles/articles/Woods%20et%20al%202005_Dothistroma%20and%20Climate%20Change.pdf*** (Accessed February 2009).

Extension Note

New methods for assessing Marbled Murrelet nesting habitat: Air photo interpretation and low-level aerial surveys

Alan E. Burger[1], F. Louise Waterhouse[2], Ann Donaldson[3], Carolyn Whittaker[4], and David B. Lank[5]

Abstract

This extension note summarizes the application of two new methods that were developed to assess the quality of forest habitat that Marbled Murrelets (*Brachyramphus marmoratus*) use for nesting in British Columbia: air photo interpretation and low-level aerial surveys. Both methods use comparable six-level ranking systems that are based on the availability of forest attributes deemed important for nesting murrelets. The methods were developed and refined through preliminary work done in many varied coastal regions in British Columbia; they were designed to complement each other and be applicable to either small patches (1–2 ha) or to larger polygons used in mapping for forest management. Both methods were tested in comparisons with known murrelet nest sites and both are currently being applied by government and forest industry biologists. This note provides practitioners who are proposing to use one or both of these methods a concise guide to their suitability and limitations, and also provides links to relevant reports that offer greater detail on testing and applicability.

KEYWORDS: *air photo interpretation,* Brachyramphus marmoratus*, habitat mapping, habitat suitability, low-level aerial surveys, Marbled Murrelet.*

Contact Information

1 Associate Professor (Adjunct), Department of Biology, University of Victoria, Victoria, BC V8W 3N5. Email: aburger@uvic.ca

2 Research Wildlife Ecologist, BC Ministry of Forests and Range, Coast Forest Region, 2100 Labieux Road, Nanaimo, BC V9T 6E9. Email: louise.waterhouse@gov.bc.ca

3 Consultant, 4559 Morland Road, Victoria, BC V9C 4E5. Email: asdonaldson@shaw.ca

4 Consultant, 864 Dunsmuir Road, Victoria, BC V9A 5B7. Email: carolyn.whittaker@gmail.com

5 Adjunct Professor and University Research Associate, Centre for Wildlife Ecology, Simon Fraser University, 8888 University Drive, Burnaby, BC V5A 1S6. Email: dlank@sfu.ca

***JEM* — VOLUME 10, NUMBER 1**

Burger, A.E., F.L. Waterhouse, A. Donaldson, C. Whittaker, and D.B. Lank. 2009. New methods for assessing Marbled Murrelet nesting habitat: Air photo interpretation and low-level aerial surveys. *BC Journal of Ecosystems and Management* 10(1):4–14.

Introduction

The Marbled Murrelet (*Brachyramphus marmoratus*) is a small seabird that forages in nearshore seas and nests in the canopies of old seral forests, usually within 30 km of the coast (Nelson 1997; Burger 2002). The species is listed as Threatened in Canada, is on the British Columbia "Red List" (legally designated or being considered for legal designation as Endangered or Threatened), and is a Species at Risk under the Identified Wildlife Strategy of the *Forest and Range Practices Act* (Province of British Columbia 2004). It is also listed as Threatened in Washington, Oregon, and California. Loss of forest nesting habitat is identified as one of the main threats for this species (CMMRT 2003).

Marbled Murrelets require a very specific set of nest site features to breed successfully (Table 1). This combination of features is typical of trees greater than 200 years old on the coast and explains the overwhelming use of old seral forests for nesting. Nevertheless, not all forest stands meeting the age criterion provide the required canopy structure and mossy platforms for nests, and identifying likely nesting habitat is a key step in managing the murrelet's nesting habitat.

Understanding habitat relationships and managing for habitat is difficult because nesting murrelets are secretive and well-camouflaged, and nests are extremely hard to find. Currently, murrelet nesting habitat in British Columbia is described from data that is obtained at nest sites or in stands where occupancy by breeding murrelets is likely, as identified from audio-visual surveys (CMMRT 2003). From these data, habitat suitability models (algorithms) are developed to predict, rank, and map potential murrelet habitat using a combination of forest cover (i.e., Vegetation Resources Inventory [VRI]; Resources Inventory Committee 2002), topographic, and biogeoclimatic data. Models built from this information are usually applied broadly using Geographic Information Systems (GIS) to landscapes covering hundreds or thousands of hectares, and are not always good predictors of whether or not the forest has the attributes necessary for murrelets to nest (Tripp 2001; Burger 2002).

Understanding habitat relationships and managing for habitat is difficult because nesting murrelets are secretive and well-camouflaged, and nests are extremely hard to find.

In recent years, new techniques based on air photo interpretation and low-level aerial surveys from helicopters have been developed in British Columbia

TABLE 1. Key microhabitat characteristics for Marbled Murrelets nest sites in British Columbia (for more details see Nelson 1997 and Burger 2002).

Murrelet requirements	Key habitat attributes
Sufficient height to allow stall-landings and jump-off departures	Nest trees are typically > 40 m tall (range: 15–80 m), and nest heights are typically > 30 m (range: 11–54 m); nest trees are often larger than the stand average.
Openings in the canopy for unobstructed flight access	Small gaps in the canopy are typically found next to nest trees, and vertical complexity of the canopy is higher in stands with nests than in other nearby stands.
Sufficient platform diameter to provide a nest site and landing pad	Nests are typically on large branches or branches with deformities, usually with added moss cover; nest limbs range from 15 to 74 cm in diameter; nests typically located within 1 m of the vertical tree trunk.
Soft substrate to provide a nest cup	Moss and other epiphytes provide thick pads at most nest sites, but duff and leaf litter are used in drier areas.
Overhead cover to provide shelter and reduce detection by predators	Most nests are overhung by branches.

TABLE 2. General description of the six-level ranking system used in the protocols for air photo interpretation and aerial surveys of Marbled Murrelet habitat (see Burger [editor] 2004 for details).

Rank	Habitat value	General description of habitat quality and availability of key habitat features	Surveyed area or proportion of canopy trees with habitat feature present (%)[a]
1	Very High	The key habitat feature is present in abundance; nesting highly likely.	51–100
2	High	The key habitat feature is common and widespread; nesting likely.	26–50
3	Moderate	The key habitat feature is present but uncommon and patchy; nesting likely but at moderate to low densities.	6–25
4	Low	The key habitat feature is evident but patchy and sparse; nesting possible but unlikely or at very low density.	2–5
5	Very Low	The key habitat feature is very sparse and might be absent; nesting highly unlikely.	about 1
6	Nil	The key habitat feature is absent; nesting impossible (e.g., bogs, bare rock).	0

[a] This column shows how the ranking system is applied in aerial surveys when assessing the relative abundance of a particular feature, such as large trees or trees with platforms.

to add finer-scale detail to GIS-based methods. The air photo interpretation focuses on murrelet habitat criteria related to forest canopy structure (Donaldson 2004). The low-level air surveys focus on canopy microhabitat features such as epiphyte cover and availability of potential nest platforms (Burger et al. 2004).

The purpose of this extension note is to review the application and value of these two methods in managing the murrelet's nesting habitat, to describe situations in which the methods might be applied, to discuss tips that improve their use (based on input from biologists who have used the methods), and to provide links to studies which have used these methods. In short, we aim to provide practitioners who are planning to use either or both methods with a decision tool to help select and implement either method. This note is not a substitute for the full protocols, which are explained in detail elsewhere (Burger [editor] 2004). We emphasize that classifying forest structure for habitat potential does not account for external factors such as predators or microclimate that may affect habitat quality and the success of a nesting site.

Goals and criteria

Both air photo interpretation and low-level aerial survey methods can be applied to either strategic (long-range planning and management covering large spatial areas such as landscape units or conservation regions) or operational situations (short-term decision making usually applied to smaller areas such as proposed cutblocks or Wildlife Habitat Areas [WHAs]).

Both air photo interpretation and aerial survey protocols use a six-level ranking system to assess the suitability of forests as murrelet nesting habitat (Table 2; Burger [editor] 2004); this is loosely based on the six-level British Columbia Wildlife Habitat Rating Standards (Resources Inventory Committee 1999). For both methods, each habitat attribute is ranked independently and an overall habitat suitability rank is then assessed based on the collective ranks of all the other habitat attributes. Both methods can be applied to either small forest patches (e.g., generally 2–5 ha with air photos and < 1 ha with aerial surveys) and larger areas such as polygons typically used in VRI mapping.

Air photo interpretation

In general, air photo interpretation quantifies the structure and complexity of the forest canopy, tree size, micro-topography, and other features important for murrelets, and is intended for application to an entire landscape (Donaldson 2004). Attributes are associated with structures that murrelets need for nesting, stand

TABLE 3. Summary of key attributes interpreted on air photos[a] (Resources Inventory Committee 2002; Donaldson 2004).

Variable	Variable classes and definitions of classes
Air Photo Habitat Quality	Qualitative ranking using the six-class system with habitat rated Nil to Very High based on CMMRT (2003) recommendations.
Stand Age	Average age (year) weighted by basal area of the dominant, co-dominant, and high intermediate of the leading species for each tree layer identified.
Tree Height	Average estimated height (m) of the dominant, co-dominant, and high intermediate trees for the upper tree layer.
Crown Closure	Percent estimate of the vertical projection of tree crowns (upper layer) upon the ground.
Canopy Complexity	Estimate of overall variability of canopy structure and the distribution and abundance of large crowns and canopy gaps created by local topography (e.g., slope, hummock, and streams), vertical complexity, and/or past stand disturbance (standing dead or down trees). Further details in Waterhouse et al. (2004, 2008).
Vertical Complexity	Describes uniformity of the forest canopy by considering estimates of the total difference in height of leading species and average tree layer height.

[a] Reference photos are available illustrating the classification (contact F. L. Waterhouse, BC Ministry of Forests and Range)

TABLE 4. Summary of features assessed during low-level aerial surveys (Burger et al. 2004).

Feature	Description
Overall Field Ranking	Qualitative six-class system with habitat ranking Nil to Very High based on a cumulative assessment of the other features in this table. See Figure 1.
Large Trees	The percentage of canopy or emergent trees greater than 28.5 m in height (i.e., height class = 4+).
Trees with Platforms	The percentage of canopy and emergent trees with one or more platforms (limbs or deformities >15 cm in diameter).
Moss Development	The percent of canopy or emergent trees with obvious mossy mats.
Canopy Cover	The estimated percentage of the ground that would be covered by canopy vegetation.
Vertical Canopy Complexity	Vertical complexity is subjectively ranked from least (most uniform canopy) to highest (very non-uniform).
Topographic Complexity	An assessment of the effect of slope, rocky outcrops, avalanche chutes, large boulders, creeks, etc. in creating small gaps subjectively ranked from Nil to Very High.
Age Class	The estimated age of the forest stand classified as less than 8 (< 140 years), 8 (140–250 years), or 9 (> 250 years).
Leading Tree Species	The dominant, secondary, tertiary tree species.
Slope Position	Macro-slope position.
Slope Grade	Steepness based on slope segment.

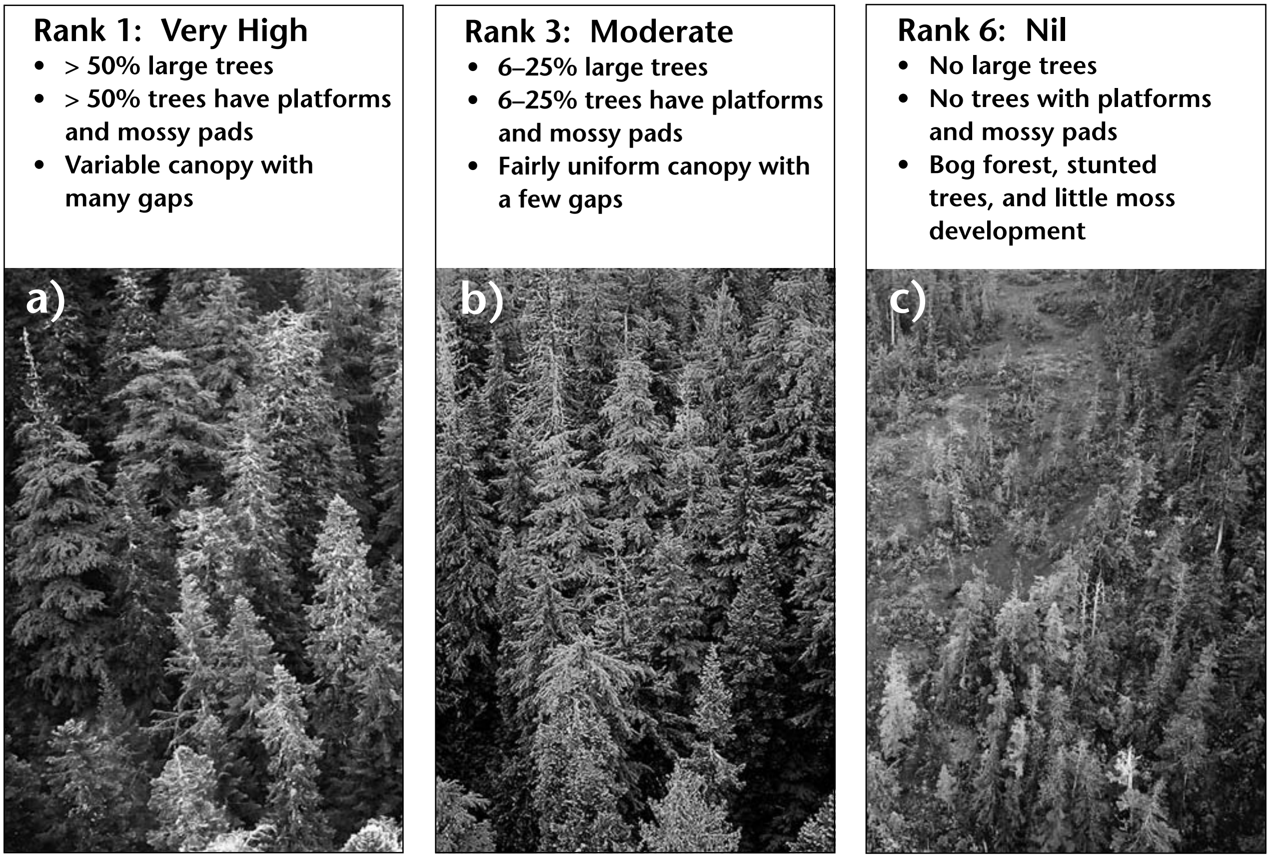


FIGURE 1. Examples of sites with the overall habitat quality ranked as 1, Very High (a); 3, Moderate (b); and 6, Nil (c) from low-level aerial surveys.

access, and the protection provided by the canopy around the nest site against weather and predation risk (Table 3). Following the standards requires the use of accredited interpretation techniques by an experienced interpreter (Resources Inventory Committee 2002).

Low-level aerial surveys

Aerial surveys use low-flying helicopters to provide a "murrelet's eye view" of the forest canopy to check the presence and relative abundance of the microhabitat features important for nesting murrelets (Table 4, Figure 1). Details of the protocol are given in Burger et al. (2004). In particular, the surveys provide information on the presence and abundance of potential nest platforms (defined as branches or deformities > 15 cm in diameter, including any epiphyte growth) and epiphyte cover (moss, lichens, and ferns), which are not detectable from air photos, maps, or GIS databases. Aerial surveys also allow confirmation and re-assessment of important stand features such as height class, age class, vertical complexity, crown closure, and topographic features. Aerial surveys should be used once potential habitat has been identified to confirm the presence of microhabitat features that are important to nesting murrelets.

Testing with actual nest sites

Both methods have been applied in research that compares actual nest sites with randomly selected points in the same watersheds. These studies used nests located with radio-telemetry in Desolation Sound (62 nests) and Toba Inlet (24) on the southern mainland, Clayoquot Sound (32) on west Vancouver Island, and Haida Gwaii/Queen Charlotte Islands (QCI) (7). The results of this research are summarized in Table 5.

Application and limitations

Using comparable six-rank classification and several shared parameters, the air photo interpretation and aerial-survey methods were meant to complement each other or be used independently. The shared and

TABLE 5. Key research findings using air photo interpretation and low-level aerial surveys applied to actual murrelet nest sites in British Columbia (Waterhouse et al. 2002, 2004, 2007, 2008).

Air photo interpretation	Low-level aerial surveys
Stand age improves the probability of murrelets nesting in a stand, but at a decreasing rate for stands greater than 200 years old.	Murrelets use a range of habitats rated Very Low to Very High in overall habitat quality—most nests occurred in the Moderate to Very High classes. Selectivity was indicated for the Very High class, avoidance for the pooled Moderate, Low, and Very Low classes, and the High class was used in proportion to availability.
A mixture of forest characteristics interpreted from air photos best describes nesting habitat, and different combinations of characteristics may similarly predict potential murrelet habitat.	Trees with mossy pads providing potential nest platforms are a key feature for identifying habitat used by murrelets for nesting.
Murrelets use a range of habitats ranked Very Low to Very High in Air photo Habitat Quality—most nests occurred in the Moderate to Very High classes. The data indicated preferential selection of High and Very High classes and avoidance of the Low and Very Low classes. Moderate habitat was used in proportion to its availability.	Aerial assessments of macroslope suggest that murrelets avoid upper slopes and ridge tops; they are more likely to use mid-slopes, which tend to be steeper slopes at this scale.
Occurrence of large dominant trees, relative to the main canopy, may be as important as tree height itself as an indicator of nesting habitat. Complex canopies created by large trees and lower mesoslopes associated with large trees both describe selected habitats.	When mapping habitat using the aerial method, ensure that the mapping resolution is fine enough that smaller patches of high-quality habitat are not missed within larger stands of lower-quality habitat. Patches 100 m in diameter (~3 ha) were assessed around each nest in this research, and patches of high-quality habitat were sometimes used for nesting that were surrounded by larger areas rated lower in overall quality.
Evaluating stand access by assessing gappy openings and natural edges can help identify nesting habitat, but the benefit of openings for murrelet access must be balanced against protection from weather and predator detection that canopy cover provides.	
When interpreting habitat quality, consideration must be given to the landscape, its disturbance history, and potential threats (e.g., predators).	

unique features of the methods and their limitations are summarized in Table 6.

Decisions on which habitat quality ranks to include as "suitable nesting habitat" will depend on the management objectives, spatial scales of the mapping, regional habitat differences, and local amounts of existing habitat. Generally ranks 1–3 (Table 2), or 1–4 in some situations, are considered more likely to include suitable habitat than lower ranks and, hence, are valuable for management planning (Burger and Waterhouse 2009). When both methods have been applied to the same forest patches (100 m radius around nest sites or randomly selected points) the rankings given by air photo interpretation tended to be slightly lower than those from the aerial surveys (Waterhouse et al. 2007; Burger and Waterhouse 2009; L. Waterhouse, unpublished data). The differences, generally less than one rank, were probably due to the inability to assess platforms and moss development in the canopy from air photos. These differences need to be taken into account when using air photos for large strategic mapping; surveyors must recognize that some polygons might be ranked slightly higher with aerial surveys.

Based on published reports, workshops, and informal input from several biologists experienced with these methods (see Acknowledgements), we present suggestions for the efficient application of these methods (Sidebars 1 and 2, next page) and reiterate the need for practitioners to thoroughly review the published protocols (Burger [editor] 2004).

Air photo interpretation tips

- Digital photography using three-dimensional software has been used extensively on the British Columbia coast and is more efficient than handling hardcopy photographs. Viewing at 1:10 000 to 1:20 000 scale provides similar results as mid-scale hardcopy photography, while the software also allows for zooming in to larger scales for viewing stands of particular interest.
- Mid-scale (1:15 000 to 1:20 000) hardcopy air photos are most appropriate. Larger scales (e.g., 1:10 000) give good views of the canopy, but require numerous photos. Smaller-scale photos provide insufficient detail.
- A stereoscope with a minimum two-power magnification works well on mid-scale photos. Field stereoscopes with no magnification are usually not suitable.
- Be aware of distortions towards the edges of photos, and height distortion on higher-elevation sites.
- Use knowledge of local species-age-height-elevation-site relationships to provide a check of the interpreted attributes.
- In evaluating vertical complexity, give consideration to the stand gappiness as well as tree height differences because canopy gaps contribute to stand accessibility for murrelets.
- Recent forest cover or vegetation maps are useful for the following:
  - To update logging information.
  - To calibrate photo scale, especially when several flight lines are used for a project. Air photos are not an exact or consistent scale as labelled. For example, trees look significantly larger on 1:14 000 scale photos than on 1:16 000 photos and, unless taken into account, this difference could lead to inconsistent habitat ranking. Digital photography software identifies exact scale, which eliminates potential error from scale inconsistencies.
  - To provide forest cover information, be aware that the quality of forest inventories varies; the newer Vegetation Resources Inventories generally provide more reliable information. Ground-based forest cover data are particularly valuable for interpreting and calibrating age and height classes.
- Find out from a local biologist/planner if there are "known" rank 1 and 2 habitats in the study area, and use photos of these areas to calibrate your eyes to the study area (see Waterhouse et al. 2004 regarding availability of coastal reference sets).
- The most difficult break is between ranks 3 (Moderate) and 4 (Low). Review, keep notes, and photo examples of the attributes for these two ranks for handy reference.
- If the project covers a large area (landscapes), review previous work periodically to ensure consistency.

Current management applications

Air photo interpretation

This method is being used for region-wide assessment and mapping of murrelet habitat; maps of Haida Gwaii/QCI are complete (A. Cober, BC Ministry of Environment, pers. comm., December 2008), while those of the central and north coast regions are nearing completion (D. Donald, BC Ministry of Environment, pers. comm., December 2008). Maps derived from air photo interpretation are a key element in strategic planning of the central and north coast regions, which is currently being undertaken by the multi-stakeholder Ecosystem-based Working Group. Air photos were also used in conjunction with a habitat suitability model and aerial surveys to map management units in Clayoquot Sound (Chatwin et al. 2006). The air photo method is also routinely used in many parts of coastal British Columbia for mapping prior to aerial surveying, especially in the selection of WHAs.

Tips for aerial surveys

- Having two observers, plus the pilot and navigator, helps to ensure that each observer evaluates a slightly different perspective of the forest from both sides of the helicopter.
- A turbine-powered helicopter capable of carrying this crew, while flying safely and slowly just above the treetops, is essential.
- Slow figure-8 flight by the helicopter usually gives the best views into the canopy.
- Pre-plan a flight route in consultation with the pilot to minimize flight time between survey sites, taking into account fuel depots, rest stops, and options for weather.
- Be sure to use the appropriate map datum on the GPS (usually NAD 83)—some helicopter GPS units are set in older datums.
- Pre-program the survey sites into the GPS and, if you are using the helicopter's GPS, fax or email the co-ordinates to the pilot well in advance of your flight.
- A hand-held GPS usually works well in the front of the cockpit, but might take a minute or two to locate satellites—get it going before takeoff.
- Be aware that air photos and forest cover maps are sometimes out of date and you might spend flight time looking for forest features that no longer exist
- Training using videos before any flights and doing a few surveys with an experienced observer is essential to achieve consistency.
- Review the key features of the locally common tree species before the flight.
- Photos and videos of each site are essential to permanently document each survey. Report where these are archived for future reference.
- It is useful to think of the % categories in Table 2 as proportions of the trees having the required feature; for example, 5% is 1 in 20 trees, 25% is 1 in 4 trees, so between 1/20 and 1/4 of the trees having platforms would be rank 3 (Moderate).
- Observers should discuss their evaluations to reach a consensus on the suitability and ranking of the site before moving to the next site.

Mapping methods for aerial surveys

- Static maps and photos: Use a combination of GPS, topographic maps, satellite imagery, 1:20 000 air photos, plus a detailed overview map. Pre-stratify for potential habitat using air photos or satellite imagery (e.g., SPOT5). Map polygons and rank habitat directly on the maps during flight. Focus on potential suitable habitat areas, but investigate areas designated as non-habitat before eliminating as Nil. Post-trip, produce shape files in GIS by editing original GIS database.
- Real-time, moving-map technique: Uses a program running on a laptop computer with a GPS feed (e.g., OziExplorer). Pre-stratify landscape using model-generated habitat polygons on satellite imagery (e.g., SPOT5) and base map data. During the flight, locate waypoints and rate habitat quality in polygons and/or at polygon transition boundaries. Post-flight processing is required to link waypoints with the same rating, taking into account underlying satellite imagery and other land information, to produce polygons.

TABLE 6. Summary of the shared features and different capabilities and limitations of air photo interpretation and low-level aerial survey methods.

Air photo interpretation	Low-level aerial surveys	Both methods
Can be used to narrow down areas that require more expensive aerial surveys. Cannot ensure the availability of suitable platform structures. Does not usually identify individual trees and is generally done for larger scale overview (i.e., areas > 2 ha).	Can confirm the suitability (presence of platforms and other canopy features) of potential habitat for management (e.g., proposed WHAs). Are more costly than GIS and air photo mapping; therefore, practitioners may need to weigh the additional value of aerial survey information relative to cost. Might be less costly if air photo interpretation is used to pre-stratify areas and hence focus efforts on stands having some potential as murrelet habitat. Can be undertaken on the same flights as other activities such as evaluations for operability. Should not be reduced in intensity for broad-scale assessments as habitat evaluations may be scale-sensitive (i.e., smaller patches of high-quality habitat can be missed if minimum map unit is too large) and observers might miss small patches of suitable habitat. Allow interpretation of small patches (~ 1 ha) or even individual trees.	Produce maps rating forest structure relative to potential habitat use by nesting murrelets. Provide reliable habitat maps for either strategic (long-range planning over large areas such as watersheds or landscape units) or operational implementation (shorter-term plans for proposed cutblocks or WHAs). Can map or refine murrelet habitat polygons that need not rely on existing forest cover polygons (e.g., in VRI mapping). Provide seamless and consistent measures of habitat suitability over the area of interest, in contrast to forest cover data, which often have spatial gaps (e.g., parks and other non-timber lands) and are often recorded in slightly different ways by different management agencies or companies. Can refine or replace the results of a local GIS-based algorithm, thereby providing a higher-resolution overview of potential habitat in a large study area or landscape unit.

Low-level aerial surveys

The high cost of helicopters may limit the application of this method to verification of habitat suitability following the application of either habitat suitability algorithms or air photo interpretation. Examples include the verification of habitat algorithms (central coast: Hobbs 2003; north coast: Burger et al. 2005; Vancouver Island: Donald 2005, D. Donald unpublished data), verification of mapping based on air photo interpretation in Haida Gwaii/QCI (Cober et al. in prep.), and operational mapping confirming management areas on Vancouver Island and the southern mainland (Deal and Smart 2004; Chatwin et al. 2006; T. Chatwin and I. McDougall, BC Ministry of Environment). In addition, aerial surveys covering multiple landscape units have also been used for strategic habitat mapping of large areas of Vancouver Island, and the southern and central mainland (W. Wall, International Forest Products and S. MacDonald, Western Forest Products, pers. comm., January 2008).

Conclusions and the way ahead

The air photo and aerial survey methods summarized here provide flexible and complementary approaches to assessing habitat suitability for nesting Marbled Murrelets. They can also be used in combination with other methods such as habitat suitability models, which are based on forest cover and topographic data. Both methods will continue to be refined as they are more widely applied across coastal British Columbia. Future work will also focus on reconciling the differences in rank between these methods. We do not anticipate having a much larger sample of actual nest sites to test, due to the high costs of telemetry studies needed to find large numbers of nests. LiDAR (Light Detection and Ranging) is being tested in British Columbia for forestry use (BC-CARMS 2006) and might provide detailed three-dimensional measures of canopy structure that could be extremely valuable for large-scale assessments of Marbled Murrelet nesting habitats.

Acknowledgements

We acknowledge all the biologists who have contributed to the development and refining of the air photo and aerial survey methods for marbled murrelets, especially Louise Blight, Trudy Chatwin, Alvin Cober, John Deal, David Donald, Bill Harper, Anne Hetherington, Jared Hobbs, Stewart Guy, Sally Leigh-Spencer, Monica Mather, Sue McDonald, Ian McDougall, Nadine Parker, Bernard Schroeder, Brian Smart, Doug Steventon, Wayne Wall, and other participants in several workshops on these topics. Funding for this research was provided by the British Columbia Forest Science Program (Forest Investment Account), BC Ministry of Forests and Range, and BC Ministry of Environment.

References

? *Test Your Knowledge* *Questions on page 113*

BC-CARMS. 2006. LiDAR–Overview of technology, applications, market features and industry. British Columbia Centre for Applied Remote Sensing, Modelling and Simulation, University of Victoria, Victoria, BC. ***carms.geog.uvic.ca/documents.html***

Burger, A.E. 2002. Conservation assessment of Marbled Murrelets in British Columbia: Review of the biology, populations, habitat associations, and conservation. Canadian Wildlife Service, Pacific and Yukon Region, Delta, BC. Technical Report Series No. 387. ***www.sfu.ca/biology/wildberg/bertram/mamurt/PartA.pdf***

________ (editor). 2004. Standard methods for identifying and ranking nesting habitat of Marbled Murrelets (*Brachyramphus marmoratus)* in British Columbia using airphoto interpretation and low-level aerial surveys. BC Ministry of Water, Land and Air Protection, Victoria, BC and BC Ministry of Forests, Nanaimo, BC. ***wlapwww.gov.bc.ca/wld/documents/fia_docs/mamu_standard.pdf***

Burger, A.E., B.R. Smart, L.K. Blight, and J. Hobbs. 2004. Part Three: Low-level aerial survey methods. *In* Standard methods for identifying and ranking nesting habitat of Marbled Murrelets (*Brachyramphus marmoratus*) in British Columbia using airphoto interpretation and low-level aerial surveys. A.E. Burger (editor). BC Ministry of Water, Land and Air Protection, Victoria, BC and Ministry of Forests, Nanaimo, BC. ***wlapwww.gov.bc.ca/wld/documents/fia_docs/mamu_standard.pdf***

Burger, A.E., J. Hobbs, and A. Hetherington. 2005. Testing models of habitat suitability for nesting Marbled Murrelets, using low-level aerial surveys on the North Coast, British Columbia. BC Ministry of Water, Land and Air Protection, Smithers, BC.

Burger, A.E. and F.L. Waterhouse. 2009. Relationships between habitat area, habitat quality, and populations of nesting Marbled Murrelets. BC Journal of Ecosystems and Management 10(1):101–112. ***www.forrex.org/publications/jem/ISS50/vol10_no1_art10.pdf***

Chatwin, T., J. Cragg, T. Dunlop, and S. Leigh-Spencer. 2006. Marbled Murrelet management strategy for Clayoquot Sound. Environmental Stewardship Division, BC Ministry of Environment, Nanaimo, BC.

(CMMRT) Canadian Marbled Murrelet Recovery Team. 2003. Marbled Murrelet Conservation Assessment 2003, Part B: Marbled Murrelet Recovery Team advisory document on conservation and management. Canadian Wildlife Service, Pacific and Yukon Region, Delta, BC. Canadian Marbled Murrelet Recovery Team Working Document No. 1. ***www.sfu.ca/biology/wildberg/bertram/mamurt/PartB.pdf***

Deal, J.A. and B. Smart. 2004. Low-level aerial assessment of potential Marbled Murrelet nesting habitat in TFL 37 and FLA 19233, Northern Vancouver Island: Phase 2. Canfor Ltd., Woss, BC.

Donald, D.S. 2005. Testing a Marbled Murrelet predictability model using low level aerial assessment in the Zeballos Landscape Unit, Vancouver Island. BC Ministry of Environment, Victoria, BC Wildlife Working Report No. WR-108. ***www.env.gov.bc.ca/wld/documents/techpub/wr108.pdf***

Donaldson, A. 2004. Part two: Air photo interpretation. *In* Standard methods for identifying and ranking nesting habitat of Marbled Murrelets (*Brachyramphus marmoratus*) in British Columbia using airphoto interpretation and low-level aerial surveys. A.E. Burger (editor). BC Ministry of Water, Land and Air Protection, Victoria, BC and BC Ministry of Forests, Nanaimo, BC. ***wlapwww.gov.bc.ca/wld/documents/fia_docs/mamu_standard.pdf***

Hobbs, J. 2003. Marbled murrelet nesting habitat in the mid-coast forest district: An assessment of the mid-coast model. BC Ministry of Water, Land and Air Protection, Habitat Branch, Victoria, BC.

Nelson, K. 1997. Marbled Murrelet (*Brachyramphus marmoratus*). *In* Birds of North America, No. 276. A. Poole and G. Gill (editors). Academy of Natural Sciences, Philadelphia, PA, and American Ornithologists' Union, Washington, DC.

Province of British Columbia. 2004. Identified wildlife management strategy. Accounts and measures for managing identified wildlife: Marbled Murrelet *Brachyramphus marmoratus.* BC Ministry of Water, Land and Air Protection, Victoria, BC. ***www.env.gov.bc.ca/wld/frpa/iwms/documents/Birds/b_marbledmurrelet.pdf***

Resources Inventory Committee. 1999. British Columbia wildlife habitat rating standards Version 2.0. BC Resources Inventory Committee, Victoria, BC.

_____. 2002. Photo interpretation procedures V2.4. BC Ministry of Sustainable Resource Management, Terrestrial Information Branch, Victoria, BC. ***ilmbwww.gov.bc.ca/risc/pubs/teveg/vri-photointerp2k2/photo_interp2k2.pdf***

Tripp, T. 2001. A synopsis of Marbled Murrelet habitat suitability models in British Columbia. BC Ministry of Water, Land and Air Protection, Habitat Branch, Victoria, BC.

Waterhouse, F.L., R. Bradley, J. Markila, F. Cooke, and L. Lougheed. 2002. Use of airphotos to identify, describe, and manage forest structure of Marbled Murrelet nesting habitat at a coastal British Columbia site. BC Ministry of Forests, Vancouver Forest Region, Nanaimo, BC. Forest Research Technical Report TR-016. ***www.for.gov.bc.ca/rco/research/wildlifereports/tr016.pdf***

Waterhouse, F.L., A.E. Burger, A. Cober, A. Donaldson, and P.K. Ott. 2007. Assessing habitat quality of Marbled Murrelet nest sites on the Queen Charlotte Islands/Haida Gwaii, by algorithm, airphoto interpretation, and aerial survey methods. BC Ministry of Forests and Range, Coast Forest Region, Nanaimo, BC. Forest Research Technical Report TR-035. ***www.for.gov.bc.ca/rco/research/wildlifereports/tr035.pdf***

Waterhouse, F.L., A.E. Burger, D.B. Lank, P.K. Ott, E.A. Krebs, and N. Parker. 2009. Using the low-level aerial survey method to identify Marbled Murrelet nesting habitat. BC Journal of Ecosystems and Management 10(1):80–96. ***www.forrex.org/publications/jem/ISS50/vol10_no1_art8.pdf***

Waterhouse, F.L., A. Donaldson, and D.B. Lank. 2004. Using airphotos to interpret Marbled Murrelet nesting habitat in British Columbia: Application of a preliminary classification scheme. Forest Research Technical Report TR-029. BC Ministry of Forests. Nanaimo, BC. ***www.for.gov.bc.ca/rco/research/mamu/tr029.pdf***

Waterhouse, F.L., A. Donaldson, D.B. Lank, P.K. Ott, and E.A. Krebs. 2008. Using air photos to interpret quality of Marbled Murrelet nesting habitat in south coastal British Columbia. BC Journal of Ecosystems and Management 9:17–37. ***www.forrex.org/publications/jem/ISS47/vol9_no1_art3.pdf***

ARTICLE RECEIVED: **July 9, 2007**
ARTICLE ACCEPTED: **December 1, 2008**

Extension Note

Profitability of manual brushing in young lodgepole pine plantations

Christopher Opio[1], Karima Fredj[2], and Baotai Wang[2]

Abstract

Manual brushing is an important silvicultural tool commonly used to control competing vegetation in young conifer plantations. Yet little is known about the short-term economic benefits of one versus two brushing treatments. Using forest establishment data from the Fraser Lake and Bednesti areas of the Central Interior of British Columbia, we examined the profitability of one and two applications of brushing treatments under different internal rates of return (IRR) and three brushing radii (0.75, 1.00, and 1.25 m). Our results showed that 1 year of brushing treatment would be profitable for almost all brushing radii since profitability required only a short reduction in cutting age and lower IRRs. Applying two consecutive years of brushing would clearly require either higher discount rates or a longer waiting period for the brushing to be profitable. We believe that the approach described in this extension note will assist forest practitioners when analyzing the value of brushing in terms of return on investment over time. The economic framework will also assist forest practitioners when deciding on brush control options for young conifer plantations.

KEYWORDS: *Central Interior of British Columbia, internal rate of return, manual brushing, profitability, time gain.*

Contact Information

1 Ecosystem Science and Management Program, University of Northern British Columbia, 3333 University Way, Prince George, BC V2N 4Z9. Email: opio@unbc.ca

2 Economics Program, University of Northern British Columbia, 3333 University Way, Prince George, BC V2N 4Z9.

Opio, C., K. Fredj, and B. Wang. 2009. Profitability of manual brushing in young lodgepole pine plantations. *BC Journal of Ecosystems and Management* 10(1):15–21.

Introduction

Forest managers endeavour to use the most effective methods to control competing vegetation in young conifer plantations. Shrubs, herbaceous plants, and deciduous trees compete for light, nutrients, and water, and potentially restrict tree growth and cause plantation failure (Opio et al. 2000, 2003; Jacob and Opio 2003). Efficacious vegetation control treatments improve conifer survival and growth by minimizing vegetative cover and future competition while causing negligible damage to crop trees (Newton and Comeau 1990). Brush control in forestry includes manual brushing, chemical control, grazing, and mechanical site preparation (Baker 1998). For the forest practitioner, choice of vegetation management treatments will depend primarily on biological and environmental factors, and secondarily on social and economic considerations. In other words, cost and profitability, while very important, are not the main criteria.

This extension note focuses on manual brushing using machetes, brush hooks, handsaws, and chainsaws to cut and remove the competing vegetation (Newton and Comeau 1990). This method is commonly used in forestry because it is environmentally safe and socially acceptable (Baker 1998). Previous brushing studies in young 1- to 10-year-old conifer plantations show that manual brushing improves short-term plantation development (Hart and Comeau 1992; Simard and Heineman 1996; Opio et al. 2000, 2003); however, the studies fail to address the benefits of one versus two consecutive years of brushing treatments.

Comparing the profitability of a "new" method or treatment (e.g., 1 or 2 years of manual brushing) with that of a "standard" treatment (e.g., no brushing) typically requires considerable investment in money and time spent installing, measuring, and analyzing field studies. Moreover, assumption statements and estimation errors might affect the validity of the conclusions. As an alternative, Garcia (1996) proposed a simple economic model that eliminated the need for detailed stand information. Assuming that a "new" treatment produced a time gain (δ) or reduced the number of years to cutting age, then the break-even relative additional cost of the "new" treatment could be calculated using only internal rate of return (IRR) and δ.

The objective of our study was to illustrate a simple method for evaluating the profitability of vegetation

For the forest practitioner, choice of vegetation management treatments will depend primarily on biological and environmental factors, and secondarily on social and economic considerations. In other words, cost and profitability, while very important, are not the main criteria.

management treatments. More specifically, we used Garcia's (1996) method to determine the break-even relative additional costs of brushing treatments in young lodgepole pine plantations in the Central Interior of British Columbia using IRR or discount rates between 0.5 and 5% and one versus two consecutive years of brushing at radii of 0.75, 1.00, and 1.25 m.

Economic model

The break-even relative additional cost (BeRAC) provided the basis for evaluating the profitability or economic viability of the manual brushing treatments used in this study. The BeRAC was a critical value that should not be exceeded by a brushing treatment's actual relative additional cost (ARAC) for the treatment to be economically viable (Garcia 1996). This approach was appealing considering it was relatively simple and required little data. In our study, we applied this approach using three main steps:

1. We calculated the BeRAC. As shown by Garcia (1996), based on the profit maximization (or cost minimization) theory, the break-even relative additional cost (BeRAC) was calculated using the internal rate of return (IRR) or discount rate (i) and the time gain (δ) as follows:

$$BeRAC = (1 + i)^{\delta} - 1 \qquad [1]$$

2. The actual relative additional cost (ARAC) of a new treatment was calculated using the treatment's additional cost (the difference between the new total cost [$\overline{C}$] and the establishment cost [C] relative to the

value of a newly established stand (the sum of the establishment cost C and the land expectation value):[1]

$$ARAC = \frac{\bar{C} - C}{L + C} \qquad [2]$$

3. The break-even cases or treatments yielding zero profits were those where ARAC was equal to the BeRAC. On the other hand, a treatment was considered economically viable when ARAC was less than BeRAC, but unprofitable when ARAC was greater than BeRAC.

BeRAC and ARAC vary with the IRR or discount rate applied. Both IRR and discount rate are the same, but the different terminology reflects the different roles of interest rate in this study. In other words, interest rate is the internal rate of return (IRR) when used to compute the break-even relative additional costs, and interest rate is the discount rate when used to discount the future value of a treatment. Since rates change with time and market conditions, we used a range of discount rates to determine how they affected the results. In reality, forest manager would use current discount rates.

Data source and application

Data

Our study focused on young lodgepole pine plantations in the Sub-Boreal Spruce dry warm (SBSdw) and dry cool (SBSdk) biogeoclimatic subzones of the Central Interior of British Columbia. Lodgepole pine comprises a major portion of the forested land base in British Columbia (DeLong et al. 1993) and is of considerable commercial interest. During early growth stages in the SBSdw and SBSdk, lodgepole pine is subject to adverse competition from a variety of broadleaf tree species including trembling aspen (*Populus tremuloides* Michaux) and sitka alder (*Alnus crispa* ssp. *sinuate* [Regel] Hulten) (Opio et al. 2003). Manual brushing is one of several tools used to control competing vegetation in these biogeoclimatic regions (Opio et al. 2003).

We used 2004 land expectation values and establishment and brushing costs from the Fraser Lake and Bednesti areas. Land expectation value (L) was \$16 500 per hectare. Estimated establishment cost (C) was \$1100 per hectare, and included \$300 per hectare for site preparation and \$800 per hectare for planting cost, seedlings, supervision, and snowplowing. Additional costs for one brushing treatment $\bar{C} - C$ were \$300, \$350, and \$375 per hectare for brushing radii of 0.75, 1.00, and 1.25 m, respectively.

Model application

The first step was to use Equation 1 to calculate BeRACs using IRR ranging from 0.5 to 5% and time gains of 1–10 years. Table 1 illustrates these critical values which represent, for each specific IRR (or discount rate) and time gain period, the relative additional cost under which brushing will be profitable and above which it will not be profitable. The results show, for example, that for an IRR of 2% and a time gain of 3 years, a brushing treatment is profitable if its cost did not increase more than 6.012% relative to the stand value. The table also shows that if the ARAC for a brushing treatment is about 5% at a discount rate of 2.5%, the treatment must produce a time gain of at least 2 years to be economically viable.

The next step was to compute the ARACs using Equation 2, the data for land expectation values, and actual establishment and treatment costs. For two consecutive years of brushing, costs for the second year were discounted at rates of 0.5–5% when calculating the ARAC. For example, for 1 year of brushing at a radius of 0.75 m, the ARAC was:

$$1.70\% = \frac{300}{16\,500 + 1100} \times 100 \qquad \text{[Table 2A]}$$

[1] The land expectation value or net present value represents the cash flow over an infinite number of rotations of optimal length discounted at a factor of

$$\alpha = \frac{1}{1 + i}$$

where i is the IRR. Land expectation value can be calculated using the following formula:

$$L = \max_t \left\{ \frac{\alpha^t R(t) - C}{1 - \alpha^t} \right\}$$

where $R(t)$ is the revenue function and C is the establishment cost. (For more information see Garcia 1996, Faustmann 1995, and Leuschner 1990.)

TABLE 1. Break-even relative additional cost (%).The solid line shows the break-even line for 1 year of brushing at 1.25 m. The dashed line shows the break-even line for 2 years of brushing at 1.25 m.

Time gain	Discount rate or IRR (%)									
(years)	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0
1	0.500	1.000	1.500	2.000	2.500	3.000	3.500	4.000	4.500	5.000
2	1.000	2.001	3.002	4.004	5.006	6.009	7.012	8.016	9.020	10.025
3	1.501	3.003	4.507	6.012	7.519	9.027	10.537	12.048	13.561	15.075
4	2.002	4.006	6.014	8.024	10.038	12.054	14.074	16.096	18.122	20.151
5	2.503	5.010	7.523	10.040	12.563	15.090	17.623	20.161	22.703	25.251
6	3.004	6.015	9.034	12.060	15.094	18.136	21.185	24.241	27.306	30.378
7	3.505	7.021	10.547	14.084	17.632	21.190	24.759	28.338	31.928	35.529
8	4.007	8.028	12.063	16.112	20.176	24.254	28.345	32.452	36.572	40.707
9	4.509	9.036	13.581	18.145	22.726	27.326	31.945	36.581	41.237	45.911
10	5.011	10.045	15.102	20.181	25.283	30.408	35.556	40.728	45.922	51.140

TABLE 2A. Actual relative additional costs using one brushing treatment.

Radius	Actual relative additional costs (%)
0.75 m	1.70
1.00 m	1.99
1.25 m	2.13

TABLE 2B. Actual relative additional costs using two brushing treatments with the second-year treatment discounted over a range of rates.

	Discount rates (%)									
Radius	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0
0.75 m	3.40	3.39	3.38	3.38	3.37	3.36	3.35	3.34	3.34	3.33
1.00 m	3.97	3.96	3.95	3.94	3.93	3.92	3.91	3.90	3.89	3.88
1.25 m	4.25	4.24	4.23	4.22	4.21	4.20	4.19	4.18	4.17	4.16

For two consecutive years of brushing at 0.75 m and at a discount rate of 1.5% for the second year's costs, the ARAC was:

$$3.38\% = \frac{300}{16\,500 + 1100} \times 100 + \frac{1}{1 + 0.015} \times \frac{300}{16\,500 + 1100} \times 100 \qquad \text{[Table 2B]}$$

In other words, 1 year of brushing at 0.75 m radius resulted in an actual additional cost increase of 1.70% relative to the stand value, while 2 years of brushing treatments increased costs by 3.38% at a discount rate of 1.5%.

The final step was to compare the ARAC (Tables 2A and 2B) and BeRAC estimates (Table 1) to evaluate the profitability of the various treatments. As a first example, one brushing treatment applied at a radius of 1.25 m resulted in an ARAC of 2.13%. The resulting break-even line (solid line in Table 1) separated the lower, profitable cases from the upper, non-profitable ones. In other words, at an IRR of 2.0%, brushing at 1.25 m would be profitable if it reduced cutting age by at least 2 years, but unprofitable if it reduced cutting age by only 1 year.

When deriving the second break-even line for two consecutive years of brushing at 1.25 m (dashed line in Table 1), the discount rate for determining ARACs had to be matched with the IRR used to estimate BeRAC. Therefore, at a brushing radius of 1.25 m, and an IRR of 0.5%, the ARAC was 4.25%. This meant that 2 years of brushing had to reduce cutting age by at least 9 years to be profitable. At a more intermediate IRR of 2.5%, the ARAC was 4.21% and the treatment had to produce a 2-year time gain to be profitable.

Treatment profitability

Following two consecutive years of brushing at 1.25 m radius, a forest company will fail to make positive profits at a discount rate of 0.5% unless growth gains exceed 9 years. On the other hand, the company will profit with a growth gain of 1 year if the discount rate is 4.5% or higher.

Brushing radii had no effect on treatment profitability at higher IRRs; however, 1 or 2 years of brushing at 1.00 m or 0.75 m radii will improve profitability at IRRs less than or equal to 2%. In addition, at IRRs of 3.5 and 4.0%, 2 years of brushing at 1.25 m was profitable if it produced a 2-year growth gain. However, a 1-year growth gain would be profitable if the brushing radius was reduced to 0.75 m at an IRR of 3.5% and 1.00 m at an IRR of 4.0%.

The concepts and principles discussed here are important. The evaluation process was relatively simple and illustrated how a theoretical economic framework can be used to successfully compare vegetation management options with limited data. We also believe that this approach will assist forest practitioners when evaluating treatment success based on return on investment over time.

Overall, comparing the break-even lines for 1 and 2 years of brushing showed that, in general, at the same radius, the profitability of 2 years of brushing was dependent upon higher discount rates and greater growth gains.

Conclusions and recommendations

In this extension note, we applied the break-even criterion to analyze the profitability of manual brushing of young lodgepole pine plantations in the Central Interior of British Columbia. Comparing a range of brushing radii and IRRs revealed three main points. First, 1 year of brushing was the most profitable treatment given growth gains of 1 or 2 years and relatively low IRRs. In other words, from an economic point of view, foresters should consider brushing young lodgepole pine plantations only once. Second, economic justification for two consecutive years of brushing would require either higher IRRs or greater growth gains. Third, IRRs significantly affect the profitability and, therefore, choice of brushing treatment.

The concepts and principles discussed here are important. The evaluation process was relatively simple and illustrated how a theoretical economic framework can be used to successfully compare vegetation

We recommend conducting further profitability studies on manual brushing in young conifer plantations in other regions in British Columbia to gain a more comprehensive understanding of the economic benefits of brushing treatments under different locations and conditions.

management options with limited data. We also believe that this approach will assist forest practitioners when evaluating treatment success based on return on investment over time.

We recommend the following steps when evaluating brush control options for young conifer plantations.

1. Use current discount rates (i).
2. Determine site-specific land expectation values (L) and establishment costs (C) including site preparation, planting, seedlings, supervision, and snowplowing costs.
3. Calculate actual brushing treatment costs based on brushing radius and site.
4. Examine the profitability of 1 and 2 years of brushing treatments using a range of internal rates of return and different brushing radii.
5. Determine if the brushing treatment can be applied only once or repeated for two consecutive years.

We recommend conducting further profitability studies on manual brushing in young conifer plantations in other regions in British Columbia to gain a more comprehensive understanding of the economic benefits of brushing treatments under different locations and conditions. We expect that actual relative additional cost will vary by location and conditions in British Columbia. We also recommend that profitability studies on other brush control methods be considered to determine and compare their relative benefits with those of manual brushing. Results from such studies could provide foresters with a range of management options that can be used to effectively control brush problems in young conifer plantations.

Acknowledgements

We would like to thank Oscar Garcia for his advice on the initial steps undertaken in this study. We would also like to thank the anonymous reviewers for providing thoughtful and constructive comments on the paper.

References

? TEST YOUR KNOWLEDGE
Questions on page 113

Baker, S. 1998. Vegetation management: A comparative analysis between herbicide and manual brushing and weeding. University of Northern British Columbia, Prince George, BC. Unpublished undergraduate professional report.

DeLong, S.C., D. Tanner, and M.J. Jull. 1993. A field guide for site identification and interpretation for the southwest portion of the Prince George Forest Region. BC Ministry of Forests, Research Branch, Victoria, BC. Land Management Handbook No. 24.

Faustmann, M. 1995. Calculation of the value which forest land and immature stands possess for forestry (translation from the original German of 1849). Journal of Forest Economics 1:7–44.

Garcia, O. 1996. Easy evaluation of establishment treatments. *In* Forest management planning and managerial economics. Proceedings of the S4.04 meetings sponsored by International Union of Forestry Research Organizations (IUFRO) XX World Congress. August 6–12, 1995, Tampere, Finland.

Hart, D. and P.G. Comeau. 1992. Manual brushing for forest vegetation management in British Columbia: A review of current knowledge and information needs. BC Ministry of Forests, Research Branch, Victoria, BC. Land Management Report No 77.

Jacob, N and C. Opio. 2003. Correction factors for mid-growing season measurements of height to diameter ratios in young lodgepole pine and white spruce plantations in the Vanderhoof Forest District of British Columbia. Report prepared for West Fraser Mills, Ltd., Fraser Lake, BC, University of Northern British Columbia, Prince George, BC. Unpublished report.

Leushner, W.A. 1990. Forest regulation, harvest scheduling, and planting techniques. John Wiley and Sons, Inc., New York, NY.

Newton, M. and P.G. Comeau. 1990. Control of competing vegetation. *In* Regenerating British Columbia's forests. D.P. Lavender, R. Parish, C.M. Johnson, G. Montgomery, A. Vyse, R.A. Willis, and D. Winston (editors). University of British Columbia Press, Vancouver, BC.

Opio, C., K. Van Diest, and N. Jacob. 2003. Intra-seasonal changes in height to diameter ratios for lodgepole pine in the central interior of British Columbia. Western Journal of Applied Forestry 18:52–59.

Opio, C., N. Jacob, and D. Coopersmith. 2000. Height to diameter ratio as a competition index for young conifer plantations in northern British Columbia, Canada. Forest Ecology and Management 137:245–252.

Simard, S. and J. Heineman. 1996. Nine-year response of Douglas-fir and mixed hardwood-shrub complex to chemical and manual treatments on an ICHmw2 site near Salmon Arm. BC Ministry of Forests, Research Branch, Victoria, BC. FRDA Report 257.

ARTICLE RECEIVED: **May 2, 2007**
ARTICLE ACCEPTED: **October 24, 2008**

Discussion Paper

An overview of the effects of forest management on groundwater hydrology

Brian D. Smerdon[1], Todd E. Redding[2], and Jos Beckers[3]

Abstract

This paper provides an introduction to the role of groundwater in watersheds, presents an overview of groundwater resources in British Columbia, and reviews the potential effects of forest management activities (e.g., harvest operations, road building, reforestation, management of mountain pine beetle infestation) on groundwater hydrology. A regional-scale classification of hydrogeologic landscapes for British Columbia is outlined, integrating major physiographic, biogeoclimatic, and groundwater regions. The classification considers characteristics of climate, geology, aquifer type, and interaction with surface water in a generalized way, and summarizes broad-scale expectations about the groundwater hydrology in each hydrogeologic landscape category. In all of the landscapes, a rise in the water table can be expected to follow forest harvesting, though the magnitude and duration of this increase vary according to the area's geology and topography. In wet, steep watersheds, for example, shallow groundwater flow is likely to increase, in turn leading to the potential for increased runoff and decreased slope stability. Local-scale water table changes are often more apparent than those at the regional scale.

KEYWORDS: *forest harvesting, groundwater recharge, hydrogeology, hydrology, watershed management.*

Contact Information

1 Consulting Hydrogeologist, WorleyParsons Komex, 8658 Commerce Court, Burnaby, BC V5A 4N6.

2 Watershed Management Extension Specialist, FORREX Forum for Research and Extension in Natural Resources, Suite 702, 235 1st Avenue, Kamloops, BC V2C 3J4. Email: Todd.Redding@forrex.org

3 Consulting Hydrogeologist, WorleyParsons Komex, 8658 Commerce Court, Burnaby, BC V5A 4N6.

JEM — Volume 10, Number 1

Smerdon, B.D., T.E. Redding, and J. Beckers. 2009. An overview of the effects of forest management on groundwater hydrology. *BC Journal of Ecosystems and Management* 10(1):22–44.

Introduction

Groundwater, generally defined as water occurring beneath the land surface, is a valuable, renewable but "hidden" natural resource. Groundwater contributes to runoff generation from headwater hillslopes (Moore and Wondzell 2005), strongly influences slope stability (Sidle and Ochiai 2006), and is critically important to ecosystems across the Pacific Northwest (Brown et al. 2007). It provides water supply as baseflow during the low-flow season (Pike and Scherer 2003), regulates stream temperature by providing cool water inputs (Moore et al. 2005), and delivers nutrients that are important for the ecology of riparian zones and wetlands (Devito et al. 1996; Freeman et al. 2007).

With groundwater's wide-ranging influence—on, for example, streamflows, slope stability, water quality, wetland sustainability, and operational activities such as site access and silvicultural options—better understanding of this resource is required if resource planning is to achieve sustainable forest management.

Groundwater is also important from a human perspective. In some areas of British Columbia, it is the only viable source for individual and community water supply systems, as well as for agricultural and industrial uses. For the entire province, groundwater sources are estimated to supply about 25% of the total municipal water demand (British Columbia Ministry of Environment 1994). As surface water supplies in the province become fully allocated, water managers and individual users are increasingly turning to groundwater to meet future demands.

Over the years, many researchers have invested significant effort in trying to better understand how groundwater resources can be sustained for human use and protected from over-exploitation and pollution. Nevertheless, comparatively little is yet known about the potential interactions between forest management activities and groundwater systems. In the Interior of British Columbia, the need for both greater knowledge of the effects of forest management on groundwater and an improved inventory of groundwater resources has been identified (Pike and Scherer 2003; Redding and Nickurak 2008; Redding et al. 2008). Several studies suggest that forestry-related activities—including harvesting, road building, and alteration of upland creeks—do impact the groundwater regime and subsequently streamflow (e.g., Pike and Scherer 2003). At the same time, other studies have shown that changes in groundwater regime on some sites can impact future forest productivity. For example, research by Rex and Dubé (2006) suggests that in stands killed by the recent large-scale mountain pine beetle infestation in the central Interior, groundwater regimes may be changing enough to result in the wetting-up of sites that in turn may limit salvage-harvesting activities and forest regeneration success.

Few published case studies on the effect of forest management activities on groundwater regime (e.g., aquifers) exist. This discussion paper aims to address that gap by increasing awareness of the importance of groundwater hydrology in watersheds. Better defining of the role of groundwater in a watershed context will, we hope, assist scientists and forest managers in anticipating changes caused by management activities. This is especially important given that, under the provincial *Forest and Range Practices Act* (British Columbia Ministry of Forests and Range 2002), recognizing the impact of forest practices is critical to ensuring core resource values are protected. With groundwater's wide-ranging influence—on, for example, streamflows, slope stability, water quality, wetland sustainability, and operational activities such as site access and silvicultural options—better understanding of this resource is required if resource planning is to achieve sustainable forest management.

The specific objectives of this discussion paper are to:

- introduce the principles of groundwater hydrology and the role of groundwater in the hydrologic cycle;
- provide an overview of groundwater resources in British Columbia;
- introduce the concept of hydrogeologic[1] landscapes (i.e., distinct groundwater regions) in the province;

[1] Hydrogeology is the study of the distribution and movement of groundwater in the subsurface.

- summarize findings of the literature on the hydrogeologic effects resulting from forest harvesting and road building; and
- outline the potential implications of forest management activities (e.g., harvest operations, road building, and revegetation) on groundwater hydrology variables such as low flows, groundwater recharge, and water residence times.

Our intent was not to make specific predictions for various forestry activities, but rather to provide a conceptual framework for use in evaluating potential groundwater–forestry interactions and to focus future research efforts. This approach will, we hope, offer forest management planners and others insight into the complex groundwater dependency of watershed core resource values that should be considered if groundwater is to be protected, and the ecosystems and communities that depend on it.

Groundwater hydrology background

"Groundwater" means more than just "water below the ground." According to the US Geological Survey, groundwater is water that occurs within the zone of saturation beneath the Earth's surface (Meinzer 1923). This definition is still used in many introductory references on hydrogeology (e.g., Freeze and Cherry 1979; Fetter 2001). It would be an oversimplification, however, to think that groundwater is any water occurring in the ground. Rather, it is the liquid water that completely fills pore spaces in the subsurface. It is the water occurring within the saturated zone, where pore pressure is equal to or greater than atmospheric pressure (Figures 1 and 2). Recent introductions to groundwater hydrology have been published by Smerdon and Redding (2007) and Anderson (2007).

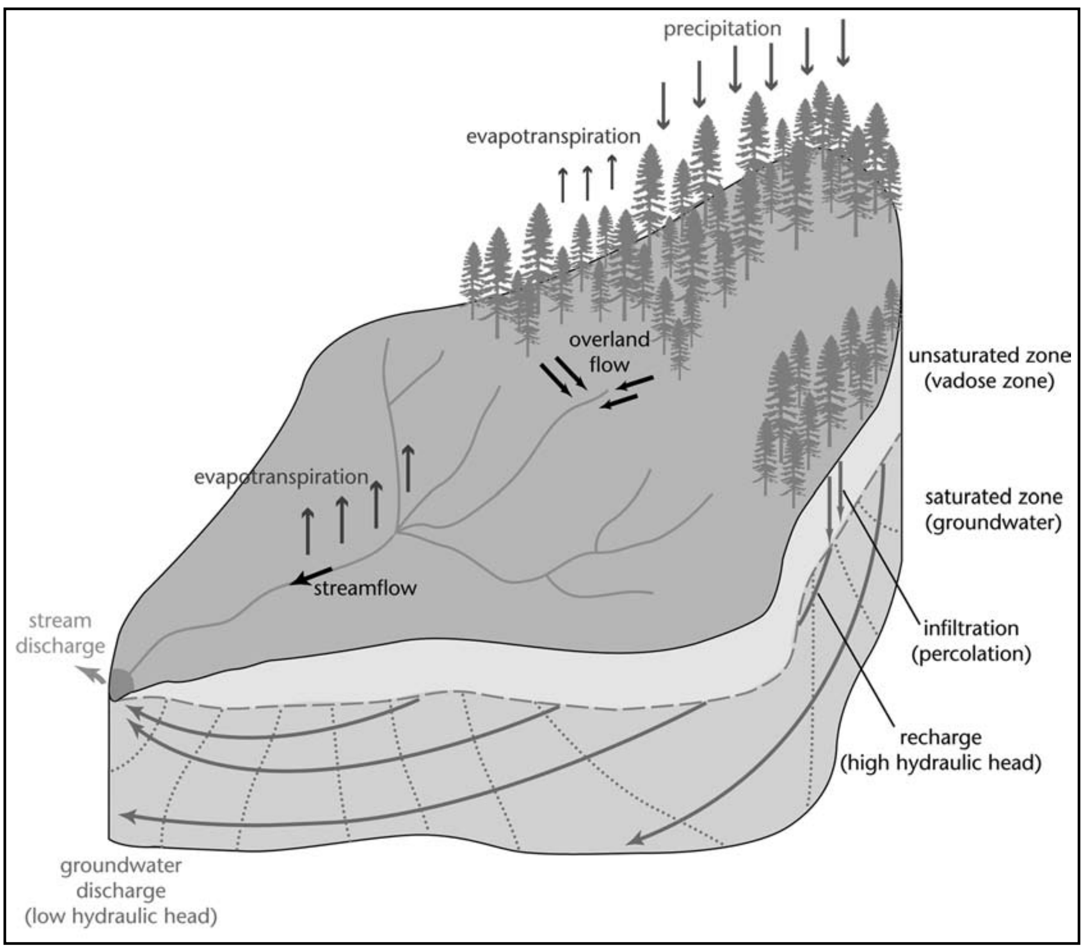


FIGURE 1. Components of the hydrologic cycle within a watershed. Groundwater flow lines are denoted by solid blue arrows. Contours of equal hydraulic head are denoted by dashed blue lines in the saturated zone.

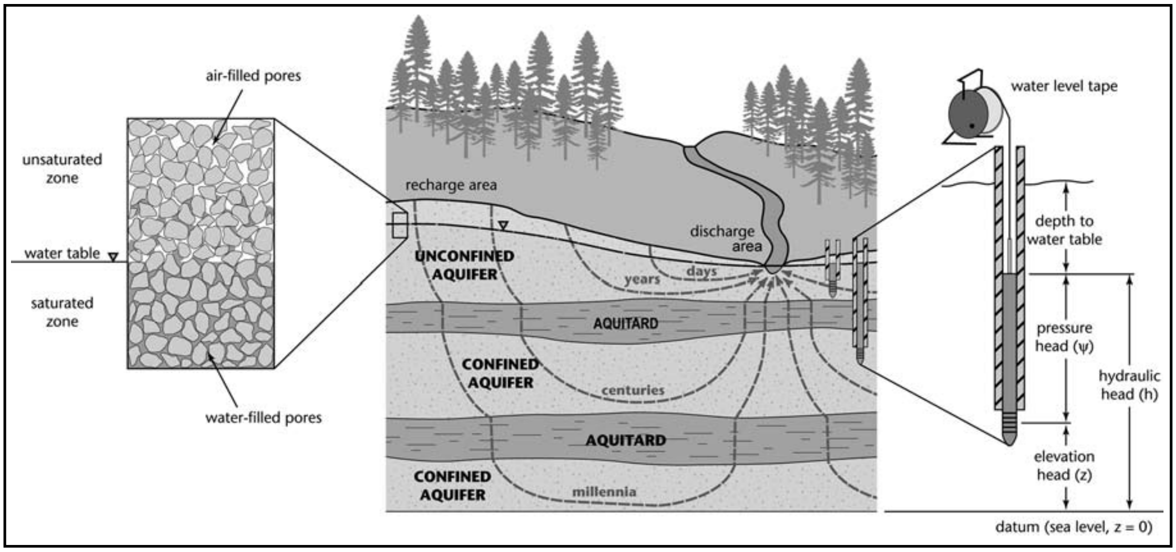


FIGURE 2. Groundwater flow system with water table, aquifers, and aquitards. Local flow systems occur close to the stream and have short travel times (days) relative to regional flow systems which have longer travel times (decades to centuries). Side schematics illustrate the difference between the unsaturated and saturated zones (left) and components of hydraulic head (right).

All geologic materials are composed of solids (i.e., actual grains, sediment, or rock matrix) and pore space (i.e., voids). The volume of available pore space, the size of pores, and the interconnectivity of pores in the rock, soil, or sediment are three of the main factors governing the storage and transmission of groundwater. If the pore spaces in a porous medium are filled with liquid, then the medium is considered to be saturated. Alternatively, if the pores are filled with air, the material is considered to be unsaturated (Figure 2). The division between zones of the subsurface that are unsaturated and zones that are saturated depends on the location of the water table. At the top of the saturated zone, the pore water pressure is equal to atmospheric pressure. Below the water table, the pore water pressure is greater than atmospheric pressure. It is the spatial and temporal differences in pore water pressure that create the potential for groundwater to flow.

The magnitude and direction of groundwater flow is driven by differences in the potential energy supplied by elevation and pore water pressure (termed "total hydraulic head"). The magnitude of flow varies according to the magnitude of the gradient in hydraulic head and the ability of the porous medium to transmit water (i.e., its "hydraulic conductivity").

Subsurface materials (soil and rock) can be defined by their ability to store and transmit water. An aquifer is a geologic unit of porous material that can transmit "significant" quantities of water to a well, spring, or surface water body. Usually, aquifers are composed of:

- unconsolidated sand and gravel deposits,
- consolidated deposits that are highly permeable (e.g., sandstone, limestone), or
- consolidated formations that are less permeable (e.g., granitic and metamorphic rocks) but that have become fractured.

Often, what constitutes a "significant" quantity of water is defined based on human need rather than on an absolute standard.

An aquitard is a saturated geologic unit that restricts the flow of groundwater from one aquifer to another, and is incapable of transmitting useful quantities of water. Typically, aquitards are composed of clay, silt, shale, or other dense geologic materials that are less permeable than aquifer materials.

Aquifers may be unconfined (those permeable geologic units open to the atmosphere where the water table forms the upper boundary) or confined (those covered by an aquitard), as illustrated on Figure 2. Additionally, aquifers and aquitards may have preferential flow pathways, such as fractures in bedrock or macropores, which allow water to be transported at higher rates than to that in the surrounding soil or rock matrix. It is along these pathways that runoff generation and the transport of solutes (e.g., nutrients and pollutants) often occurs from hillslopes to the water table or surface waters.

In some situations, an isolated unit of saturated material may become "perched" above a deeper, regional water table. This occurs when a saturated zone develops atop a layer of low hydraulic conductivity unsaturated material (called a perching layer). Perched water tables are often transient features, occurring seasonally or after a storm event. They are common in environments with high rainfall and shallow permeable soils over less permeable substrates.

Role of groundwater in watersheds

A watershed is made up of a surface drainage network (streams) and the underlying subsurface geologic framework (aquifers and aquitards) that constitute the terrestrial portion of the hydrologic cycle. Water that infiltrates the ground surface and moves vertically through the unsaturated zone is referred to as "unsaturated flow" or "percolation." When it reaches the water table, thus entering the saturated zone, it becomes "groundwater recharge." Although often used interchangeably, there is a distinction between the terms infiltration, unsaturated flow, and recharge when used to describe water flowpaths.

Within a watershed, regions where water is infiltrating and percolating to the groundwater regime are termed "recharge areas." Groundwater flows from areas of high hydraulic head to areas of low hydraulic head, typically as a result of a decrease in elevation or in pore pressure (e.g., caused by pumping groundwater from a well). In natural settings, groundwater may reach the surface and discharge to springs, streams, or wetlands (Figures 1 and 2). Travel times of groundwater from recharge to discharge areas may be as short as days or as long as centuries, depending on the hydraulic conductivity of the soils and rocks and on whether flow occurs through shallow, local-scale flow systems or deeper, regional-scale systems (Toth 1962). In general, however, travel times for groundwater are much longer than for water flowing through streams in the surface drainage network.

Water is constantly moving through a watershed (Figure 1). The inflow is supplied by precipitation (usually rain and snow). The outflow occurs by evapotranspiration and discharge into basin outlets through surface and groundwater pathways. For any given timeframe, the difference between inflow and outflow is stored in the watershed in the subsurface unsaturated and saturated zones, in vegetation, and in surface water bodies. Averaged over sufficiently long timeframes (e.g., years or decades), changes in the amount of water stored in a watershed are small, with inflow balancing outflow (ignoring any effects of long-term climate changes).

The general equation for the water balance (or "water budget") in a watershed helps illustrate water movement:

$$I - O = \Delta S$$

where: I = inflows, O = outflows, and ΔS = change in storage.

The science of hydrogeology (the study of groundwater) applies this water budget principle to subsurface regions that are saturated. Inflow is supplied by recharge and outflow leaves by discharge to surface waters or by the pumping of water out of wells. One factor complicating the balance is that surface drainage networks and groundwater flow systems (recharge and discharge zones) do not always have the same catchment area (Winter et al. 2003). Furthermore, a well-defined surface water catchment area may not be the same as the groundwater catchment area in that region, which is controlled by both topography and geology.

In a watershed, the subsurface geologic framework interacts with the overlying surface drainage network. The exchange of surface water and groundwater can be quite complex because surface water bodies, such as streams and rivers, may be both sources and sinks for groundwater (Figure 3). Gaining streams receive discharge from groundwater when the stage of the stream is lower than the elevation of the water table. Conversely, losing streams recharge groundwater when the stage is higher than hydraulic heads in adjacent groundwater. Such conditions may occur, for example, on an alluvial fan. This is a common source of groundwater recharge for many valley-bottom aquifers in British Columbia. Because of the variability that exists in subsurface materials (soils and [or] rock) and topography in a watershed, streams and rivers can have reaches or sections that are gaining or losing (Winter 1999). The same reach can be gaining or losing at different times of the year. The amount of groundwater that discharges to a stream is commonly referred to as the stream's "baseflow." Baseflow is important for maintaining streamflow volumes during dry times of the year.

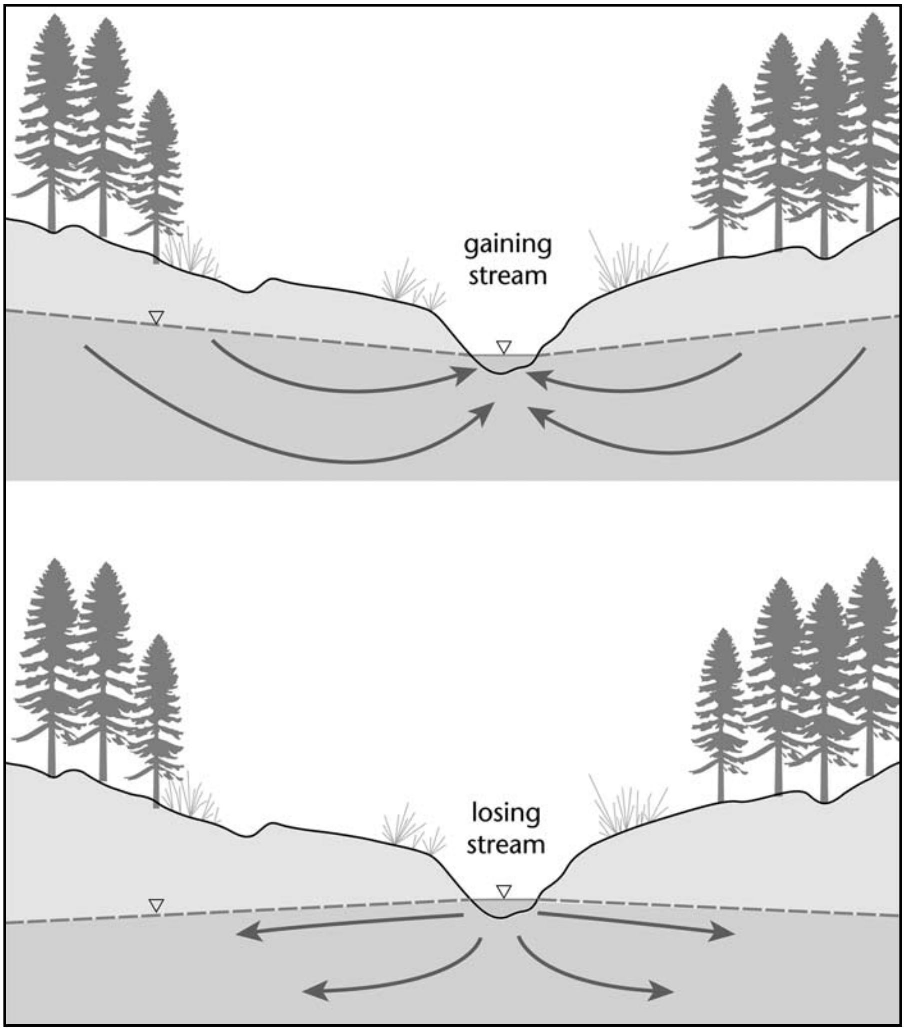


FIGURE 3. Examples of surface-water–groundwater interaction for gaining and losing streams.

Given the comparatively long travel times for groundwater, baseflow amount is typically not determined by specific storm events or seasonal phenomena such as snowmelt. Rather, it reflects the amount of groundwater recharge that occurred in previous years.

Groundwater in British Columbia

In British Columbia, the Water Stewardship Division of the British Columbia Ministry of Environment is responsible for assessment, inventory, and governance of groundwater resources (for more information, go to: ***www.env.gov.bc.ca/wsd/plan_protect_sustain/groundwater/index.html***). Protection and regulation of groundwater is legislated through the *Water Act* (BC Regulation 299/2004; British Columbia Ministry of Environment 2004), which specifies codes of practice for the development and protection of water wells and sets the qualification requirements of well drillers/installers and groundwater professionals. The *Water Act* does not require a groundwater user to have a licence. However, any waterworks system servicing more than three households is regulated under the *Health Act*, Sanitary Regulations (BC Regulation 142/59; British Columbia Ministry of Health 1996), and requires a permit. Remediation of groundwater contamination is regulated under the Contaminated Sites Regulation of the *Environmental Management Act* (BC Regulation 375/96; British Columbia Ministry of Environment 2003), which sets standards for groundwater quality based on its likely uses (e.g., as drinking water, to support aquatic life, or to supply agricultural purposes).

Groundwater inventory and assessment activities in the province have typically been limited to populated areas. The British Columbia Ministry of Environment's Water Stewardship Division maintains a water well database, observation well network, and aquifer classification system to aid groundwater resources management. These tools can be viewed on the BC Water Resource Atlas (for more information, go to: ***www.env.gov.bc.ca/wsd/data_searches/wrbc/index.html***). The ministry's WELLS Database also contains legal descriptions of wells, well locations, and well construction details for more than 85 000 water wells in the province, and has been used to identify, map, and categorize more than 800 individual aquifers (BC Aquifer Classification System and Maps). In addition, the ministry maintains nearly 200 observation wells to monitor groundwater levels and support assessment of impact to groundwater in targeted areas.

Hydrogeologic landscapes of British Columbia

British Columbia's physiographic setting includes mountain ranges, highland plateaus, and valleys that have developed over millions of years (Church and Ryder 2007). Throughout the province's geologic history, tectonic events and glaciations have resulted in complex sedimentary deposits and rock formations that form diverse hydrogeologic settings. Information on the groundwater resources of British Columbia is limited primarily to settled areas. Vast portions of the province are relatively undeveloped and thus have little exploratory information pertaining to hydrogeology. Therefore, a first step in assessing the nature of groundwater resources in British Columbia and the potential impacts of forest management practices on those resources is to gain an understanding of the climatic, physiographic, and geologic setting (Livingstone 1994; Winter 2001; Devito et al. 2005a).

To do this, we started by devising a regional-scale classification of hydrogeologic landscapes for British Columbia (Figure 4). This allowed us to provide a framework in which to synthesize findings from those few studies that have directly addressed forest management impacts to groundwater. The classification incorporates a combination of the major physiographic units (Church and Ryder 2007), groundwater regions (Foweraker 1994), and biogeoclimatic zones of the province. It also generally follows both a climatic gradient (i.e., from very humid to semi-arid) and topographic gradient (i.e., from steep mountain regions to broad plains). For each of the seven hydrogeologic landscapes identified, the general characteristics of climate, geology, and interaction with surface water are described, similar to the Fundamental Hydrologic Landscape Units approach of Winter (2001).

Within each broad-scale hydrogeologic landscape described below, the types of aquifers occurring in them also have unique characteristics that could be investigated at a finer level of detail. For example, a formal characterization of aquifers has been proposed by Wei et al. (2007) for the Cordilleran region, and includes six main aquifer types (four with sub-categories). Although the broad hydrogeologic landscape categories presented here are at a larger scale than is directly applicable for specific forest management investigations, the characteristics of each are distinct, and allow integration of knowledge gained from studies in other areas. Table 1 summarizes the characteristics of each of the seven hydrogeologic landscapes.

Coastal Basins & Lowlands

This region, located along the mainland and island coasts of the province, contains very productive temperate rain forests of hemlock and Douglas-fir. It is characterized by a rainfall-dominated and humid climate (annual precipitation is much greater than potential evapotranspiration), which drives a hydrologic system dominated by surface water and near-surface flows (runoff). However, the region also contains alluvial valley and fractured bedrock aquifers, which are major drinking water resources for the lower Fraser Valley of the southwest British Columbia mainland and the Gulf Islands (Dakin et al. 1994). Bedrock groundwater flow is controlled by the prevalence of intrusive igneous and foliated metamorphic rocks in which tectonic stresses have established fractures and faulting. Alluvial aquifers generally contain thick deposits of sand and gravel bounded by coastal mountains.

Coastal Mountains

The Coastal Mountains rise to about 2000 m above sea level. Orographic precipitation (as rain and snow) and a significant snowpack characterize the region. The British Columbia Ministry of Environment has not

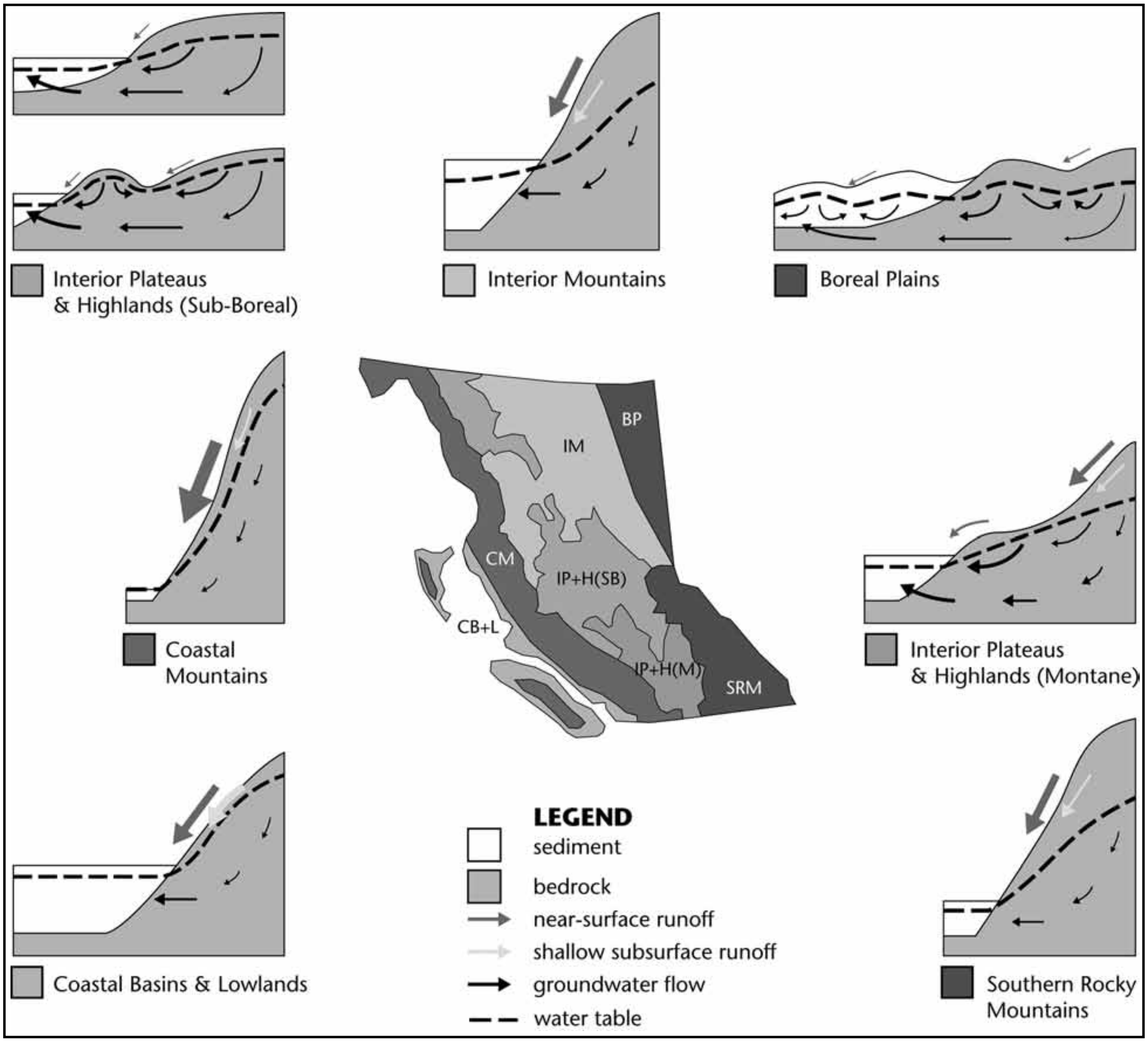


FIGURE 4. Hydrogeologic landscapes for British Columbia, indicating general variations in depth of the water table and types of groundwater flow systems that may develop. Letters shown within the map are short forms for each landscape: CB+L – Coastal Basins & Lowlands; CM – Coastal Mountains; IP+H(M) – Interior Plateaus & Highlands (Montane); IP+H(SB) – Interior Plateaus & Highlands (Sub-Boreal); IM – Interior Mountains; SRM – Southern Rocky Mountains; and BP – Boreal Plains.

mapped many aquifers in coastal mountains. However, groundwater flow likely occurs in the upper portions of bedrock (Parsons and Quinn 1994), which is fractured and faulted as has occurred in the Coastal Lowlands. The bedrock here is intrusive igneous and foliated metamorphic rocks, with faulted lava flows present on coastal islands and some inland regions (e.g., Squamish area). Considering the relatively steep topography in this region, many of these flow systems may be perched and have localized seepage areas. Rapid runoff (from rainfall or snowmelt), very shallow subsurface (possibly perched) flow, and surface water dominate the hydrologic regime.

Southern Rocky Mountains

The faulted and folded sedimentary mountains of southeast British Columbia rise to more than 2500 m above sea level. Orographic precipitation characterizes the region, falling as snow in the winter and rain from convective storms in the summer. The timing of snowmelt plays a major role in the hydrology.

TABLE 1. Attributes of hydrogeologic landscapes in British Columbia, together with effects of forest harvest, road building, and potential influence on aquatic ecosystems.[a]

Hydrogeologic landscape	Climate	Hydrogeology	Harvest	Road building
Coastal Basins & Lowlands	very humid (P >> ET)	Productive aquifers in thick valley sediments and fractured bedrock. Bedrock groundwater flow controlled by tectonic structures.	Increase to water table (perched or regional) and potential for increase to groundwater recharge.	High water table in downslope locations could pose trafficabilty problems. However, good natural surface drainage should reduce problems.
Coastal Mountains	very humid (P >> ET)	Dominated by rainfall and snowmelt runoff processes. Groundwater flow in fractured rock, some transient perched water table conditions expected.	Increase to water table (perched or regional) and potential for increase to groundwater recharge. Potential for pore pressure increase to affect slope stability.	Roads may cut into SSSF zone and become seepage faces, causing groundwater discharge to occur.
Southern Rocky Mountains	humid (P > ET)	Perched water table and seepage in upland areas. Productive alluvial valley aquifers interact with river systems and are bounded by steep valley walls.	Increase to water table (perched or regional) and potential for pore pressure increase to affect slope stability.	Roads may cut into SSSF zone and become seepage faces, causing groundwater discharge to occur.
Interior Mountains	humid (P > ET)	Wide valleys and highly variable bedrock geology lead to complex hydrogeology.	Increase to water table, but limited chance of rising to ground level. Increase in shallow subsurface flow.	Roads may cut into SSSF zone and become seepage faces, causing groundwater discharge to occur.
Interior Plateaus & Highlands (Sub-Boreal)	humid (P > ET) to sub-humid (P ≥ET)	Broad upland areas and wide valleys. Groundwater flow controlled by variation in terrain. Presence of nested groundwater flow systems.	Effect depends on landscape position. Soil moisture and water table increase, with increase to groundwater recharge. Effect could be noticed in local-scale groundwater flow within years (e.g., higher baseflow) or could be masked/buffered in regional-scale groundwater flow by other large-scale effects (e.g., climate cycles).	Effect of roads depends on landscape position and relative location of groundwater recharge/ discharge areas. Road crossings over regional groundwater discharge areas expected to be wet and problematic. High water table from harvest and/or mountain pine beetle salvage could pose trafficability issues.
Interior Plateaus & Highlands (Montane)	sub-humid in highlands (P ≥ ET) to semi-arid in valleys (P ≤ ET)	Wide valleys (dry) and broad uplands (humid). Wide variation in groundwater flow and aquifer productivity, depending on type of valley-fill sediments.	Effect depends on landscape position and timing of harvest. Water table and groundwater recharge may increase, depending on upland hydrology.	Effect of roads depends on landscape position and relative location of groundwater recharge/ discharge areas. Road crossings over regional groundwater discharge areas expected to be wet and problematic. High water table from harvest and/or mountain pine beetle salvage could pose trafficability issues.
Boreal Plains	sub-humid (P ≥ ET)	Vast, broad, glaciated terrain. Thick glacial deposits may contain aquifers. Groundwater flow setting controlled by climate and geology, with nested flow systems.	Effect depends on landscape position and timing of harvest compared to climate cycles. Soil moisture increases, but water table may not rise because of large available soil moisture storage capacity.	Effect of road depends on landscape position, underlying geology, and relative location of groundwater recharge/discharge areas. Roads through coarse-textured surficial materials will be easier to maintain than roads through low-lying clay plains.

[a] P = precipitation; ET = evapotranspiration; SSSF = sub-surface storm flow.

The hydrogeology of the region is thought to be similar to that in the Coastal Mountains region (i.e., having perched flow systems and seepage areas), but with the addition of karst bedrock and wider alluvial valleys bounded by steep mountain walls. Surface flow and shallow groundwater recharge the alluvial valley aquifers, which in turn interact with the major river systems that experience snowmelt-dominated streamflow regimes. Thus, the hydrogeologic regime in this region is likely one of dynamic interaction between surface water and groundwater.

Interior Mountains

The remaining mountains of the interior—Cariboo and Northern Rocky Mountains—have similar orographic precipitation and general landform shape as the Southern Rocky Mountains. More than half of the annual precipitation falls as snow, thus driving a snowmelt-dominated hydrologic setting. Very little is known about the hydrogeology of the region, and the geologic setting is complex including, for example, karst bedrock in the Northern Rocky Mountains. Groundwater systems are generally thought to be similar to those in the Southern Rockies, with the relatively steep mountains contributing seasonal flow to thick valley aquifers. The interior mountain ranges are headwaters for major river systems.

Interior Plateaus & Highlands (Sub-Boreal)

In the central and northern portion of the province, broad upland areas of flat-lying lava flows are covered by sub-boreal spruce forests. The region is characterized by a humid to sub-humid climate and a broad, rolling topography with wide river valleys. The variations in climate and topography favour the formation of "nested" groundwater flow regimes: local-scale groundwater flow may originate and terminate in highland areas, and regional-scale systems may drive deeper groundwater flow to sedimentary aquifers in the valley bottom.

Interior Plateaus & Highlands (Montane)

In the southern portion of the province, a warmer and drier climate supports montane forests of lodgepole pine and Douglas-fir. As in the Sub-Boreal region, wide valleys rise to broad rolling uplands. However, the valleys are typically dry (semi-arid) compared with upland areas. The presence of populated areas along the valley bottoms and a growing concern for residential, industrial, and agricultural water demands have generated considerable knowledge of groundwater resources, especially among people in the Okanagan Basin. The interactions between snowmelt-driven upland forest watersheds and arid valley bottoms create a wide variety of groundwater conditions. The uplands are composed of fractured bedrock; and the valley bottoms have been filled in with a thick, complex arrangement of sediments from repeated glaciation and alluvial processes. Although knowledge about the hydrologic connection between uplands and valley bottoms is limited, the assumption is that the highlands have perched groundwater conditions and a complex relationship between runoff from headwater catchments and groundwater recharge. Seasonal surface runoff (e.g., in alluvial fan settings) and deeper groundwater flow (e.g., mountain block recharge) are expected to recharge valley-bottom aquifers.

Boreal Plains

The northeast section of the province is covered by a small portion of the Boreal Plains, which are characterized by thick glacial sediments over generally flat-lying sedimentary bedrock. The climate is generally sub-humid, and soil water storage, groundwater flow, and evapotranspiration dominate annual water budgets. In general, the surface water storm runoff potential is minimal because of the flat-lying terrain. Consequently, there are numerous wetlands, ponds, and lakes on the landscape. Gentle undulating topography combined with a wide array of landform textures (ranging from coarse-textured outwash to fine-textured glaciolacustrine) produces a range of nested groundwater flow systems and complex interactions between groundwater and surface water.

In summary, these seven hydrogeologic landscapes represent a cross-section of broad-scale groundwater movement for distinct regions in British Columbia (Table 1; Figure 4). Each region has unique characteristics that control subsurface flow. The underlying differences in climate and terrain result in distinct groundwater flow systems that may in turn be affected differently by forest management activities.

The effects of forest management activities on groundwater: Literature review

There is a large body of research into the effects of forest management on surface hydrological processes, hillslope runoff, slope stability, and riparian zone processes. Overviews of streamflow, runoff generation, low flows, and hyporheic exchange have been completed by, among others, Moore and Wondzell (2005), Pike and Scherer

(2003), and Bonell (1993). Few studies, however, have focused on the direct link between forest management activities and groundwater (Tables 2 and 3). Although exact effects would largely depend on site-specific watershed characteristics, the same factors that underpin the hydrogeologic landscapes classification (Table 1; Figure 4) come into play. We therefore summarize results for the studies on the effects of forestry on groundwater in the context of these hydrogeologic landscapes.

Other criteria guided our literature review:

- In most of our review, we focused on literature pertaining to groundwater regimes, including observed changes to the position of the water table, estimated changes to groundwater recharge (in some cases inferred from changes in water yield), and changes in baseflow to streams. We also looked at articles dealing with hydrological processes, such as hillslope runoff and changes in the unsaturated zone, but we were mainly interested in data on saturated zone processes and recharge.
- Similar to what Pike and Scherer (2003) did in their review, we considered three aspects of forest management: timber harvest, road construction, and silviculture activities. We found that most of

TABLE 2. Summary of literature review: Harvest impact on water table.

Source	Study site	Location	Average annual precipitation (mm)	Management practice[a]	Water table change
Bliss and Comerford (2002)	—	Gainesville, Florida	1150	CC	A 21–49 cm rise after 900 days. Larger seasonal fluctuations observed for 4 years following harvest.
Dubé et al. (1995)	Beaurivage Forest	St. Lawrence lowlands, Quebec	957	CC	A 7–52 cm rise, depending on soil texture.
Pothier et al. (2003)	Villroy	St. Lawrence lowlands, Quebec	510	PC + CC	Up to 22-cm rise in cut areas. Water table rise increased linearly with percentage of cut area in the first year following harvest. Five years after harvest, water tables remained elevated, but less dependent on the percentage of area cut.
Fannin et al. (2000)	Carnation Creek	Vancouver Island, British Columbia	2100–4800	CC	A 50–150 cm rise (approx.) following individual storm events. Large spatial variability because of soil conditions, but all water table response was rapid. An upper limit to pressure head increase was observed, above which preferential flow pathways activated.
Hetherington (1998)	Carnation Creek	Vancouver Island, British Columbia	2100–4800	CC	A 30–50 cm rise that persisted for 10 years following harvest.
Megahan (1983)	Pine Creek	central Idaho	890	CC (+ burned)	A 90-cm rise in water table, decreasing to approx. 40 cm after 2 years. A 41% increase in snow accumulation in cut area.
Rockefeller et al. (2004)	—	northern Idaho	1050	CC	Perched water table approx. 8 cm higher in cut area. Perched water table had earlier formation and longer duration in cut area compared with uncut area.
Rex and Dubé (2006)	Vanderhoof Forest District	central British Columbia	496	CC + mountain pine beetle	A 10-cm (approx.) higher water table in toe-slope of cut area compared to area killed by mountain pine beetle. A 30-cm (approx.) higher water table in upland of cut area compared to area killed by mountain pine beetle.
Peck and Williamson (1987)	Collie River Basin	Western Australia	820–1120	CC + PC	A 100–40 cm rise following wet season. Water table increased by 260 cm/yr in clearcut areas and 90 cm/yr in partially cleared areas.
Evans et al. (2000)	TROLS	Lac La Biche, Alberta	468	PC	Was 26 cm higher in cut area compared to uncut area.
Urie (1971)	—	northwest Michigan	790	PC	A 100-cm (approx.) rise as a result of higher snowpack in strip cut areas.

[a] CC = clear cut; PC = partially cut.

TABLE 3. Summary of literature review: Harvest impact on groundwater recharge.

Source	Study site	Location	Average annual precipitation (mm)	Management practice[a]	Change in groundwater conditions (recharge, chemistry, temperature)
Bates (2000)	Fernow Experimental Forest	West Virginia	1470	PC	Harvested watershed supplied more low flow (baseflow) to headwater streams because of higher soil moisture in the years following harvest. The effect of storm events was minor compared with deeper subsurface flow.
Cornish (1993)	Karuah	Australia	1450–1750	PC	Yield increased 150–250 mm/yr following harvest, depending on percentage of area cut. Increased recharge and overall water yield remained higher for 3 years following harvest.
Bent (2001)	Cadwell Creek	Massachusetts	1174	PC	Groundwater recharge increased by 68 mm/yr for six seasons following harvest.
Bren (1997)	Cropper Creek	Southeast Australia	660	CC	Increase in amplitude of diurnal fluctuation in streamflow following removal of slope vegetation as a result of increased subsurface flow.
Henriksen and Kirkhusmo (2000)	—	Norway	750	CC	A 2–3° increase in groundwater temperature and increase in nitrate, potassium, and organic carbon following harvest. Elevated nitrate and potassium was detected in groundwater for 11 years after harvest and initial herbicide application.
Cook et al. (1989)	Western Murray Basin	South Australia	340	CC	Recharge found to increase by 20 mm/yr very gradually following harvest (~200 yr).
Rusanen et al. (2004)	—	Finland	700	PC	Study of long-term groundwater monitoring data (1975–1995) from Finland groundwater database. Nitrate concentrations increased for 4 years following harvest, released from shallow soils.

[a] CC = clear cut; PC = partially cut.

the literature we reviewed was related to the first aspect—the effect of timber harvest.

- Given the scarcity of groundwater and forestry studies, we considered studies from nearly any geographic location, but with a goal of transposing findings to British Columbia conditions using the hydrogeologic landscape perspective. The purpose of this approach was to determine the potential effects of forest management activities according to the hydrogeologic characteristics of each region. Some speculation was required on our part to extrapolate the findings of research not directly linking forest management and groundwater hydrology. Thus, the potential effects described are based on our informed opinions, derived from our knowledge of groundwater principles.

Effect of forest harvesting on water table position

Timber harvesting through clearcutting or partial or selective cutting has been shown to result in wetter soils (Adams et al. 1991; Keppeler et al. 1994) and greater catchment water yield (Hetherington 1987b; Moore and Wondzell 2005). This wetting-up results when interception and evapotranspiration are reduced. Evapotranspiration is the sum of water vapour fluxes from transpiration from leaf stomata and evaporation from soils and wet leaves (because of forest canopy interception of rain and snow). The literature reviewed about the effects of forest harvesting on water table position is summarized in Table 2 and discussed below in terms of British Columbia's hydrogeologic landscapes.

The effect of changes in canopy rain and snow interception has been relatively well documented. Changes in plant transpiration pre- and post-harvest, on the other hand, are complex and vary by the type of vegetation present in cut areas. The resulting increase in soil moisture increases the flow of water in the unsaturated zone, which in turn may increase runoff and groundwater recharge. The net effect will depend on the characteristics of a given hydrogeologic landscape—such as its bedrock geology, surficial geology, soil type, and topography.

In regions similar to the Coastal Basins & Lowlands, increases in water table elevation have been measured in the order of 50 cm following harvest of peatland forest stands (Dubé et al. 1995) and shown to remain elevated for three or more years following harvesting (Bliss and Comerford 2002; Pothier et al. 2003). As watershed slope and precipitation increase, water table increases of up to 50–150 cm have been observed at Carnation Creek on west Vancouver Island. However, this peak water table response was observed immediately following storm events (Fannin et al. 2000; Dhakal and Sidle 2004). Longer-term water level rises of 30–50 cm associated with clearcutting were also recorded at Carnation Creek, and persisted for 10 years post-harvest (Hetherington 1998). Water table increases in coastal regions affect runoff generation to headwater streams. Carnation Creek provides a well-documented example of the importance of shallow groundwater in overall catchment function. Rapid water level rises trigger preferential flow (e.g., Beckers and Alila 2004), which must be considered when the effects of forest management on peak flows are being assessed.

For mountainous settings in the British Columbia Interior (e.g., Columbia Mountains, Rocky Mountains, and Interior Mountain landscapes), the duration and volume of storm precipitation is typically less than on the coast, although the intensity of convective thundershowers may be higher. Harvesting's effect on the water table may be similar, but there is a higher probability in the mountains that perched water table conditions will develop in the shallow subsurface (above the regional water table). This type of post-harvest response was observed in northern Idaho (Rockefeller et al. 2004), where the perched water table formed earlier, was approximately 8 cm higher than in uncut areas, and lasted longer in the season before dissipating (Table 2). However, the perching in the Idaho case occurred above a dense, silica-rich horizon with low permeability (fragipan)—soils known not to be extensive in British Columbia. Harvested areas in interior mountainous settings also tend to accumulate more snow than do uncut areas, which can lead to water table rises of as much as 90 cm (Megahan 1983). Deeper snowpacks create favourable conditions for low-flow (baseflow) increases later in the season (Pike and Scherer 2003), since peak flow intensity is governed by the rate of snowmelt. In the Coastal Mountain region, by contrast, harvesting tends to result in more rapid peak flow responses (Whitaker et al. 2003).

For the Interior Plateau & Highland hydrogeologic landscapes (Sub-Boreal and Montane), the effect of harvest on the water table depends on:

1. the location of the harvested area in the larger-scale groundwater flow system (e.g., flow systems scales described by Toth, 1962; see Figure 2); and
2. the change in water inputs relative to groundwater flow rates.

At higher landscape positions, water table fluctuations are generally greater than at locations lower in the landscape (Webster et al. 1996; Winter 2000). Increased seasonal water table fluctuation is primarily due to the differences in precipitation (water inputs) pre- and post-harvest, compared to transient water movement through the basin (i.e., groundwater flow). On the other hand, at locations of lower topographic elevation (e.g., regional groundwater discharge areas; see Figure 2), the water table position is often more consistent, maintained by larger-scale groundwater flow and connectivity with surface water such as lakes. Temporal differences in water table fluctuations are often the basis for inferring changes in groundwater recharge, and in turn, subsurface flow rates. Thus, how forest harvesting in the Plateaus & Highlands regions might affect groundwater flow varies by the location of the cut area within the topographic landscape and groundwater flow system. Given the long timeframes associated with these flow systems, there are no field-based studies reported in hydrologic literature. However, for the Vanderhoof Forest District, Rex and Dubé (2006) identified differences in water table increase for toe-slope and upland areas, suggesting that water table response does indeed depend on larger-scale groundwater flow. In the different climatic regime of Western Australia, but which has similar amounts of annual precipitation as in the Plateaus & Highlands, the water table was observed to rise between 100 and 400 cm after harvest (Peck and Williamson 1987).

On the Boreal Plains, climate conditions and the sediment texture of landforms have as much control over water table position as forest harvesting does (Devito et al. 2005b). Some sites on the Boreal Plains also appear to have subsurface conditions favourable for perching (Riddell 2008). At the Terrestrial and Riparian Organisms, Lakes and Streams (TROLS) project sites in northeast Alberta, water table elevation was found to be 26 cm higher in harvested areas than in unharvested areas (Evans et al. 2000). However, soil moisture storage and a deeper water table were also found to mask the impact of harvest when compared to the impact of climatic variability (Macrae et al. 2005, 2006). Research on forest hydrology, wetlands, and groundwater on the Boreal Plains near Utikuma Lake in north-central

Alberta has also begun to indicate the dominance of substrate texture on water table dynamics (e.g., Ferone and Devito 2004; Smerdon et al. 2005)—a factor that could be large enough to mask effects of harvest.

Effect of forest harvesting on groundwater recharge

Soil moisture increase and higher water table after harvest may also lead to an increase in the net rate of groundwater recharge, although the amount of recharge depends on the ability of subsurface to store and transmit water. Groundwater recharge is a difficult component of the water cycle to quantify (de Vries and Simmers 2002), but the effect of higher recharge can be observed through detailed field measurement or inferred from changes in baseflow to streams (Bates 2000). Inferring changes in baseflow (water output) relative to changes in recharge (water input) requires an understanding of the role of water storage in a particular region. These potential changes to the subsurface flow regime will depend on the characteristics of the specific hydrogeologic landscape, including its climate and geology. Groundwater flow systems will adjust to the increase in water input, and this effect may be short- or long-lived, depending on the scale of system. Steep, bedrock-controlled catchments will experience more rapid changes in groundwater flows and groundwater travel times than will low-relief plains or upland areas with longer groundwater travel times. In British Columbia, the majority of published studies on groundwater recharge have focused on areas with productive aquifers and sensitive water resource issues. Such areas include Abbottsford-Sumas, Grand Forks (Allen et al. 2004; Scibek and Allen 2006), the Gulf Islands (Denny et al. 2007; Surrette et al. 2008), and, more recently, the Okanagan Valley (Liggett et al. 2007; Toews 2007). The literature reviewed about the effects of forest harvesting on groundwater recharge is summarized in Table 3 and discussed below in terms of British Columbia's hydrogeologic landscapes.

Hydrologic studies of the Coastal Mountains have typically found that greater runoff is generated from harvested areas than forested areas (e.g., Keppeler et al. 1994; Hetherington 1998; Fannin et al. 2000). In general, hydrogeologic landscapes with relatively steep terrain would not be expected to have an appreciable amount of groundwater recharge compared to runoff (e.g., Hudson and Anderson 2006). For hydrogeologic landscapes similar to the Coastal Basin & Lowlands, precipitation would be sufficient, in combination with low enough relief, to favour groundwater recharge. Although there are no published studies in which increased rates of groundwater recharge were directly measured, a few studies have indicated increases in catchment water yield, which may be a result of higher groundwater recharge following harvest. For example, in the northeastern United States, one harvested headwater was found to supply more baseflow in the years following harvest than appeared to be generated just from shallow storm flow (Bates 2000). We speculate that this increase may have been provided by higher recharge following harvest. Pike and Scherer (2003) have summarized similar results for snowmelt-dominated hydrologic regimes. The magnitude of increase to water yield and potentially to groundwater recharge may be linearly related to the percentage of area cut (partial harvesting or clearcutting), especially in the first few years following harvest (e.g., Bosch and Hewlett 1982; Stednick 1996).

For hydrogeologic landscapes similar to the Interior Plateaus & Highlands, a wider variation in possible changes to groundwater recharge exists. Areas with coarse-textured soil, fracturing, and preferential flowpaths promote increased vertical drainage below the rooting zone following harvest. At the Upper Penticton Creek Experimental Watershed in the Okanagan Highlands, the results of stand water balance models show that the amount of water draining out of the soil rooting zone (i.e., water that is potentially available to raise water tables, recharge groundwater, or generate streamflow) is greater in harvested areas or disturbed areas (e.g., damaged by mountain pine beetle) than in undisturbed mature forest stands. In this watershed, Spittlehouse (2007) found 65% drainage of annual precipitation in the harvested or disturbed areas versus 40% in the undisturbed stands. At a site in the northeastern United States, groundwater recharge increased by 68 mm/yr for 6 years following harvest (Bent 2001). The implications of such changes in recharge vary. The Interior Plateaus & Highlands are characterized by undulating topography, which favours development of nested local-, intermediate-, and regional-scale groundwater flow systems. Thus, recharge that is part of a local-scale system may discharge relatively quickly to nearby headwaters (e.g., Bren 1997) such that effects of harvesting could be detectable and ecologically significant. On the other hand, recharge that is part of a larger-scale flow regime maintains valley-bottom aquifers over long time periods (e.g., centuries in the case of "mountain block recharge"). In this case, the effects of relatively short-term forest disturbances (i.e., decades) may not be detectable. The details of these highland-to-lowland linkages are emerging for studies in the Okanagan Valley (e.g., Smerdon et al. 2008) and are the topic of ongoing research.

Low topographic relief favours vertical flow through the unsaturated zone on the Boreal Plains (Redding and Devito 2008). However, as for water table position in this landscape, groundwater recharge is as strongly controlled by soil texture and climate as by forest harvesting (Devito et al. 2000). On coarse-textured landforms (e.g., outwash plains and wide alluvial valleys), groundwater recharge increases following harvest. On fine-textured landforms (e.g., lacustrine plains and morainal deposits), however, recharge may be diminished as a result of greater soil moisture storage and subsequently increased root water uptake and soil evaporation (caused by capillary forces drawing the moisture upward through the ground). We found no long-term studies of forest harvest and groundwater recharge on the Boreal Plains in Canada. In Finland, a review of groundwater data from the national database (1975–1995) revealed that nitrate concentrations increased for approximately 4 years following partial harvest (Rusanen et al. 2004). This suggests that increased groundwater recharge moved nitrate from the upper soil zone (where it would have previously interacted with forest land cover) to the underlying saturated zone. However, the study relied on data collected for broad-scale groundwater resource assessment only and therefore lacked a finer resolution determination of controlling factors.

Effect of roads on groundwater flow and storage

Assessment of the effects of forest road construction has generally been limited to examining changes in surface drainage networks. Wemple et al. (1996) found that most forest road networks established either ditches that drained directly to streams or ditches that drained to gullies below culverts in steeper areas. This suggests that where roads exist, surface drainage from uplands to streams is likely to increase because of the expansion of the channel network associated with roads. The effect of roads, and particularly of altered surface drainage patterns on slope stability (e.g., Wemple et al. 2001), depends on local geology (Sugden and Woods 2007) and climate. The effect of road construction on groundwater has only been documented for steep, coastal mountain settings, where forest roads are cut into the hillside, intersecting shallow and possibly perched groundwater. For example, Megahan and Clayton (1983) found that in such settings, a seepage face forms along the road cut. This causes the groundwater flow to be redirected, occurring as surface water in ditches rather than as shallow subsurface flow. Such an alteration can influence the timing and magnitude of peak flows because the surface water moving through ditches typically reaches a stream more rapidly than subsurface water does. The interception of shallow groundwater may also reduce groundwater flow to downslope environments (e.g., springs and seepage areas).

In more gently sloped terrain, the potential for road cuts to intersect groundwater flow systems is typically lower than in steep terrain. The exception is where a road is built near a groundwater discharge area (stream, wetland) where the water table is shallow. Under such conditions, how the road's physical attributes compare with those of the surrounding landscape may become the most important consideration, as compacted road surfaces can limit infiltration. Whether this effect is significant depends on how much of a watershed is covered by road surfaces or areas where soils have been compacted by machinery (Putz et al. 2003). Although we found no published case studies, we anticipate that the effect of forest roads on broad plateaus or the Boreal Plains will depend on the position of the road in the groundwater flow setting. In areas of localized groundwater discharge, it is possible that roads could have a similar effect as they do on a steep mountain side: forcing seepage to occur and potentially altering groundwater flow to streams or wetlands downslope.

Implications of forest management activities on groundwater hydrology

The potential effects of forest management activities on local and regional groundwater flow and storage should clearly be considered as a part of forest planning.

An appropriate first step would be to establish whether any groundwater-dependent ecosystems exist in a watershed or whether there are nearby water users. Brown et al. (2007) developed a guide to identify potential groundwater-dependent ecosystems in the Pacific Northwest. Several "decision trees" based on readily identifiable watershed attributes are presented in the guide to help forest managers determine whether streams, wetlands, lakes, springs, phreatophytes (plants that obtain water from a permanent groundwater supply), and caves have a high or low potential to be groundwater-dependent.

Once groundwater dependency has been established, mapping groundwater flow and estimating the groundwater portions of a hydrologic budget would be the next step toward assessing the potential of forestry activities to impact groundwater. From this basis, the longevity of effects could be qualitatively estimated, the potential alteration of flow systems and interaction with surface water (streams, wetlands, and lakes) could be assessed, and operational parameters and hazards (e.g., road placement, slope stability) could be identified and mitigated.

Management implications of changes in water table position

The literature review indicated that forest harvesting will generally lead to an increase in the elevation of the water table. Forest roads may have varying effects on water table position. Road cuts may depress the water table locally, causing seepage interception and downslope culvert discharge and thus creating locally saturated conditions. The magnitude of these effects will generally depend on the hydrogeologic landscape, the location of harvest areas and road cuts within the groundwater flow system (i.e., recharge versus discharge areas), and the proportion of a watershed affected by forest management. Predicting the effects of harvest activities and forest road construction on water table position and associated consequences for ecosystems and forest operations will be site-specific.

Increases in water table elevation can, in several ways, affect an area's "trafficability" (i.e., its ability to sustain machine traffic). The impact will vary depending on the slope of the terrain and the soil characteristics. For example, in the Carnation Creek basin, Dhakal and Sidle (2004) recorded increases in pore pressure at seven of nine sites that had been harvested. Higher pore pressure may lead to waterlogged soils, which can decrease trafficability and impose time constraints on logging operations because of concerns about soil disturbance causing site productivity loss. In the Vanderhoof Forest District, this has already caused loss of summer logging ground in favour of more stable frozen soil conditions during winter (Rex and Dubé 2006).

Changes in pore pressure and water table position may also cause increases in mass wasting and landslides (Sidle and Ochiai 2006) in steeper landscapes. This in turn can lead to deterioration of surface water quality and aquatic habitat if sediment reaches streams (Hetherington 1987a). A more thorough review of terrain hazards and slope stability is beyond the scope of this discussion paper, though the role of groundwater hydrology is clear for both areas of study.

In the years following harvest, soils may be wetter and water tables higher. An increase in water table position may aid phreatophytes in riparian zones and wetland areas by reducing potential impacts of dry conditions or drought or dry conditions. Locally depressed water table conditions associated with roads could negatively impact the ability of phreatophytes to obtain an adequate water supply. On the other hand, higher water tables may cause mortality or regeneration failure because some tree species do not tolerate raised water levels (e.g., Landhausser et al. 2003). Therefore, changes in water table position may disturb both existing ecosystems and silvicultural success.

How significant the effect of forest management activities will be depends largely on the natural location of the water table. Higher water tables may be a short-lived phenomenon (e.g., when occurring in the toe-slopes of steep hillslopes) or could take many years to return to pre-harvest conditions (e.g., as in the case of the Boreal Plains). Landhausser et al. (2004), Landhausser et al. (2003), and Bridge (2003) have studied how different species that promote higher evapotranspiration might aid water table decrease following harvest. It is thought that these "nurse-crops" could be used to help re-equilibrate the water balance in a recently harvested and replanted site. Restoration of a vegetative cover that has similar evapotranspiration characteristics as the original species on a site is an important step toward minimizing the long-term effects of harvesting and other forest activities on groundwater systems, and toward maintaining site productivity.

Management implications of changes in groundwater recharge and flow

Groundwater is critical for maintaining aquatic habitat. In cold climates, where many surface streams and lakes freeze in the winter, groundwater inflows or seepage can maintain open water, thus providing temperature refuge for fish (Power et al. 1999). Winter inflows also help maintain an optimum environment for the overwintering of sockeye salmon eggs (Leman 1993) and provide free-flowing water for migration (Douglas 2008). In the summer, groundwater inflows to streams may reduce stream temperatures (e.g., Story et al. 2003; Moore et al. 2005) and dampen diurnal temperature fluctuations, both critical requirements for fish survival (Douglas 2008). Thus, the increase in groundwater recharge and groundwater flow likely to result from forest management activities may be beneficial for aquatic habitats. An exception may be for areas located downslope from a road cut that intersects significant groundwater seepage. In such areas, aquatic habitat may be negatively impacted if groundwater flow is reduced locally.

Groundwater flowing through riparian zones and wetlands brings nutrients and solutes into the surface water environment (Devito et al. 1996; Alexander et al. 2007). Even in upland areas, increased mobility (or the potential for mobility) of nutrients in groundwater has been found to occur following harvest (Evans et al. 2000). These biogeochemical fluxes are important to ensure healthy aquatic environments (Dahm et al. 1998). Furthermore, the biological activity they contribute to stream corridors has been shown to regulate aquatic health (Moore et al. 2005; Wipfli et al. 2007). Increases or decreases in groundwater flows would therefore alter existing nutrient delivery to riparian zones and wetlands, possibly changing ecosystem structure and function.

The effects of harvesting and road building on groundwater exchange with streams—and, in turn, on ecosystem health—will generally vary by site. The characteristic aquifer types described by Wei et al. (2007) provide a starting point for anyone wanting to make a more detailed assessment of a specific location. However, even though these groundwater interactions occur at the interface between stream corridors (i.e., discrete areas), they are governed by the biogeographical conditions of the broader hydrogeologic landscape (Hayashi and Rosenberry 2001).

Whether harvesting at a site will or will not have a significant effect on groundwater flows will be determined mainly by the time it takes for the groundwater to flow from the recharge area. If the groundwater travel time is of the same order of magnitude or less than the persistence of forest disturbance effects, the flow of groundwater to the receiving surface water bodies (streams, wetlands) may be substantially changed. Conversely, if the groundwater travel time is much longer than the persistence of forest disturbance effects, then no significant change is likely to occur. Therefore, predicting the potential implications of harvesting on groundwater flows depends largely on being able to characterize the connectivity between recharge and discharge areas. A hydrogeologist can map an approximate recharge area by using available soil, geologic, and physiographic spatial data. Preliminary mapping of discharge areas can also be completed with the use of spatial geologic data. However, field identification of features such as springs, seepage areas, and identification of phreatophytes will improve the interpretation (Brown et al. 2007).

Management implications for regional groundwater resources

Forest management effects on regional groundwater resources are rarely studied because of the significant timeframes involved. The long groundwater travel times in regional-scale flow systems tend to buffer short-term variability in climate and land use (including forestry), but integrate long-term changes, making deleterious impacts more difficult to reverse. With forest harvesting, for example, this means that effects of widespread forest cover changes in upland recharge areas might go unnoticed for decades in adjacent valley-bottom aquifers. The effects may also be masked or magnified by climate variation and change.

Widespread forest clearing in Western Australia throughout the 1950s and 1960s has provided a good case study of the time it takes for changes to propagate through groundwater regimes. On clearcuts located in low-rainfall (850 mm/yr) and high-rainfall areas (1120 mm/yr), groundwater response has been observed over the past few decades (Hookey 1987). Water budget studies have shown that groundwater for the study basin re-equilibrates 25–30 years after cutting. In North America, the recovery of watersheds to pre-disturbance hydrologic conditions is an area of considerable research. Time estimates for recovery range from 3 to more than 20 years, depending on climate, geology, intensity and extent of disturbance, and rate of forest regeneration (Moore and Wondzell 2005). Similar results have been observed in Finland (Rusanen et al. 2004), where a review of groundwater monitoring data from 1975 to 1995 revealed that groundwater levels (and nitrate concentrations) increased for several years following harvest.

Large-scale effects of harvest on groundwater have yet to be quantified for British Columbia. However, the current mountain pine beetle infestation and associated salvage harvesting in central British Columbia may provide some insight. In the Vanderhoof Forest District, Rex and Dubé (2006) have found that where dead pine stands occur on fine-textured soils in low-relief watersheds, the result is wet soil and a raised water table. Thus, it is also possible that the rate of groundwater recharge may be increased as well, and could result in long-term changes to groundwater discharge conditions. Further research into the relationship of water table rise and groundwater recharge would help extend these preliminary findings. Such studies provide an opportunity to learn more about the impact of forest harvest on regional groundwater regimes, and could form the basis for collaborative research between the forest hydrology and groundwater hydrology communities.

Summary

Groundwater is a major component of the hydrologic cycle and present in all forested catchments. Therefore, forest management activities will inevitably have some effect on groundwater systems. In this discussion, we have presented a broad-scale classification of hydrogeologic landscapes and have discussed forest management effects in the context of these landscapes. Because there are very few published studies on the impact of harvest and road building on groundwater hydrology, we have used the framework of hydrogeologic landscapes to integrate the findings of available studies on water table rise, increase to groundwater recharge, and the effect of such changes on groundwater hydrology.

In every hydrogeologic landscape we identify, a rise in water table can be expected to follow harvest. Water table increases may in turn have a range of effects on the surrounding environment, depending on the geology and topography of the harvested area:

- In wet, steep watersheds like those in the Coastal Mountains, groundwater effects are expected to be depth-limited. The impact on groundwater regime here is also reasonably well understood: pore pressure will increase; and there will be additional runoff. For these more humid landscapes, the watershed hydrology is dominated by shallow runoff, as opposed to deeper groundwater systems.
- In a drier climate and on lower-relief terrain, the potential for more complex groundwater responses increases. On terrain with gentle topography, water table increases can be expected to alter flow systems of various sizes, which means effects may be readily apparent (in the case of local-scale flow) or concealed within a regional-scale flow system. On the Boreal Plains, groundwater flow and water table response are seen to vary widely following harvest, strongly influenced by other site-specific factors in an area.

Effective watershed management, sustainable forest management, and protection of present and future groundwater resources will rely on our having a greater understanding of the role of each component in the hydrologic cycle.

There is a need to develop long-term research programs that include examining the role of groundwater across the province. While there has been hydrogeologic research in water-limited (e.g., Okanagan Basin) and heavy groundwater-use (e.g., lower Fraser Valley) areas, long-term study of the interaction between climate change effects, forest management, and groundwater has not been undertaken. Effective watershed management, sustainable forest management, and protection of present and future groundwater resources will rely on our having a greater understanding of the role of each component in the hydrologic cycle. Closing these knowledge gaps will help us better manage groundwater resources for the future.

Acknowledgements

Funding for the literature review and preparation of this discussion paper was provided by the Forest Investment Account–Forest Science Program through FORREX. The authors thank three anonymous peer reviewers for their helpful comments.

References

? TEST YOUR KNOWLEDGE
Questions on page 114

Adams, P.W., A.L. Flint, and R.L. Fredriksen. 1991. Long-term patterns in soil moisture and revegetation after clearcut of a Douglas-fir forest in Oregon. Forest Ecology and Management 41:249–263.

Alexander, R.B., E.W. Boyer, R.A. Smith, G.E. Schwarz, and R.B. Moore. 2007. The role of headwater streams in downstream water quality. Journal of the American Water Resources Association 43(1):41–59.

Allen, D.M., D.C. Mackie, and M. Wei. 2004. Groundwater and climate change: A sensitivity analysis for the Grand Forks aquifer, southern British Columbia, Canada. Hydrogeology Journal 12:270–290.

Anderson, M.P. 2007. Introducing groundwater physics. Physics Today, May:42–47.

Bates, N.S. 2000. Hydrological effects of forest harvesting on headwater watersheds in West Virginia. BSc thesis. Princeton University, Princeton, NJ.

Beckers, J. and Y. Alila. 2004. A model of rapid preferential hillslope runoff contributions to peak flow generation in a temperate rain forest watershed. Water Resources Research 40:W03501, DOI:10.1029/WR002582.

Bent, G.C. 2001. Effects of forest-management activities on runoff components and ground-water recharge to Quabbin Reservoir, central Massachusetts. Forest Ecology and Management 143:115–129.

Bliss, C.M. and N.B. Comerford. 2002. Forest harvesting influence on water table dynamics in a Florida flatwoods landscape. Soil Science Society of America Journal 66:1344–1349.

Bonell, M. 1993. Progress in the understanding of runoff generation dynamics in forests. Journal of Hydrology 150:217–275.

Bosch, J.M. and J.D. Hewlett. 1982. A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. Journal of Hydrology 55:3–23.

Bren, L.J. 1997. Effects of slope vegetation removal on the diurnal variations of a small mountain stream. Water Resources Research 33(2):321–331.

Bridge, G. 2003. Effects of soil temperature and water table level on *Picea glauca*, *Betula papyrifera*, *Populus tremuloides* and *Populus balsamifera* seedlings. MSc thesis. University of Alberta, Edmonton, Alta.

British Columbia Ministry of Environment. BC water resource atlas. Version 3.1.1. ***www.env.gov.bc.ca/wsd/data_searches/wrbc/index.html*** (Accessed February 2009).

British Columbia Ministry of Environment. Water Stewardship Division. Ground water. ***www.env.gov.bc.ca/wsd/plan_protect_sustain/groundwater/index.html*** (Accessed February 2009).

British Columbia Ministry of Environment. 2003. *Environmental Management Act*. Statutes of British Columbia. ***www.qp.gov.bc.ca/statreg/stat/e/03053_00.htm*** (Accessed February 2009).

_______. 1994. Ground water resources of British Columbia. BC Ministry of Environment, Groundwater Section, Victoria, BC. ***www.env.gov.bc.ca/wsd/plan_protect_sustain/groundwater/gwbc/index.html*** (Accessed February 2009).

_______. 2004. *Water Act*. Regulations and Statutes of British Columbia. ***www.qp.gov.bc.ca/statreg/stat/W/96483_01.htm*** (Accessed February 2009).

British Columbia Ministry of Forests and Range. 2002. *Forest and Range Practices Act*. Statutes of British Columbia. ***www.qp.gov.bc.ca/statreg/stat/f/02069_01.htm*** (Accessed February 2009).

British Columbia Ministry of Health. 1996. *Health Act*. Regulations and Statutes of British Columbia. ***www.qp.gov.bc.ca/statreg/stat/H/96179_01.htm*** (Accessed February 2009).

Brown, J., A. Wyers, A. Aldous, and L. Bach. 2007. Groundwater and biodiversity conservation: A methods guide for integrating groundwater needs of ecosystems and species into conservation plans in the Pacific Northwest. The Nature Conservancy.

Church, M. and J.M. Ryder. 2007. Chapter 2: Physiography of British Columbia (draft). *In* Compendium of forest hydrology and geomorphology in British Columbia. R.G. Pike et al. (editors). BC Ministry of Forests and Range, Research Branch, Victoria, BC. and FORREX Forest Research Extension Partnership, Kamloops, BC. ***www.forrex.org/program/water/PDFs/Compendium/Compendium_Chapter02.pdf*** (Accessed February 2009).

Cook, P.G., G.R. Walker, and I.D. Jolly. 1989. Spatial variability of groundwater recharge in a semiarid region. Journal of Hydrology 111:195–212.

Cornish, P.M. 1993. The effects of logging and forest regeneration on water yields in a moist eucalypt forest in New South Wales, Australia. Journal of Hydrology 150:301–322.

Dahm, C.N., N.B. Grimm, P. Marmonier, H.M. Valett, and P. Vervier. 1998. Nutrient dynamics at the interface between surface waters and groundwaters. Freshwater Biology 40:427–451.

Dakin, A., J.C. Foweraker, and K. Ronneseth. 1994. Chapter 9: Ground water resources of the basins, lowlands and plains. *In* Ground water resources of British Columbia. J. Atwater (editor). BC Ministry of Environment, Victoria, BC.

de Vries, J.J. and I. Simmers. 2002. Groundwater recharge: An overview of processes and challenges. Hydrogeology Journal 10:5–17.

Denny, S.C., D.M. Allen, and J.M. Journeay. 2007. DRASTIC–Fm: A modified vulnerability mapping method for structurally controlled aquifers in the southern Gulf Islands, British Columbia, Canada. Hydrogeology Journal 15:483–493.

Devito, K., I. Creed, T. Gan, C. Mendoza, R. Petrone, U. Silins, and B. Smerdon. 2005a. A framework for broad scale classification of hydrologic response units on the Boreal Plain: Is topography the last thing to think of? Hydrological Processes 19:1705–1714.

Devito, K.J., I.F. Creed, and C.J.D. Fraser. 2005b. Controls on runoff from a partially harvested aspen-forested headwater catchment, Boreal Plain, Canada. Hydrological Processes 19:3–25.

Devito, K.J., I.F. Creed, R.L. Rothwell, and E.E. Prepas. 2000. Landscape controls on phosphorus loading to boreal lakes: Implications for the potential impacts to forest harvesting. Canadian Journal of Fish and Aquatic Sciences 57:1977–1984.

Devito, K.J., A.R. Hill, and N. Roulet. 1996. Groundwater-surface water interactions in headwater forested wetlands of the Canadian Shield. Journal of Hydrology 181:127–147.

Dhakal, A.S. and R.C. Sidle. 2004. Pore water pressure assessment in a forest watershed: Simulations and distributed field measurements related to forest practices. Water Resources Research, 40:W02405, DOI:10.1029/2003WR002017.

Douglas, T. 2008. Groundwater in British Columbia: Management for fish and people. Streamline 11(2):20–24.

Dubé, S., A.P. Plamondon, and R.L., Rothwell. 1995. Watering up after clear-cutting on forested wetlands of the St. Lawrence lowland. Water Resources Research 31(7):1741–1750.

Evans, J.E., E.E. Prepas, K.J. Devito, and B.G. Kotak. 2000. Phosphorus dynamics in shallow subsurface waters in an uncut and cut subcatchment of a lake on the Boreal Plain. Canadian Journal of Fish and Aquatic Sciences 57:60–72.

Fannin, R.J., J. Jaakkola, J.M.T. Wilkinson, and E.D. Hetherington. 2000. Hydrologic response of soils to precipitation at Carnation Creek, British Columbia, Canada. Water Resources Research 36(6):1481–1494.

Ferone, J.M. and K.J. Devito. 2004. Shallow groundwater-surface water interactions in pond-peatland complexes along a Boreal Plains topographic gradient. Journal of Hydrology 292:75–95.

Fetter, C.W. 2001. Applied hydrogeology. Prentice Hall, Englewood Cliffs, NJ.

Foweraker, J.C. 1994. Chapter 8: Ground water regions of British Columbia. *In* Ground water resources of British Columbia. J. Atwater (editor). BC Ministry of Environment, Victoria, BC.

Freeman, M.C., C.M. Pringle, and C.R. Jackson. 2007. Hydrological connectivity and the contribution of stream headwaters to ecological integrity at regional scales. Journal of the American Water Resources Association 43(1):5–14.

Freeze, R.A. and J.A. Cherry. 1979. Groundwater. Prentice-Hall, Inc., Englewood Cliffs, NJ.

Hayashi, M. and D.O. Rosenberry. 2001. Effects of groundwater exchange on the hydrology and ecology of surface waters. Journal of Groundwater Hydrology 43:327–341.

Henriksen, A. and L.A. Kirkhusmo. 2000. Effects of clear-cutting of forest on the chemistry of a shallow groundwater aquifer in southern Norway. Hydrology and Earth System Sciences 4(2):323–331.

Hetherington, E.D. 1987a. Carnation Creek, Canada: Review of a west coast fish/forestry watershed impact project. *In* Forest hydrology and watershed management. International Association of Hydrological Sciences (IAHS), Vancouver, BC. pp. 531–538.

_______. 1987b. The importance of forests in the hydrological regime. *In* Canadian aquatic resources. W.R. McHealey (editor). Fisheries and Oceans Canada, Ottawa, Ont. pp. 179–211.

_______. 1998. Watershed hydrology. *In* Carnation Creek and Queen Charlotte Islands fish/forestry workshop: Applying 20 years of coastal research to management solutions. D.L. Hogan, P.J. Tschaplinski, and S. Chatwin (editors). BC Ministry of Forests, Victoria, BC. pp. 33–40.

Hookey, G.R. 1987. Prediction of delays in groundwater response to catchment clearing. Journal of Hydrology 94:181–198.

Hudson, R. and A. Anderson. 2006. Russell Creek: Summary of research and implications for professional practice, Forest Research Extension Note. BC Ministry of Forests and Range, Coast Forest Region, Nanaimo, BC. pp. 1–5.

Keppeler, E.T., R.R. Ziemer, and P.H. Cafferata. 1994. Changes in soil moisture and pore pressure after harvesting a forested hillslope in Northern California. Journal of the American Water Resources Association June:205–214.

Landhausser, S.M., V.J. Lieffers, and U. Silins. 2004. Utilizing pioneer species as a hydrological nurse crop to lower water table for reforestation of poorly drained boreal sites. Annals of Forest Science 60:741–748.

Landhausser, S.M., U. Silins, V.J. Lieffers, and W. Liu. 2003. Response of *Populus tremuloides*, *Populus balsamifera*, *Betula papyrifera* and *Picea glauca* seedlings to low soil temperature and water-logged soil conditions. Scandinavian Journal of Forest Research 18:391–400.

Leman, V.N. 1993. Spawning sites of chum salmon, *Oncorhynchus keta*: Microhydrological regime and viability or progeny in redds (Kamchatka River basin). Journal of Ichthyology 33:104–117.

Livingstone, E. 1994. Chapter 4: Geology and its importance in the search for, and assessment of, ground water resources in British Columbia. *In* Ground water resources of British Columbia. J. Atwater (editor). BC Ministry of Environment, Victoria, BC.

Liggett, J.E., M.W. Toews, B.D. Smerdon, and D.M. Allen. 2007. Predicting groundwater recharge for the Okanagan Basin: A little HELP from the locals. Abstract H33D–1620. EOS: Transactions of the American Geophysical Union. Fall Meeting Supplemental 88(52).

Macrae, M.L., K.J. Devito, I.F. Creed, and S.E. Macdonald. 2006. Relation of soil-, surface-, and ground-water distributions of inorganic nitrogen with topographic position in harvested and unharvested portions of an aspen-dominated catchment in the Boreal Plain. Canadian Journal of Forestry Research 36:2090–2103.

Macrae, M.L., T.E. Redding, I.F. Creed, W.R. Bell, and K.J. Devito. 2005. Soil, surface water and ground water phosphorus relationships in a partially harvested Boreal Plain aspen catchment. Forest Ecology and Management 206:315–329.

Megahan, W.F. 1983. Hydrologic effects of clearcutting and wildfire on steep granite slopes on Idaho. Water Resources Research 19(3):811–819.

Megahan, W.F. and J.L. Clayton. 1983. Tracing subsurface flow on roadcuts on steep, forested slopes. Soil Science Society of America Journal 47(6):1063–1067.

Meinzer, O.E. 1923. Outline of ground-water hydrology, with definitions. US Geological Survey. Water-Supply Paper 494.

Moore, R.D., D. Spittlehouse, and A. Story. 2005. Riparian microclimate and stream temperature response to forest harvesting: A review. Journal of the American Water Resources Association 41:813–834.

Moore, R.D. and S.M. Wondzell. 2005. Physical hydrology and the effects of forest harvesting in the Pacific Northwest: A review. Journal of the American Water Resources Association 41(4):763–784.

Parsons, M.L. and O. Quinn. 1994. Chapter 11: Ground water resources of the mountain ground water regions. *In* Ground water resources of British Columbia. J. Atwater (editor). BC Ministry of Environment, Victoria, BC.

Peck, A.J. and D.R. Williamson. 1987. Effects of forest clearing on groundwater. Journal of Hydrology 94:47–65.

Pike, R.G. and R. Scherer. 2003. Overview of the potential effects of forest management on low flows in snowmelt-dominated hydrologic regimes. BC Journal of Ecosystems and Management 3(1):44–60. ***www.forrex.org/publications/jem/ISS15/vol3_no1_art8.pdf*** (Accessed February 2009).

Pothier, D., M. Prevost, and I. Auger. 2003. Using the shelterwood method to mitigate water table rise after forest harvesting. Forest Ecology and Management 179:573–583.

Power, G., R.S. Brown, and J.G. Imhof. 1999. Groundwater and fish: Insights from North America. Hydrological Processes 13:401–422.

Putz, G., J.M. Burke, D.W. Smith, D.S. Chanasyk, E.E. Prepas, and E. Mapfumo. 2003. Modelling the effects of boreal forest landscape management upon streamflow and water quality: Basic concepts and considerations. Journal of Environmental Engineering and Science 2:S87–S101.

Redding, T.E. and K.J. Devito. 2008. Lateral flow thresholds for aspen forested hillslopes on the Western Boreal Plain, Alberta, Canada. Hydrological Processes 22:4287–4300.

Redding, T.E. and K. Nickurak. 2008. Northern Interior needs assessment for watershed management. FORREX Forest Research and Extension Partnership. Kamloops, BC. File Report No. 08-01. ***www.forrex.org/publications/other/FileReports/fr08-01.pdf*** (Accessed February 2009).

Redding, T.E., S. Lepsoe, and M. Laurie. 2008. Southern Interior needs assessment for watershed management. FORREX Forest Research and Extension Partnership. Kamloops, BC. File Report No. 08-02. ***www.forrex.org/publications/other/FileReports/fr08-02.pdf*** (Accessed February 2009).

Rex, J. and S. Dubé. 2006. Predicting the risk of wet ground areas in the Vanderhoof Forest District: Project description and progress report. BC Journal of Ecosystems and Management 7(2):57–71. ***www.forrex.org/publications/jem/ISS35/vol7_no2_art7.pdf*** (Accessed February 2009).

Riddell, J.T. 2008. Assessment of surface water-groundwater interactions at perched boreal wetlands, north-central Alberta. MSc thesis. Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton, Alta.

Rockefeller, S.L., P.A. McDaniel, and A.L. Falen. 2004. Perched water table responses to forest clearing in Northern Idaho. Soil Science Society of America Journal 68:168–174.

Rusanen, K., L. Finer, M. Antikainen, K. Korkka-Niemi, B. Backman, and R. Britschgi. 2004. The effect of forest cutting on the quality of groundwater in large aquifers in Finland. Boreal Environment Research 9:253–261.

Scibek, J. and D.M. Allen. 2006. Modeled impacts of predicted climate change on recharge and groundwater levels. Water Resources Research 42:W11405, DOI:10.1029/2005WR004742.

Sidle, R.C. and H. Ochiai. 2006. Landslides: Processes, prediction, and land use. American Geophysical Union. Washington, D.C. Water Resources Monograph 18.

Smerdon, B.D., D.M. Allen, S. Grasby, M.A. Berg, and E. Belland. 2008. Linking upland water sources and valley bottom aquifers in a mountainous watershed. *In* 9th Joint CGS/IAH−CNC Groundwater Conference, Edmonton, Alta.

Smerdon, B.D., K.J. Devito, and C.A. Mendoza. 2005. Interaction of groundwater and shallow lakes on outwash sediments in the sub-humid Boreal Plains of Canada. Journal of Hydrology 314:246–262.

Smerdon, B.D. and T.E. Redding. 2007. Groundwater: More than water below the ground. Streamline 10(2):1–6.

Spittlehouse, D. 2007. Influence of the mountain pine beetle on the site water balance of lodgepole pine forests. *In* Proceedings of mountain pine beetle and watershed hydrology workshop: Preliminary results of research from BC, Alberta and Colorado. T. Redding (editor). Kelowna, BC. pp. 25–26. ***www.forrex.org/program/water/PDFs/ Workshops/mpb/MPB-Hydrology_Workshop_Handbook.pdf*** (Accessed February 2009).

Stednick, J.D. 1996. Monitoring the effects of timber harvesting on annual water yield. Journal of Hydrology 176:79–95.

Story, A., R.D. Moore, and J.S. Macdonald. 2003. Stream temperatures in two shaded reaches below cutblocks and logging roads: Downstream cooling linked to subsurface hydrology. Canadian Journal of Forestry Research 33:1383–1396.

Sugden, B.D. and S.W Woods. 2007. Sediment production from forest roads in Western Montana. Journal of the American Water Resources Association 43(1):193–206.

Surrette, M., D.M. Allen, and M. Journeay. 2008. Regional evaluation of hydraulic properties in variably fractured rock using a hydrostructural domain approach. Hydrogeology Journal 16(1):11–30.

Toews, M. 2007. Modelling climate change impacts on groundwater recharge in a semi-arid region, southern Okanagan, British Columbia. MSc thesis. Department of Earth Sciences, Simon Fraser University, Burnaby, BC.

Toth, J. 1962. A theory of groundwater motion in small drainage basins in Central Alberta, Canada. Journal of Geophysical Research 67(11):4375–4387.

Urie, D.H. 1971. Estimated groundwater yield following strip cutting in pine plantations. Water Resources Research 7(6):1497–1510.

Webster, K.E., T.K. Kratz, C.J. Bowser, J.J. Magnuson, and W.J. Rose. 1996. The influence of landscape position on lake chemical response to drought in northern Wisconsin. Limnology and Oceanography 41(5):977–984.

Wei, M., K. Ronneseth, D. Allen, A.P. Kohut, B. Turner, and S. Grasby. 2007. Typed and general characteristics of aquifers in the Canadian Cordillera Hydrogeologic Region. *In* Proceedings of 8th Joint CGS/IAH−CNC Groundwater Conference, Ottawa, Ont.

Wemple, B.C., J.A. Jones, and G.E. Grant. 1996. Channel network extension by logging roads in two basins, Western Cascades, Oregon. Water Resources Bulletin 32(6):1195–1207.

Wemple, B.C., F.J. Swanson, and J.A. Jones. 2001. Forest roads and geomorphic process interactions, Cascade Range, Oregon. Earth Surface Processes and Landforms 26:191–204.

Whitaker, A., Y. Alila, J. Beckers, and D. Toews. 2003. Application of the distributed hydrology soil vegetation model to Redfish Creek, British Columbia: Model evaluation using internal catchment data. Hydrological Processes 17:199–224.

Winter, T.C. 1999. Relation of streams, lakes, and wetlands to groundwater flow systems. Hydrogeology Journal 7(1):28–45.

_______. 2000. The vulnerability of wetlands to climate change: A hydrologic landscape perspective. Journal of the American Water Resources Association 36(2):305–311.

_______. 2001. The concept of hydrologic landscapes. Journal of the American Water Resources Association 37(2):335–349.

Winter, T.C., D.O. Rosenberry, and J.W. LaBaugh. 2003. Where does the ground water in small watersheds come from? Ground Water 41(7):989–1000.

Wipfli, M.S., J.S. Richardson, and R.J. Naiman. 2007. Ecological linkages between headwaters and downstream ecosystems: Transport of organic matter, invertebrates, and wood down headwater channels. Journal of the American Water Resources Association 43(1):72–85.

ARTICLE RECEIVED: **March 14, 2008**
ARTICLE ACCEPTED: **October 24, 2008**

Research Report

Aerial overview survey of the mountain pine beetle epidemic in British Columbia: Communication of impacts

Michael A. Wulder[1], Joanne C. White[2], Danny Grills[3], Trisalyn Nelson[4], Nicholas C. Coops[5], and Tim Ebata[6]

Abstract

In western Canada, the current outbreak of mountain pine beetle (*Dendroctonus ponderosae*) is of unprecedented proportions. Annual aerial overview surveys (AOS) are the primary means of accounting for the area and severity of mountain pine beetle impacts. Typically, reports of impacted areas do not consider severity—the proportion of trees killed within a given area. A common misconception is that all impacted areas will experience 100% pine mortality.

We examined a time series of AOS data collected in British Columbia from 1999 to 2005. The year-to-year trends indicated that the AOS data effectively captured the infestation's increasing area, severity, and spatial variability. The cumulative area impacted between 1999 and 2005 was estimated at 11 million ha; 39% of this area was attacked in only one year. The approximate year of death was estimated by assuming a 50% severity threshold. Approximately 6.5 million ha experienced mortality. The results of this study emphasize the importance of reporting severity, as well as considering the cumulative effects of the infestation over time.

KEYWORDS: *aerial overview survey,* Dendroctonus ponderosae, *GIS, infestation, mountain pine beetle, severity, strategic survey, tessellation, time series.*

Contact Information

1 Senior Research Scientist, Canadian Forest Service, Pacific Forestry Centre, Natural Resources Canada, 506 West Burnside Road, Victoria, BC V8Z 1M5. Email: mwulder@nrcan.gc.ca

2 Spatial Analyst, Canadian Forest Service. Email: jowhite@nrcan.gc.ca

3 Spatial Analyst, Canadian Forest Service. Email: dgrills@nrcan.gc.ca

4 Assistant Professor, University of Victoria, Department of Geography, PO Box 3060 Stn CSC, Victoria, BC V8W 3R4. Email: tnelson@office.geog.uvic.ca

5 Associate Professor, Canada Research Chair in Remote Sensing, University of British Columbia, Department of Forest Resource Management, 2424 Main Mall, Vancouver, BC V6T 1Z4. Email: nicholas.coops@ubc.ca

6 Forest Health Project Specialist, BC Ministry of Forests and Range, Forest Practices Branch, Harvesting and Silviculture Practices Section, PO Box 9513 Stn Prov Govt, Victoria, BC V82 9C2. Email: Tim.Ebata@gov.bc.ca

JEM* — *Volume 10, Number 1

Wulder, M.A., J.C. White, D. Grills, T. Nelson, N.C. Coops, and T. Ebata. 2009. Aerial overview survey of the mountain pine beetle epidemic in British Columbia: Communication of impacts. *BC Journal of Ecosystems and Management* 10(1):45–58.

Introduction

In western Canada, the current outbreak of mountain pine beetle (*Dendroctonus ponderosae*) is of unprecedented proportions. In 1999, the area impacted by the beetle in British Columbia was estimated to be 164 000 ha; by 2006, it had increased to approximately 9.2 million ha (Westfall 2007). From a forest management perspective, estimates of the location and extent of mountain pine beetle red attack are critical. However, the degree of precision required for these estimates varies according to the management objective under consideration and the nature of the mountain pine beetle infestation. The information required for managing mountain pine beetle is provided by a hierarchy of different data sources that are used to map red attack damage. Each data source offers a different level of detail on the location and extent of beetle damage (Wulder et al. 2006b).

Aerial overview surveys (AOS; colloquially known as "sketch maps") are conducted annually in British Columbia. They are designed to cover the maximum possible area, and provide rapid, province-wide reconnaissance on a number of forest health threats, including mountain pine beetle infestation. As the AOS includes information on the extent and severity of attack—the proportion of trees killed within a given area—both characteristics should be considered when reporting mountain pine beetle impacts. Typically, the gross area impacted is reported without distinguishing severity. A common misconception is that all areas impacted will experience 100% pine mortality. To address these issues and gain a better understanding of the province-wide impacts of the current mountain pine beetle outbreak, we obtained annual AOS data of mountain pine beetle infestations across British Columbia from 1999 to 2005. The overall goal of this research is to explore and present the full potential of AOS data for communicating the impacts of the mountain pine beetle outbreak in British Columbia. Specifically, our objectives are to:

- compare area summaries from annual AOS spatial data to data reported in annual forest health reports;
- assess if the AOS data captures temporal and spatial variability in the severity and area impacted;
- estimate the cumulative area of impact and assess the amount of area captured in multiple years of survey data;
- assess temporal trends in severity codes over time; and
- estimate the approximate year of death for the majority of pine within a specified analysis unit.

The goal of this research is to explore and present the full potential of aerial overview surveys data for communicating the impacts of the mountain pine beetle outbreak in British Columbia.

Background

Manifestation of mountain pine beetle attack

Once a host tree has been attacked and killed by mountain pine beetle, its foliage will remain green for an initial period known as the green attack stage (Wulder et al. 2006a). The foliage will gradually fade, and within 12 months after attack 90% of the trees will have red foliage (Amman 1982; Henigman et al. [editors] 1999). This is the visually distinct red attack stage that is captured by the AOS. Within 3 years of the initial attack, most of the trees will have lost all of their needles—the grey attack stage (BC Ministry of Forests 1995). Variability in the rate of foliage discolouration depends on species and site conditions (Safranyik 2004).

AOS data

Aerial overview surveys are conducted using fixed-wing aircraft flying at speeds of 150–170 km/hr, at altitudes ranging from 500 to 1000 m (BC Ministry of Forests 2000). Trained forest health personnel record the extent and severity of red attack damage—and other forest health issues—onto hardcopy base maps produced at a scale of 1:100 000 or 1:250 000. The information on the maps is manually digitized according to established standards (BC Ministry of Forests 2000). Figure 1 provides an example of the systematic spatial coverage of the AOS data in 2005.

From 1914 to 1995 the Canadian Forest Service conducted the AOS program, but the British Columbia Ministry of Forests has assumed responsibility for the surveys since then (BC Ministry of Forests 1995). Other jurisdictions also use AOS as an effective, low-cost method for detecting and mapping mountain pine beetle red attack damage (BC Ministry of Forests 2000; Alberta Sustainable Resource Development 2004; Schraeder-Patton 2003).

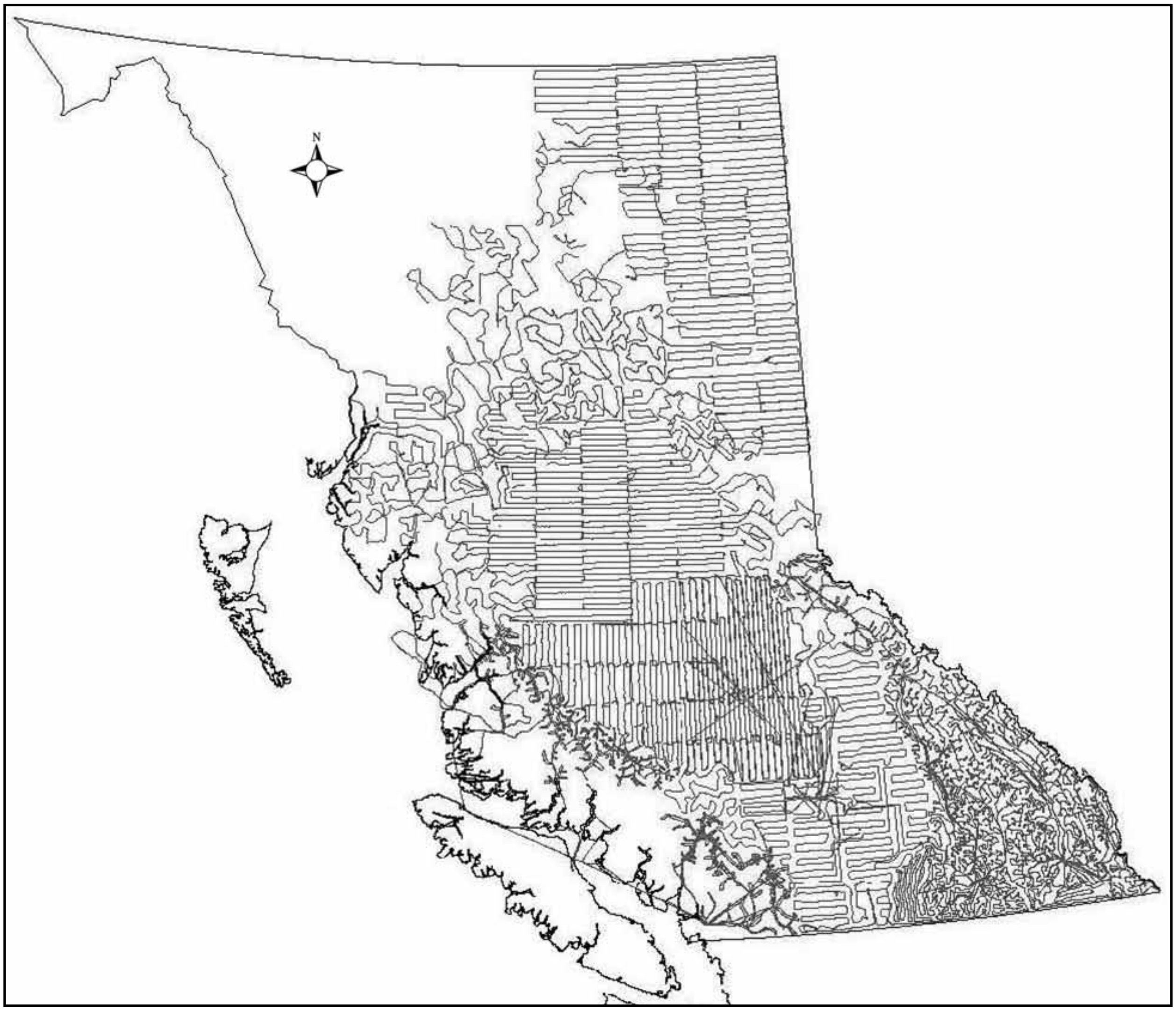


FIGURE 1. Distribution of flight lines used to acquire Aerial Overview Survey (AOS) data in 2005.

Due to the inherent speed and efficiency of AOS data collection, forest managers have access to the information within 3 months of survey completion (Wulder et al. 2006b). In the context of mountain pine beetle, the data is used to characterize the general location of damage, approximate the gross area of damage, and indicate trends in damage from one year to the next. The data facilitates strategic planning and the allocation of resources for mitigation, and provides an initial stratification of the landscape for determining locations for more intensive surveys (BC Ministry of Forests 2003a). The information is also used for timber supply forecasting and for adjusting the annual allowable cut (BC Ministry of Forests 2003b).

Weaknesses of the AOS data include errors of omission when damage is very light, a lack of rigorous positional accuracy, and variability in estimates of attack magnitude. Location inaccuracies result from off-nadir viewing, variations in lighting conditions, and interpreter experience and fatigue, among others (Aldrich et al. 1958; Leckie et al. 2005). Harris and Dawson (1979) found that amongst several interpreters, estimates of red attack damage varied from the actual amount of red attack damage by a range of –42% to 73%. They also compared estimates of AOS red attack damage to those of aerial photography interpretations. The total area identified as red attack from the AOS was 34% larger than the area of attack interpreted from air photos, while the number of red attack trees estimated from the AOS was 39% less than the number of red attack trees estimated from the photos. The underestimation of attacked trees increased with increased red attack density. This discrepancy is largely a function of scale—the field of view of the AOS interpreter is much larger than that of a photo interpreter. As a result, the AOS interpreter can see large areas of red attack damage, but cannot readily discern individual trees. Conversely, the increased spatial resolution afforded by the air photos allows the photo interpreter to delineate units of impact that are more spatially discrete.

The strengths of the AOS program include its cost-effectiveness and the speed with which the data can be collected and made available. Its flexibility (e.g., aircraft can fly below cloud cover that might otherwise impede the use of satellite remotely sensed data) allows the survey to be conducted within the appropriate biological window for mountain pine beetle (i.e., the period when the attack damage is most visible). By utilizing their expertise at identifying tree species and their knowledge of pest habitats and past infestations, in combination with expansive views of the landscape, AOS interpreters can identify damage. Furthermore, the AOS is the only consistently collected forest health survey data that exists for the majority of the provincial land base, providing valuable historical context to infestations over time and space. As a result, no other currently available data source combines the synoptic view and level of detail afforded by this program (Wulder et al. 2006a, 2006b).

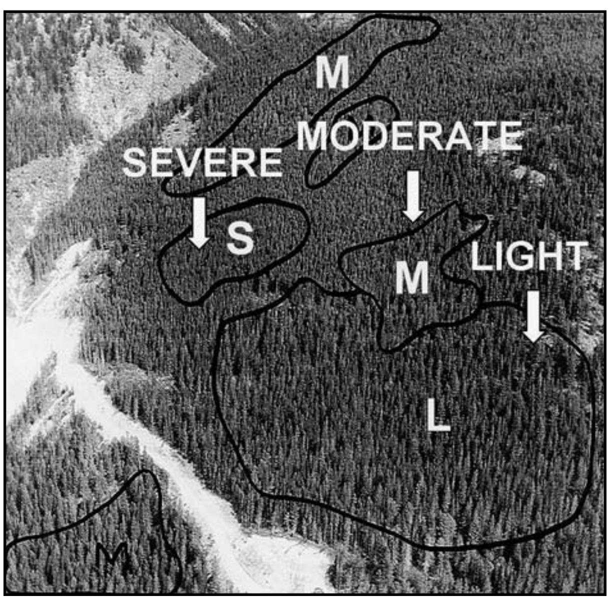


FIGURE 2. Enlargement of original 70-mm photograph with examples of light, moderate, and severe mortality of lodgepole pine caused by mountain pine beetle.
* See page 58 endnote re: colour version.

Figure 2 indicates how the different AOS severity ratings for mountain pine beetle may be interpreted: a large area with a small number of dispersed red attack trees is rated as light severity (1–10% of the trees attacked); and a smaller area with many spatially clustered red attack trees is rated as severe (31–50% of trees attacked). Areas with light and severe ratings could cover equivalent geographic areas, but the implications of each in terms of mortality, planning, and management, will prompt a different management response. Although the area occupied by individual severity classes is recorded in annual forest health surveys, communication of survey results typically emphasizes the total area impacted, regardless of severity. A common misconception is that there is 100% mortality of pine across all areas impacted by the beetle. For example, in 2006, 9.2 million ha of forest were impacted by the beetle, with 50% of this area having a severity rating of trace or light (Westfall 2007). Reporting only the total area impacted by mountain pine beetle does not provide the full context of the state of the infestation.

Study area

The 95 million ha province of British Columbia has approximately 59 million ha of forests, of which 83% is dominated by coniferous tree species. The most prevalent species, lodgepole pine (*Pinus contorta*), covers approximately 14.8 million ha (BC Ministry of Forests 2004). The distribution of mountain pine beetle is determined by the distribution of suitable host species and climatic conditions (Swaine 1925). Research has indicated that the mountain pine beetle is expanding into new geographic areas outside its known range (Carroll et al. 2004). This expansion is primarily a result of two factors: (1) intensive fire suppression activities that have caused the amount of mature lodgepole pine forest to triple in the past century (Taylor and Carroll 2004); and (2) several years of favourable climatic conditions that have increased climatically suitable areas for brood development (Carroll et al. 2004). In the early 1900s, approximately 17% of pine forests in British Columbia were in age classes susceptible to mountain pine beetle attack; currently 55% are considered susceptible (Taylor et al. 2006).

Data

The AOS data are collected to an established standard (BC Ministry of Forests 2000) and are made freely available to all users by the BC Ministry of Forests and Range.[1] The areas delineated by the AOS interpreters are manually digitized as polygons into a Geographic Information System (GIS) compatible format and are distributed by the BC Ministry of Forests and Range in ArcView™ shapefile format (BC Ministry of Forests 2000). Shapefiles contain attributes for all forest health issues covered by the AOS, including mountain pine beetle. We downloaded AOS data from 1999 to 2005 for our analysis. The AOS contains five severity classes ranging from trace to very severe. Larger areas of infestation are delineated by the interpreter and assigned a severity rating according to the percentage of killed trees present (Table 1). Small infestations of up to 50 trees are recorded by interpreters as spot infestations (points) and are always classified as severe. These spot infestations are provided as separate shapefiles and were not included in our analysis.

Between 1999 and 2003, only three severity classes were used: light, moderate, and severe. In 2003, surveyors noticed "large areas of previously uninfested pine that had developed a very unusual pattern of widely scattered, very low intensity mortality" (Westfall 2005:3). By recording these areas as spot infestations (points only—no area) the surveyors believed they were underestimating the mortality. Conversely, by delineating them as polygons and coding them as light, they believed they were overestimating mortality. Therefore, in 2004 two additional severity classes were added: trace (< 1% mortality) and very severe (> 50% mortality). All categories of severity were considered in our analysis.

Other data sources used in the analysis of the AOS data included a GIS layer of forest district boundaries representing 32 unique administrative areas used to manage the province's forest resources, and a seamless forest inventory dataset that identified the location and extent of all pine species—potential hosts for mountain pine beetle (BC Ministry of Forests 2004). Although the date of the forest inventory data varied across the province, the majority of data represent pre–1999 forest conditions.

Methods

Polygons that specifically identified the location and extent of red attack damage were selected and extracted from each year of AOS data to a separate vector layer. A numeric attribute was added to each polygon within the vector layer to correspond to each of the severity classes (Table 1). These vector-based shapefiles were converted to 1 ha raster grid files based on their numeric severity code. The entire landmass of British Columbia was tessellated into 1 ha grid cells, resulting in a raster that was 12 885 rows by 15 940 columns. The cells in the provincial grid were then populated with the severity codes from each year of rasterized AOS data. Grid cells thaat were located on the boundary between two grid cells were assigned to the polygon with the greatest area in the grid cell.

A range of analyses was then conducted on this time series of AOS data to meet the objectives of this research. Annual summaries of red attack damage by severity code were generated and compared against those totals reported in the annual forest health reports. This served as a quality control mechanism to ensure the rasterization of the data did not change the distribution or amount of

TABLE 1. Severity codes used in the AOS program and mid-point values used to calculate cumulative severity.

Severity	Numeric values for rasterization and analysis	Proportion of trees killed within a specified area (%)	Mid-point of range used to calculate cumulative severity over time (%)
Trace (T)	1	< 1	0.5
Light (L)	2	1–10	4.5
Moderate (M)	3	11–30	20.5
Severe (S)	4	31–100 (1999–2003)	65.5 (1999–2003)
		31–49 (2004–2005)	40.5 (2004–2005)
Very Severe (VS)	5	≥ 50	75

[1] *www.for.gov.bc.ca/ftp/HFP/external/!publish/Aerial_Overview* (Accessed July 2006).

red attack damage area. Temporal and spatial variability in severity codes were examined by overlaying the forest district boundaries and generating summaries by year and district. The cumulative area of attack was identified. The sequence of severity codes within each grid cell and for each year was also examined for trends of increasing or decreasing severity.

Trees killed by mountain pine beetle may still provide viable wood products for a limited period of time. Shelf life[2] estimates vary, while research on this issue is ongoing (Lewis and Hartley 2006). Determining the year the tree was attacked and killed is important in estimating shelf life. By combining the AOS data for 1999–2005, we estimated the year of death for each 1 ha grid cell in the provincial tessellation. Using the mid-points of the infestation severity classes to indicate a proportion of attack for a given 1 ha cell (Table 1), we summed the values and determined when mortality in each cell exceeded 50%. Because it takes an average of 1 year for the characteristic red foliage to appear, we assigned the year previous as the year of death.

Results and discussion

Table 2 summarizes the comparison of total area by year and severity, between the annual forest health reports and our provincial tessellation. Through this comparison, some discrepancies between the provincial reports and our data emerged. These differences were not statistically significant (two-sample paired *t*-test; Table 2) and were primarily attributable to the omission of spot infestations from our analysis. Point features representing spot infestations were not included in the analysis because they are assumed to have an area of only 0.25 ha or 0.5 ha, depending on the number of red attack trees present at the point (BC Ministry of Forests 2000). By not including these areas, we would have moderately underestimated severe areas; conversely, if we had rasterized these spot infestations to 1 ha and included them in our analysis, we would have grossly overestimated the areas rated as severe.

The greatest discrepancy in estimates of total impacted areas was for years 1999 and 2000. The

TABLE 2. Comparison of AOS area by severity rating. Non-parenthetical numbers represent data used in this analysis, parenthetical numbers are those reported in the annual forest health survey reports.

	AOS area (ha)						
Year	Trace[a] (< 1%)	Light (1–10%)	Moderate (11–30%)	Severe (31–50%)	Very severe[a] (≥ 50%)	Total area impacted	*t*-test results
1999	n/a	68 397	44 526	31 139	n/a	144 062	$t = 1.243$
		(71 444)	(45 004)	(48 973)		(165 421)	$p = 0.282$
2000	n/a	77 339	92 554	94 473	n/a	264 366	$t = 1.01$
		(77 467)	(92 554)	(114 889)		(284 910)	$p = 0.371$
2001	n/a	358 905	241 052	171 560	n/a	771 517	$t = 1.031$
		(358 989)	(241 301)	(185 207)		(785 497)	$p = 0.361$
2002	n/a	885 308	499 964	571 615	n/a	1 956 887	$t = 0.529$
		(885 888)	(492 160)	(590 592)		(1 968 640)	$p = 0.624$
2003	n/a	2 608 308	751 681	510 737	n/a	3 870 726	$t = 0.007$
		(2 608 202)	(751 801)	(706 814)		(4 066 817)	$p = 0.994$
2004	1 960 043	2 469 705	1 852 163	583 703	152 682	7 018 296	$t = 1.446$
	(1 960 313)	(2 469 999)	(1 852 981)	(585 841)	(152 750)	(7 021 884)	$p = 0.221$
2005	2 268 747	2 332 465	2 148 509	1 196 636	784 202	8 730 559	$t = -1.341$
	(2 273 060)	(2 332 551)	(2 148 886)	(1 197 533)	(784 039)	(8 736 069)	$p = 0.251$

[a] These categories were not used before 2004.

[2] Shelf life is the length of time since attack within which mountain pine beetle killed trees are still economically merchantable.

province reported a total of 165 421 ha impacted by mountain pine beetle in 1999 and 284 910 ha in 2000. Our data indicated 144 062 ha and 264 366 ha were impacted in each of these years, respectively (Table 2). Spot infestations represented 19 099 ha in 1999 and 20 418 ha in 2000. In 1999, 74 695 separate spot infestations of mountain pine beetle were identified. If we had rasterized these points to 1 ha and included them in our data, we would have reported an additional 74 695 ha as severe in 1999 (55 596 ha more than the actual 19 099 ha represented by these spots).

The total area impacted by the beetle increased from 144 062 ha in 1999 to 8 730 559 ha in 2005. During this same period, the amount of area identified as lightly infested increased from 68 397 ha (47% of the total impacted area) to 4 601 212 ha (53% of the total

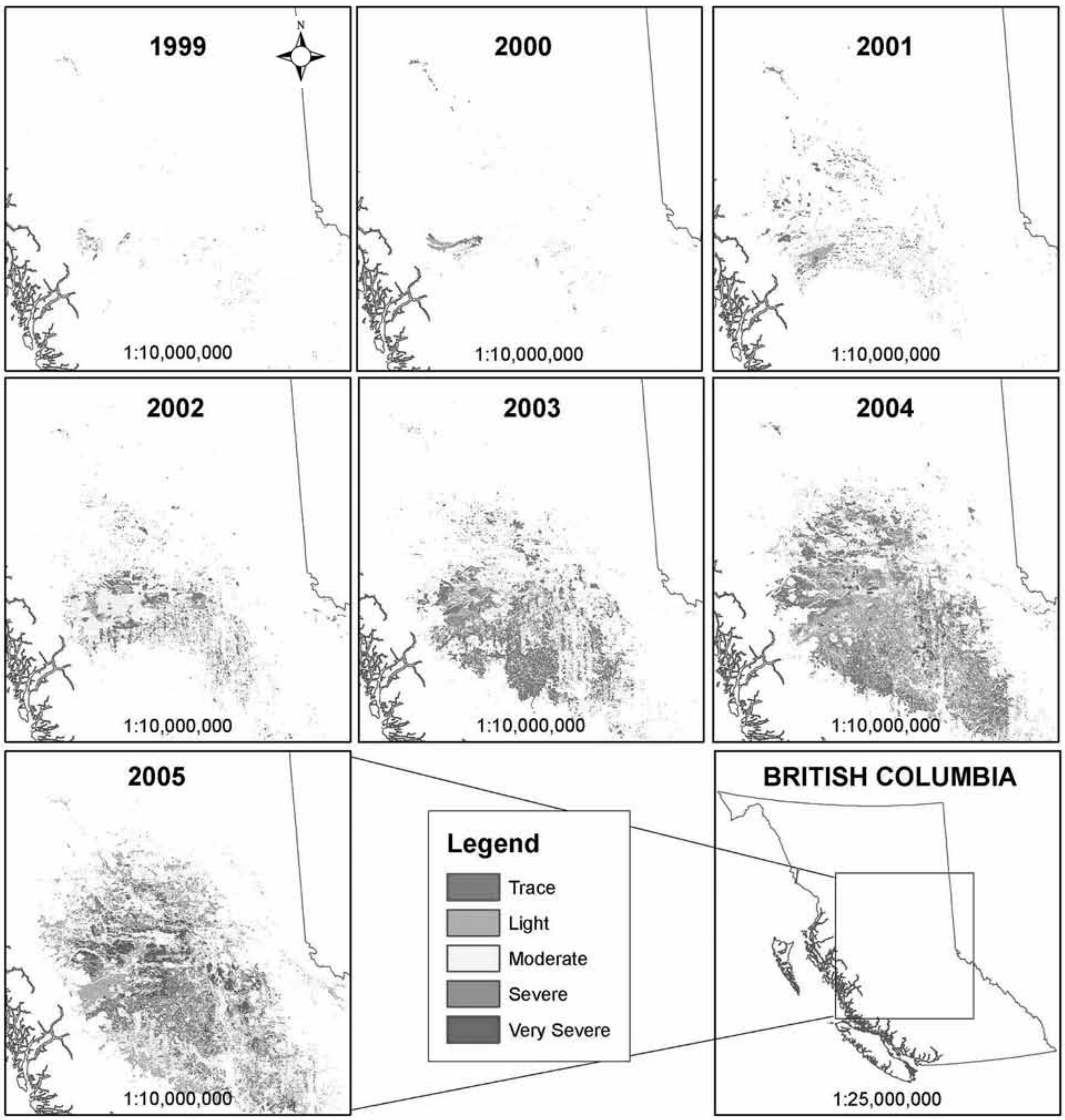


FIGURE 3. Expansion of area impacted by mountain pine beetle in British Columbia from 1999 to 2005.
* See page 58 endnote re: colour version.

impacted area, combining trace and light severity classes) (Table 2). The proportion of impacted area classified as severe changed less dramatically: 31 139 ha in 1999 (22% of the total impacted area) to 1.98 million ha in 2005 (23% of the total impacted area, including both severe and very severe). Figure 3 shows the increasing area impacted by the beetle from 1999 to 2005.

Figure 4 indicates the differential spatial distribution of impacted area by forest district. For example, the Nadina Forest District experienced a large increase in total impacted area by 2002, while the Central Cariboo Forest District's greatest impacted area occurred in 2005. Figure 4 demonstrates the utility of the AOS program for forest management, as it identifies forest districts that require proportionally more resources to conduct detailed surveys and address the infestation. However, the information would be further enhanced if severity was also considered. For example, Figure 4 illustrates the total area impacted in 2003, shaded by severity rating. For example, Quesnel has more moderate and severe areas than Chilcotin, which has a large area rated as light. Depending on the management strategy being implemented, forest districts with significant increases in areas rated as trace or light from one year to the next might not need the same level of resources for mitigation of the beetle as districts with large increases in moderate or severe rated areas. At a strategic level, the AOS data is useful for capturing the spatial and temporal variability of mountain pine beetle impacts across the province.

A British Columbia Ministry of Forests report (2003a) discusses the difficulty in calculating the cumulative area of mountain pine beetle attacks and suggests that the same area of infestation may be captured by the AOS in multiple years. For example, if the area impacted each year is summed, the total area impacted between 1999 and 2005 will exceed 22 million ha; lodgepole pine are estimated to occupy only 14.8 million ha in British Columbia (BC Ministry of Forests 2004). The time series of AOS data used in our analysis allowed us to determine the location and extent of areas captured in multiple years, and to estimate the cumulative area of impact without "double-counting" areas. The location of persistent impacts is shown in Figure 5 and areas impacted are summarized in Table 3. The total cumulative area of attack between 1999 and 2005 is estimated to be 11 048 271 ha. The area mapped as having mountain pine beetle impacts in all 7 years of AOS data was 3753 ha. Our analysis indicated that approximately 39% of the accumulated area was attacked in only one year, with 89% attacked in three or fewer years.

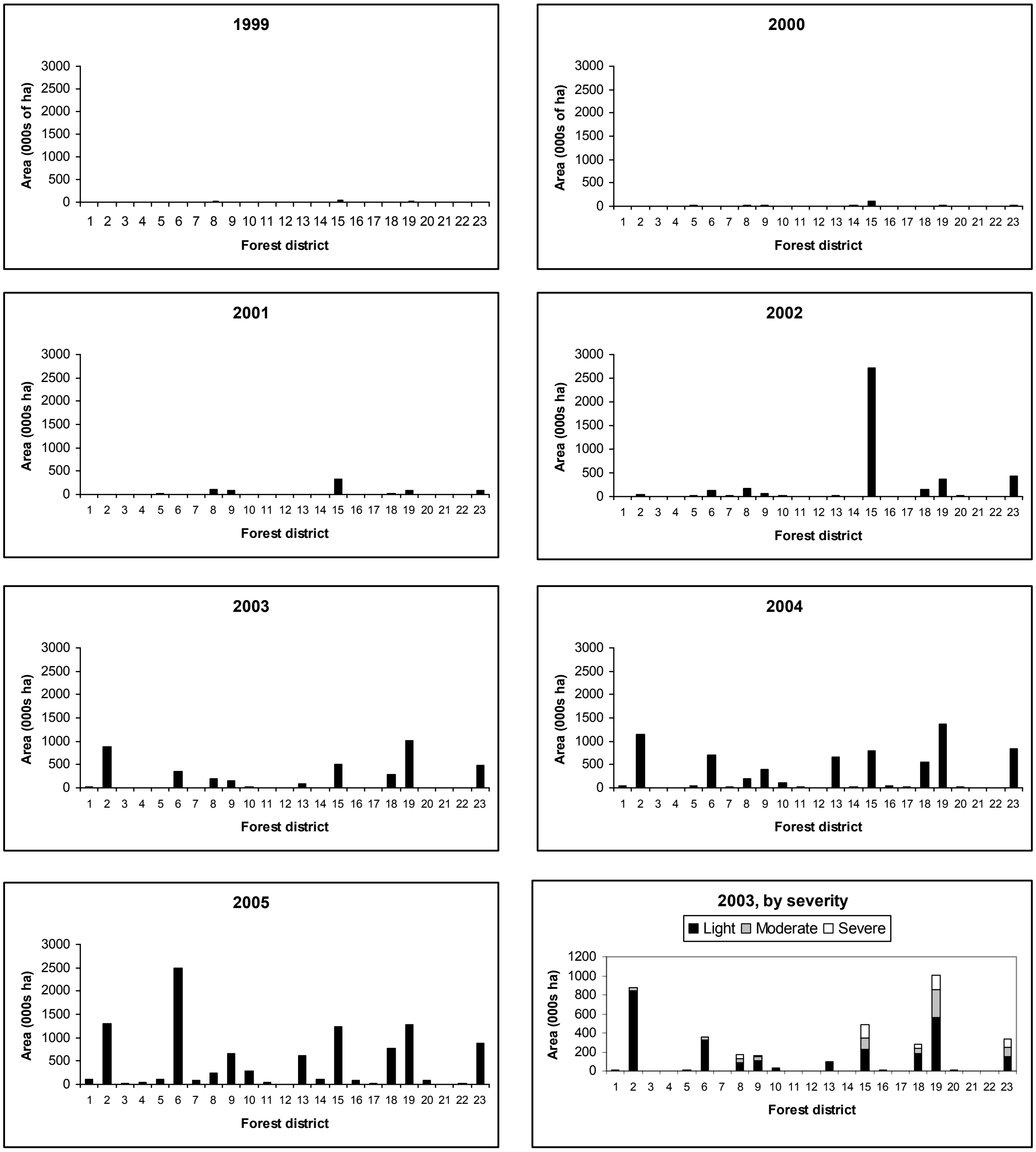
We also examined the trends in severity codes over time. Table 4 provides a summary of the amount of area experiencing no change, an increase, or a decrease in severity rating over 1, 2, 3, 4, or 5 years between 1999 and 2005. Given that there were seven possible years of attack in the timeframe analyzed, there were a maximum of six transitions between years. However, due to the small area that was attacked in all 7 years (< 4000 ha; Table 3), effectively, the maximum number of transitions was five.

TABLE 3. The number of years a given area experienced attack.

Number of years of attack	Area (ha)
1	4 277 639
2	3 157 317
3	2 431 206
4	922 714
5	186 650
6	68 992
7	3 753
Total	11 048 271

TABLE 4. A summary of the trends in transitions between years of AOS data.

Number of transitions between years	Decreasing severity (ha)	Increasing severity (ha)	No change in severity (ha)
1	1 720 529	3 525 951	2 420 315
2	323 928	590 163	507 406
3	28 492	13 562	33 761
4	850	169	1 168
5	0	0	32
Total	2 073 799	4 129 845	2 962 682



Code	Forest District	Code	Forest District	Code	Forest District
1	Arrow Boundary	9	Fort St. James	17	Peace
2	Chilcotin	10	Kamloops	18	Prince George
3	Chilliwack	11	Kootenay Lake	19	Quesnel
4	Columbia	12	Kalum	20	Rocky Mountain
5	Cascades	13	100 Mile House	21	Squamish
6	Central Cariboo	14	Mackenzie	22	Skeena Stikine
7	Headwaters	15	Nadina	23	Vanderhoof
8	North Island–Central Coast	16	Okanagan Shuswap		

FIGURE 4. Variation in the spatial distribution of mountain pine beetle impacted areas, by forest district.

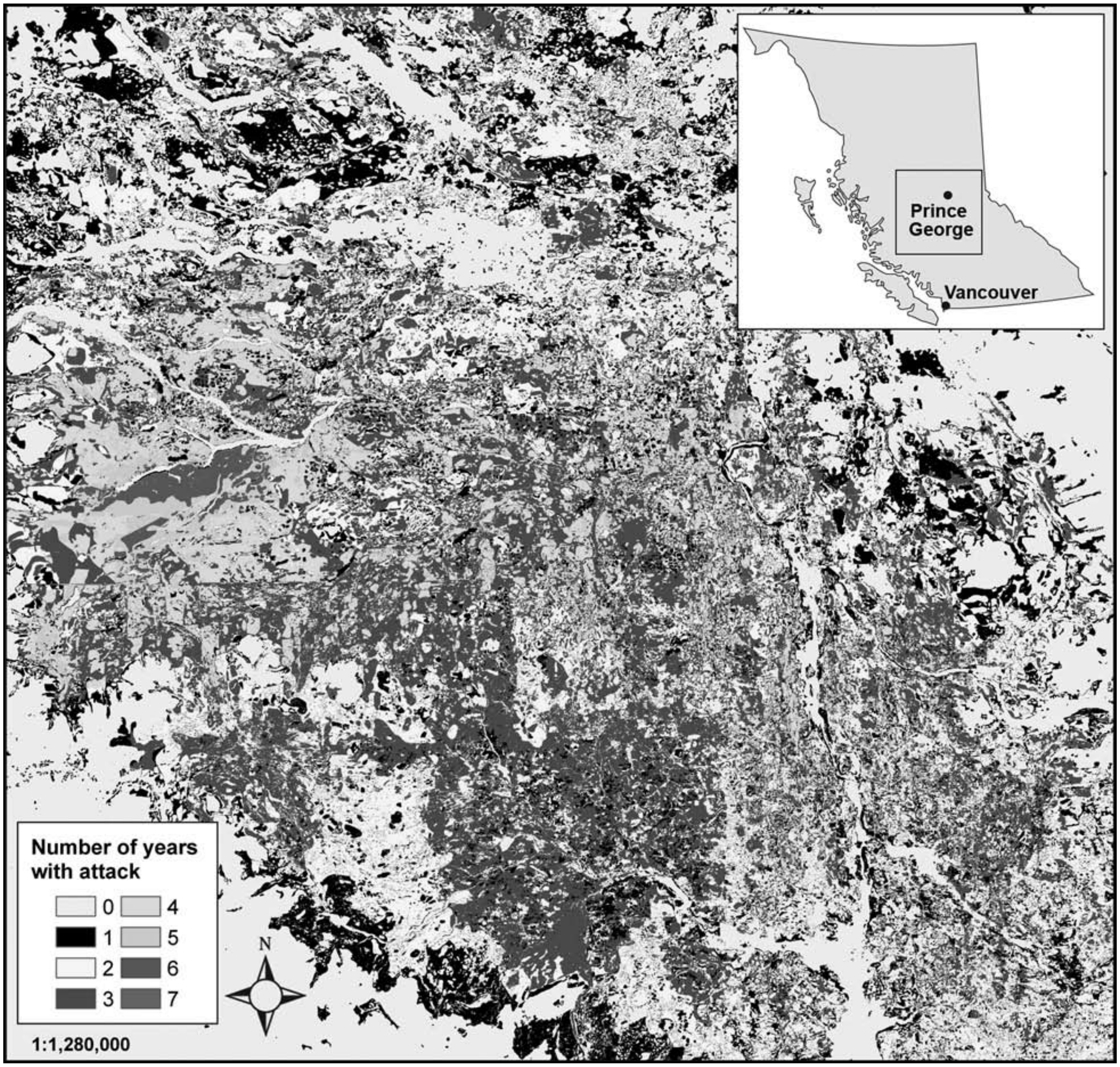


FIGURE 5. Number of years in which mountain pine beetle attack was recorded at that location in the AOS data.
* See page 58 endnote re: colour version.

There were 2.4 million ha where there was no change in severity rating over a single transition from one year to another; conversely, there were only 32 ha where the severity rating remained unchanged for all five transitions between years (Table 4). In other trends, 1.7 million ha experienced a decline in severity, while 3.5 million ha experienced an increase in severity over a single transition between years. The expectation over time was that the severity of an infestation in an area might increase as the mountain pine beetle population continued to grow. Some of the decreases in severity observed in our analysis may be attributed to changes in the severity classification system in 2004 with the addition of a new trace category. For example, in our analysis of the AOS data, we found that 354 756 ha assigned a severity of light in 2003 were assigned a severity of trace in 2004. Also, positional errors and the generalized nature of the AOS boundary delineation likely accounted for decreasing severity from one year to the next. More difficult to explain are the 28 492 ha of impacted area which our analysis revealed were assigned decreasing severity over 3 years, perhaps highlighting the subjectivity of the severity rating system.

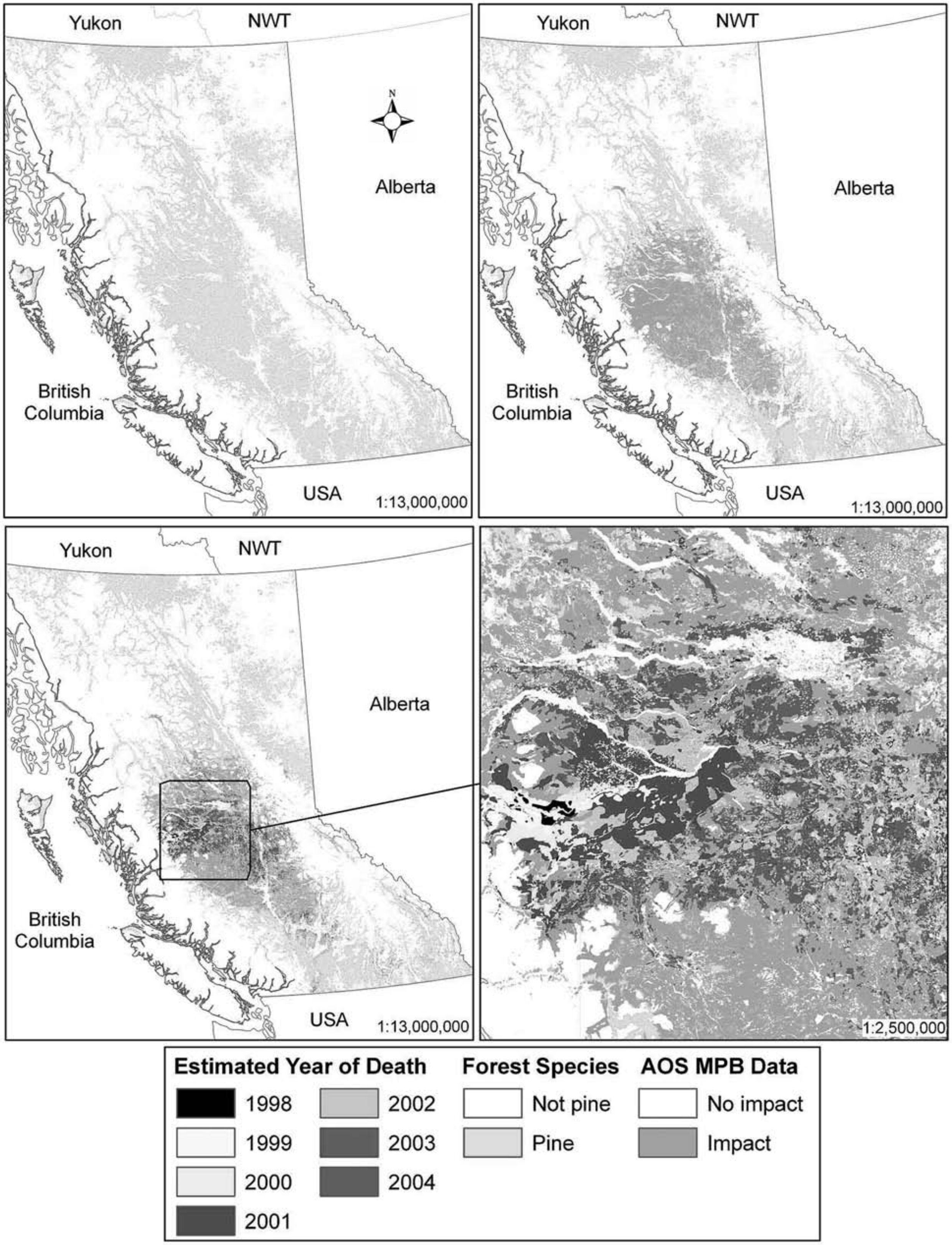


FIGURE 6. Distribution of pine species, area impacted by mountain pine beetle, and estimated year of death.
* See page 58 endnote re: colour version.

We estimated the year in which the majority of pine within a 1 ha grid cell could be considered dead. The AOS data indicated that the total cumulative area impacted by the beetle between 1999 and 2005 was 11 048 271 ha (Table 3). Based on the assumptions used in our analysis and a summation of the severity code mid-points (Table 1), the amount of area that experienced pine mortality from 1998 to 2004 was 6 565 667 ha (Table 5). In some areas, the sum of the severity codes exceeded 100% (2 322 524 ha). The greatest annual increase in mortality was in 2003, when the area of estimated mortality was 2 819 056 ha, an increase of almost 50% over 2004. This likely reflects the prolonged nature of the infestation in many of the central areas of the British Columbia. Figure 6 illustrates the total area of pine in British Columbia, the total area attacked by mountain pine beetle (as indicated in the AOS), and the estimated year of death. This figure illustrates that there is a large area of impact that may yet exceed the > 50% severity threshold we used to define mortality. With this approach, complementary maps of mountain pine beetle impacts can also be produced, indicating the cumulative impacts and mortality over the span of the current outbreak. Other thresholds could be used (e.g., 25% or 75%) to provide alternative representations of mortality under different scenarios. It should also be reiterated that difficulties with spatial positioning of AOS polygons exist, and that the 1 ha tessellation illustrates broad landscape trends and is not indicative of the actual conditions present at the geographic location represented by a given cell.

Conclusions

The total area impacted by the mountain pine beetle is often reported without a breakdown of area by severity rating. The total area alone is not necessarily representative of the area killed by the beetle. A better indication of actual mortality may be extracted by examining the severity ratings and their accumulation over a number of years. Furthermore, if severity is not reported, the perception of damage may be in excess of reality. If we consider each year separately, the area of mortality is, on average, two-thirds less than the total area impacted by the beetle each year. This implies that although a large forested area of British Columbia has been impacted by the beetle, there are still large volumes of viable pine on the land base. Because forest districts will have different severity rates, management approaches need to be developed that will respond to the severity of the infestation rather than the total area impacted.

We recommend that: (1) when producing tabular results, areas impacted by mountain pine beetle should be reported by severity class; and (2) when producing maps of the AOS data, where possible, impacts should be shaded according to severity to accurately represent the nature of the data. The AOS provides useful information for synoptic applications, and the full temporal and attributional range of this information should be utilized.

TABLE 5. Estimated year of death and corresponding area (assuming a 50% severity threshold). Areas where severity summed to > 100% are also shown.

Year	Total impact area (ha)	Area of pine mortality (sum of severity code mid-points > 50%)	Percent of total impact area	Area where severity code mid-points summed to > 100%
1998	144 062	31 139	22	0
1999	264 366	111 209	42	14 403
2000	771 517	262 997	34	33 810
2001	1 956 887	718 303	37	166 575
2002	4 064 539	1 158 009	28	423 444
2003	7 018 296	1 464 954	21	613 879
2004	8 730 559	2 819 056	32	1 070 413
Total	22 950 226	6 565 667		2 322 524

Acknowledgements

This project was funded by the Government of Canada through the Mountain Pine Beetle Program, a 3-year, $100 million program administered by Natural Resources Canada, Canadian Forest Service.

References

? *TEST YOUR KNOWLEDGE* *Questions on page 114*

Alberta Sustainable Resource Development. 2004. Mountain pine beetle management guide. Public Lands and Forests Division, Forest Management Branch, Forest Health Section, Edmonton, Alta.

Aldrich, R.C., R.C. Heller, and W.F. Bailey. 1958. Observation limits for aerial sketch mapping southern pine beetle in the southern Appalachians. Journal of Forestry 56:200–202.

Amman, G.D. 1982. The mountain pine beetle: Identification, biology, causes of outbreaks, and entomological research needs. *In* Proceedings of the joint Canada/USA workshop on mountain pine beetle related problems in Western North America. D.M. Shrimpton (editor). Environment Canada, Canadian Forestry Service, Pacific Forest Research Centre, Victoria, BC. Information Report BC-X-230, pp. 7–12.

British Columbia Ministry of Forests. 1995. Bark beetle management guidebook (Forest Practices Code). BC Ministry of Forests, Forest Practices Branch, Victoria, BC.

_______. 2000. Forest health aerial overview survey standards for British Columbia, Version 2.0. BC Ministry of Forests, Forest Practices Branch, and Canadian Forest Service, Victoria, BC.

_______. 2003a. Provincial bark beetle management technical implementation guidelines. BC Ministry of Forests, Forest Practices Branch,Victoria, BC.

_______. 2003b. Timber supply and the mountain pine beetle infestation in British Columbia. BC Ministry of Forests, Forest Analysis Branch, Victoria, BC.

_______. 2004. The state of British Columbia's forests, 2004. BC Ministry of Forests, Forest Practices Branch, Victoria, BC.

Carroll, A.L., S.W. Taylor, J. Régnière, and L. Safranyik. 2004. Effects of climate change on range expansion by the mountain pine beetle in British Columbia. *In* Mountain pine beetle symposium: Challenges and solutions. T.L. Shore, J.E. Brooks, and J.E. Stone (editors). Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, Victoria, BC. Information Report BC-X-399, pp. 223–232.

Harris, J.W.E. and A. F. Dawson. 1979. Evaluation of aerial forest pest damage survey techniques in British Columbia. Canadian Forestry Service, Victoria, BC. Information Report BC-X-198.

Henigman, J., T. Ebata, E. Allen, J. Holt, and A. Pollard (editors). 1999. Field guide to forest damage in British Columbia, 2nd edition. Canadian Forest Service and BC Ministry of Forests, Victoria, BC. FRDA II Rep. No. 17.

Leckie, D.G., E. Cloney, and S.P. Joyce. 2005. Automated detection and mapping of crown discolouration caused by jack pine budworm with 2.5 m resolution multispectral imagery. International Journal of Applied Earth Observation and Geoinformation 7:61–77.

Lewis, K.J. and I.D. Hartley. 2006. Rate of deterioration, degrade, and fall of trees killed by mountain pine beetle. British Columbia Journal of Ecosystems and Management 7:11–19.

Safranyik, L. 2004. Mountain pine beetle epidemiology in lodgepole pine. *In* Mountain pine beetle symposium: Challenges and solutions. T.L. Shore, J.E. Brooks, and J.E. Stone (editors). Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, Victoria, BC. Information Report BC-X-399, pp. 33–40.

Schraeder-Patton, C. 2003. Digital aerial sketch mapping. US Department of Agriculture Forest Service, Remote Sensing Applications Center, Salt Lake City, Utah. RSAC-1202-RPT2.

Swaine, J.M. 1925. The factors determining the distribution of North American bark beetles. Canadian Entomolologist 57:261–266.

Taylor, S.W. and A.L. Carroll. 2004. Disturbance, forest age, and mountain pine beetle outbreak dynamics in BC: A historical perspective. *In* Mountain pine beetle symposium: Challenges and solutions. T.L. Shore, J.E. Brooks, and J.E. Stone (editors). Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, Victoria, BC. Information Report BC-X-399, pp. 41–51.

Taylor, S.W., A.L. Carroll, R.I. Alfaro, and L. Safranyik. 2006. Forest, climate and mountain pine beetle outbreak dynamics in Western Canada. *In* Mountain pine beetle symposium: Challenges and solutions. T.L. Shore, J.E. Brooks, and J.E. Stone (editors). Natural Resources Canada, Canadian Forest Service, Pacific Forestry

Centre, Victoria, BC. Information Report BC-X-399, pp. 67–94.

Westfall, J. 2005. 2004 Summary of forest health conditions in British Columbia. BC Ministry of Forests, Forest Practices Branch, Victoria, BC.

_______. 2007. 2006 Summary of forest health conditions in British Columbia. BC Ministry of Forests and Range, Forest Practices Branch. Victoria, BC.

Wulder, M.A., C.C. Dymond, J.C. White, D.G. Leckie, and A.L. Carroll. 2006a. Surveying mountain pine beetle damage of forests: A review of remote sensing opportunities. Forest Ecology and Management 221:27–41.

Wulder, M.A., J.C. White, B.J. Bentz, and T. Ebata. 2006b. Augmenting the existing survey hierarchy for mountain pine beetle red attack damage with satellite remotely sensed data. Forestry Chronicle 82:187–202.

ARTICLE RECEIVED: **May 17, 2007**
ARTICLE ACCEPTED: **September 28, 2008**

* Figures 2, 3, 5, and 6 are available in colour in the online version of this article at: ***www.forrex.org/publications/jem/ISS50/vol10_no1_art5.pdf***

Extension Note

Ecological descriptions of Pacific golden chanterelle (*Cantharellus formosus*) habitat and estimates of its extent in Haida Gwaii

J. Marty Kranabetter[1], Harry Williams[2], and Jacques Morin[3]

Abstract

Ecologically based information on golden chanterelle (*Cantharellus formosus*) habitat is needed to guide decision making by forest managers. We described soils, plant communities, and stand characteristics of productive mushroom sites and used these features in a mapping exercise to estimate the extent of *C. formosus* habitat over a portion of the Haida Gwaii islands. Chanterelle sites were located at low elevations (approximately 100 m) on well-drained soils with silt loam to sandy loam textures and thin forest floors. Plant communities were sparse and characterized by low herb and shrub cover with extensive carpets of feathermosses. The stands were productive second-growth western hemlock and Sitka spruce, ranging in age from 35 to 50 years, and the sites were strongly mounded from extensive blowdown events or logging disturbances. The site and soil properties were consistent with the zonal (01) site series (western hemlock – Sitka spruce – lanky moss) of the submontane variant of the wet hypermaritime Coastal Western Hemlock (CWHwh1) subzone. A preliminary assessment of *C. formosus* habitat around Skidegate Lake indicated approximately 1785 ha of mesic forests (equal to 21% of the assessed forest area) with a major portion covered by immature stands conducive to commercial picking. This information on the nature and extent of *C. formosus* habitat provides the first step in successful co-management of timber and mushroom resources.

KEYWORDS: *biogeoclimatic ecosystem classification,* Cantharellus formosus*, commercial mushroom harvest, non-timber forest products.*

Contact Information

1 British Columbia Ministry of Forests and Range, 4300 North Road, Victoria, BC V8Z 5J3.
Email: Marty.Kranabetter@gov.bc.ca

2 Jacques Whitford-Axys Environmental Consultants, Unit 11, 2042 Mills Road West, Sidney, BC V8L 5X4.
Email: Harry.Williams@JacquesWhitford.com

3 Biology consultant, Box 661, Queen Charlotte City, BC V0T 1S0. Email: jacques@haidagwaii.net

***JEM* — VOLUME 10, NUMBER 1**

Kranabetter, J.M., H. Williams, and J. Morin. 2009. Ecological descriptions of Pacific golden chanterelle (*Cantharellus formosus*) habitat and estimates of its extent in Haida Gwaii. *BC Journal of Ecosystems and Management* 10(1):59–67.

Introduction

The Pacific golden chanterelle (*Cantharellus formosus* Corner) is a valuable non-timber forest product in Haida Gwaii (Queen Charlotte Islands), British Columbia, providing seasonal employment and economic benefits for both local residents and visiting mushroom pickers. An annual harvest ranging from 45 000 to 115 000 kg, with up to 300 pickers participating, occurs from August to October in select productive forests of the islands (Tedder et al. 2000). The island community formally expressed a desire to sustain the harvesting of mushrooms through integrated land use plans (Haida Gwaii/Queen Charlotte Island Land Use Plan 2006).

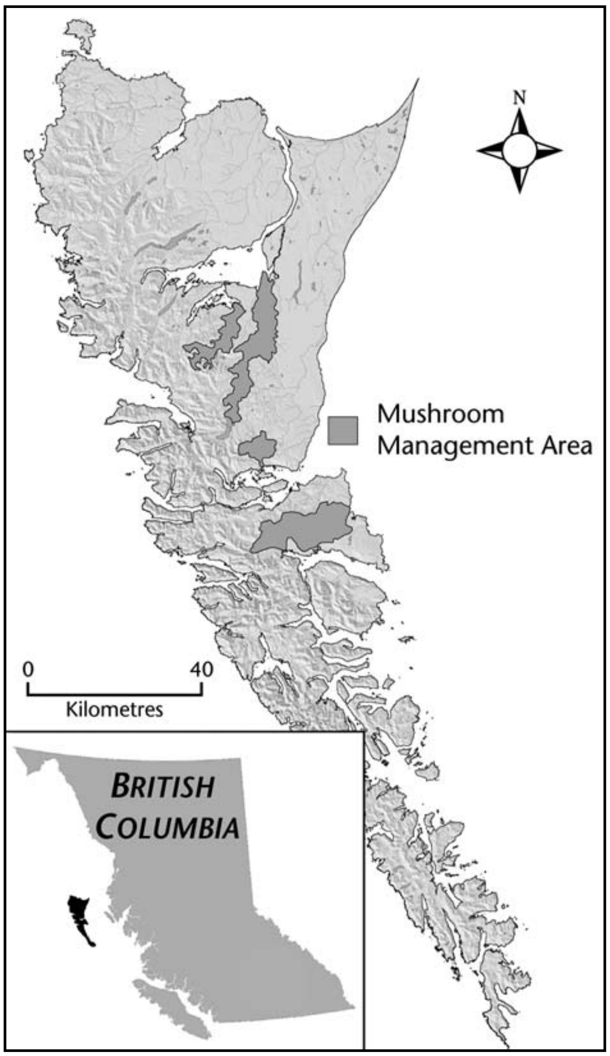


FIGURE 1. Mushroom management areas identified for Haida Gwaii (Source: Haida Gwaii/Queen Charlotte Island Land Use Plan 2006).

Although approximate areas of commercial chanterelle harvesting on Haida Gwaii are known, more ecologically based information on chanterelle habitat is needed to guide decision making by forest managers.

Approximate areas of commercial chanterelle harvesting on Haida Gwaii are known (Figure 1), but more ecologically based information on chanterelle habitat is needed to guide decision making by forest managers.

Cantharellus formosus is an ectomycorrhizal fungal species on a number of host tree species including Douglas-fir (*Pseudotsuga menziesii*), western hemlock (*Tsuga heterophylla*), and Sitka spruce (*Picea sitchensis*) (Pilz et al. 2003). *C. formosus* is generally found in low-elevation coastal forests throughout the Pacific Northwest, ranging from California to Alaska, but the more productive habitat is typically second-growth coniferous stands that were clearcut (Dunham et al. 2006). Microsite variables associated with *C. formosus* include relatively thin forest floors, low exchangeable acidity, and low levels of moss cover (Bergemann and Largent 2000), and possibly well-rotted coarse woody debris (Pilz et al. 2003). In British Columbia, the habitat of *C. formosus* has been described on Vancouver Island using the biogeoclimatic system of classification (Pojar et al. 1987). These sites are located in the Coastal Western Hemlock (CWH) zone with the majority of habitat on medium-textured soils that have moderate productivity and a low cover of herbs and shrubs with widespread feathermosses (Ehlers 2003).

The objective of this note was to contribute further ecological descriptions of *C. formosus* habitat from the more northern extent of its range in the Pacific Northwest. We described soils, plant communities, and stand characteristics of productive mushroom sites within Haida Gwaii, and examined whether *C. formosus* habitat was consistent and specific enough across these forests to potentially map commercial mushroom harvesting areas as has been successfully done with pine mushrooms (*Tricholoma magnivelare*) (Kranabetter et al. 2002). Estimates of the extent of *C. formosus* habitat were made from air photographs covering an 8500-ha study area, and this preliminary survey will help inform forest managers and the interested public on the opportunities and challenges in managing both timber resources and commercial mushroom harvests.

Materials and methods

Site selection

In September 2007, three experienced mushroom pickers based in Haida Gwaii accompanied us to sites known to be highly productive golden chanterelle habitat. Chanterelles were found in each plot to confirm habitat suitability, and locations were selected within as wide a range of landforms and site characteristics as possible. These plots were located in an area just north of Queen Charlotte City, in areas along the north and south sides of Skidegate Lake, and in areas closer to Mosquito Lake and Gray Bay.

Ecosystem descriptions

We undertook full ecological descriptions and biogeoclimatic (BEC) site classification for nine plots. Standard procedures, as described in "Field Manual for Describing Terrestrial Ecosystems" (BC Ministry of Environment and BC Ministry of Forests 1998) were used to describe site characteristics, vegetation, and soils for each plot. All plant species were listed by stratum with estimates of their percent cover. The combined percent cover for each stratum was also recorded. Plant names corresponded to those used by Pojar and MacKinnon (1994) in *Plants of Coastal British Columbia*. Soil pits were excavated to a depth of at least 50 cm (Figure 2), and descriptions of the humus form and mineral soil profiles were recorded.

Moisture regime was ranked from 0 (very dry) to 7 (wet) and nutrient regime from A (very poor) to E (very rich), with the corresponding site series identified using "A Field Guide to Site Identification and Interpretation for the Vancouver Forest Region" (Green and Klinka 1994). Landforms, soil pedons, and humus forms were classified according to the "Terrain Classification System for British Columbia" (Howes and Kenk 1997), The "Canadian System of Soil Classification" (Soil Classification Working Group 1998), and "Towards a Taxonomic Classification of Humus Forms" (Green et al. 1993), respectively.

Stand characteristics

Forest cruise plots were done at each site to determine stand characteristics (BC Ministry of Forests 2000). A full prism sweep was made at plot centre, and the diameter at breast height (DBH) was noted for each "in" tree. One or two co-dominant trees of hybrid Sitka spruce and western hemlock were cored at breast height (1.3 m) for age, and tree heights were measured using a Vertex Forester. Site indices were calculated based on tree age and height using BC Ministry of Forests Site Tool (version 3.2B).

FIGURE 2. Typical soil pit from productive mushroom sites in Haida Gwaii.

Air photograph interpretation

A pilot area encompassing 8450 ha was chosen for a mapping exercise to estimate the extent of productive chanterelle habitat. Photo signatures for the classified 01 site series were referenced from colour air photographs taken along the northern portion (Photos 15BCC04002: 98–103; scale 1:25 000) and southern portions (Photos MB94003: 162–169; scale 1:15 000) of Skidegate Lake. The photo signature for CWHwh1/01 ecosystems was based on the nine full ecological plots along with a further five mesic stands also confirmed as mushroom sites in the area. Both landscape position and crown characteristics were used to identify the appropriate habitat (minimum 90% coverage of 01 site series within a mapped polygon).

The mesic site series of the submontane variant of the wet hypermaritime Coastal Western Hemlock subzone (CWHwh1/01) occurred on convex-shaped landforms with the moderately high productivity of the stands distinguished by the slightly smaller tree crowns occurring close together and appearing as a deep green, uniform texture on the air photograph. The majority of the landscape was covered with immature forests, but we also examined older forests for a more complete inventory of potential habitat. More recently logged areas (less than 20 years) were not mapped because of the difficulties in assessing site quality. The mapped polygons were digitized to determine polygon size and the relative percent of CWHwh1/01 sites over the pilot area (excluding lakes and other non-productive areas).

Results

Site and soils

All chanterelle sites were at low elevations (70–110 m) within the wet hypermaritime subzone, submontane variant of the Coastal Western Hemlock zone (CWHwh1) (Table 1). Landforms were morainal veneers or blankets over bedrock, derived primarily from sedimentary (likely shale) parent materials, with plots predominately at mid- to upper-slope positions with variable aspects. Mineral soils were medium textured (predominantly sandy loam to silt loam) and judged to be well drained because of low clay content. Coarse fragment content was low, and rooting depth reached approximately 50 cm (Figure 2). Forest floors were thin, averaging 3 cm, usually with a matted structure and tenacious consistency (designated as an Fm horizon). Soils were classified as either Orthic Humo-Ferric Podzols or Ferro-Humic Podzols with Hemimor humus forms. All stands were logged and likely had widespread soil disturbance, and, in some cases, sites were burned as well. The sites were typically strongly mounded from extensive blowdown events, and soil horizons were well mixed and occasionally inverted. The site and soil properties corresponded to a fairly narrow range of moisture (ranked "fresh" or 3+ to 4) and nutrient regimes (ranked "medium" or C to C+), all equivalent to mesic ecosystems (Table 1).

Vegetation and stands

Tree cover (Layer A) of chanterelle habitat was exclusively western hemlock and Sitka spruce, at generally even proportions, with western redcedar being notably absent except occasionally in the shrub layer (Table 2). Western hemlock was the most abundant understorey species in the B layer, and other shrub species such as *Vaccinium parvifolium*, *V. ovalifolium*, *Rubus spectabilis*, and *Gaultheria shallon* contributed usually less than 5% cover. The herb layer (Layer C) was also low, often less than 5%, and included small amounts of *Polystichum*

TABLE 1. Site and soil attributes for productive *C. formosus* sites on Haida Gwaii.

	Plot no.								
Site-soil properties	**9128**	**9129**	**9130**	**9131**	**9132**	**9133**	**9134**	**9135**	**9136**
SITE									
Elevation (m)	71	110	na	109	91	90	95	93	93
Slope (%)	3	3	35	12	14	55	15	35	25
Aspect (degrees)	270	260	30	180	180	250	230	180	10
Mesoslope position[a]	LV	UP	MD	UP	UP	MD	UP	MD	MD
FOREST FLOOR									
Depth (cm)	3	4	4	3.5	6	4	2	2.5	1
Classification[b]	HR	RR	RR	HR	HR	HR	HR	HR	HR
MINERAL SOIL									
Dominant soil texture[c]	L	L	fSL	SiL	SL	SiL	SL	SiL	SiL
Drainage class[d]	W	W	W	W	W	W	W	W	W
Coarse fragment (%)	5	10	20	5	15	10	5	15	25
Rooting depth (cm)	60	30	55	55	40	30	50	50	40
Classification[e]	O.HFP	O.HFP	O.FHP	O.FHP	O.HFP	O.HFP	O.HFP	O.HFP	O.HFP
Moisture/nutrient regime	4 C+	4 C	4 C+	4- C+	4- C	4 C+	3+ C	3+ C	4 C

[a] LV = level, UP = upper, MD = middle
[b] HR = hemimor, RR = resimor
[c] L = loam, fSL = fine sandy loam, SL = sandy loam, SiL = silt loam
[d] W = well drained
[e] O.HFP = orthic humoferric podzol, O.FHP = orthic ferrohumic podzol

TABLE 2. Plant species and percent cover for productive *C. formosus* sites on Haida Gwaii.

	Plot no.									
Species by canopy layer	**9128**	**9129**	**9130**	**9131**	**9132**	**9133**	**9134**	**9135**	**9136**	**Average**
COVER FOR LAYER A (%)	**80**	**75**	**65**	**65**	**80**	**75**	**75**	**60**	**70**	**71.7**
Picea sitchensis	20	35	30	40	40	40	30	50	45	36.7
Tsuga heterophylla	70	40	40	30	35	40	50	30	30	40.6
COVER FOR LAYER B (%)	**16**	**6**	**12**	**14**	**16**	**6**	**20**	**16**	**25**	**14.6**
Gaultheria shallon							1	1	2	0.4
Menziesia ferruginea			0.1	0.5						0.1
Rubus spectabilis		0.5	3	2	1					0.7
Thuja plicata	2		2		1		2			0.8
Tsuga heterophylla	15	4	3	8	10	5	15	15	20	10.6
Vaccinium ovalifolium		1		0.5						0.2
Vaccinium parvifolium	1	1	2	3	5	1	2	0.5	3	2.1
COVER FOR LAYER C (%)	**1**	**2.5**	**3**	**7**	**6**	**6**	**3**	**4**	**8**	**4.5**
Blechnum spicant	0.5	1	1	2	2		0.5	0.5	3	1.2
Dryopteris assimilis	0.01	0.1	1	1	0.5	0.1				0.3
Galium triflorum								0.1		0.0
Gymnocarpium dryopteris		0.5		0.1		0.1				0.1
Listera cordata				0.1			0.1		0.1	0.0
Lycopodium clavatum			0.1	0.1	0.5		2	2		0.5
Maianthemum dilatatum		0.1			0.1		0.5	0.5	0.5	0.2
Melica subulata				0.1			0.5			0.1
Moneses uniflora			0.1	0.1	1	1		0.1		0.3
Polystichum munitum	1	1	1	4	2	5		1	5	2.2
COVER FOR LAYER D (%)	**60**	**45**	**60**	**95**	**85**	**70**	**95**	**96**	**95**	**77.9**
Atrichum selwynii	1	0.1	2	1	0.5	8			1	1.4
Barbilophozia lycopodiodes	0.5					0.1		0.1		0.1
Dicranum scoparium								1		0.1
Hylocomium splendens	10	3	5	50	30	5	20	15	55	15.9
Hypnum circinale		0.1								0.0
Kindbergia oregana		3	3	3	10	15	40	75	10	17.3
Peltigera neopolydactyla					0.1		1	0.5	2	0.4
Plagiochila porelloides	1									0.1
Plagiothecium undulatum	20	10	10	5	2	10		1	3	6.2
Pseudotaxiphyllum elegans	0.1									0.0
Rhizomnium glabrescens	20	30	30	5	5	12	3	5	4	12.1
Rhytidiadelphus loreus	10	5	20	25	40	30	30	5	20	17.8
Scapania bolanderi		0.5				0.1				0.1
Sphagnum girgensohnii		1					1		2	0.4

munitum, *Blechnum spicant*, *Melica subulata*, *Moneses uniflora*, *Listera cordata*, and *Gymnocarpium dryopteris*. The vegetation cover was undoubtedly modified to some degree, however, by extensive deer browsing found throughout the islands. Mosses in the D layer typically carpeted the forest floor, and the dominant species included *Hylocomium splendens*, *Rhytidiadelphus loreus*, and *Kindbergia oregana*. The low shrub and herb cover with extensive moss layers is consistent with the described site and soil properties (Figure 3) and would be classified as the zonal (01) site series (western hemlock – Sitka spruce – lanky moss) (Green and Klinka 1994).

The stands were all second-growth forests ranging in age from 35 to 50 years (Table 3) and likely naturally regenerated after clearcut harvesting (plot 9132 was not aged because of equipment malfunction). Stand basal area at these ages was approximately 56 m^2/ha with trees 28 m in height and 35 cm in diameter, on average. A few of these stands had been thinned in the previous decade, and all stands were relatively well spaced, healthy, and productive. Site index (height at age 50) ranged from 30 to 35 m for both Sitka spruce and western hemlock with the exception of one less productive site (plot 9136). These indices were comparable to other sites characterized by fresh moisture regimes and medium nutrient availability in the CWHwh1 (Kayahara and Pearson 1996).

Habitat mapping

A total of 231 polygons were mapped as CWHwh1/01 ecosystems within the project area surrounding Skidegate Lake. Some of these stands were adjoined but labelled as separate polygons because of significant differences in aspect or stand age. We combined the adjoined polygons for the purposes of the mapping summary, which reduced the number of total polygons to 181. The largest individual stand was 79 ha, and the more closely grouped polygons encompassed up to 110 ha. The lower size limit of polygons was 1 ha, and the average polygon size was 9.9 ha. The sum total of the mapped 01 stands was 1785 ha, which was equal to 21% of the forested landscape (note that a small portion of the project area, approximately 250 ha, had very young stands that could not be assessed). The

FIGURE 3. Typical stand and vegetation community for productive mushroom sites in Haida Gwaii.

TABLE 3. Forest stand attributes for productive *C. formosus* sites on Haida Gwaii.

	Plot no.								
Stand attributes	**9128**	**9129**	**9130**	**9131**	**9132**	**9133**	**9134**	**9135**	**9136**
Basal area (m^2/ha)	56	77	70	56	70	56	49	35	35
Age (years at DBH)	38	36	35	49	–	41	52	50	52
AVERGE HEIGHT (m)									
Spruce	23	25.5	26.5	34	21.5	31.5	31	31	24
Western hemlock	23	26.5	25	28	23	27.5	30	21	17
AVERAGE DIAMETER (cm)									
Spruce	21	33	37	51	27	38	48	43	30
Western hemlock	24	35	32	36	31	44	36	34	17
SITE INDEX (m @ 50 yr)									
Spruce	31	35	34	34	–	35	31	30	24
Western hemlock	30	35	35	32	–	31	32	23	19

majority of the 01 habitat was second-growth stands, but the exact extent is unknown because forest cover information is not publically available under the forest tenure covering this portion of Haida Gwaii.

Discussion

The descriptions of *C. formosus* habitat from Haida Gwaii were comparable with sites from Vancouver Island (Ehlers 2003) and were consistently located on low elevation, moss-dominated mesic ecosystems (CWHwh1/01 – lanky moss) with immature stands of Sitka spruce and western hemlock. Microsites with thin forest floors were consistent with productive habitat but not low moss cover (Bergemann and Largent 2000), and, as Dunham et al. (2006) also noted, the association of *C. formosus* with buried wood was not apparent from these study sites. Mesic ecosystems are generally extensive in these landscapes, which, along with large-scale logging operations in the 1950s and 1960s, have led to the widespread and abundant fruiting of *C. formosus*. We also noted large numbers of *Boletus edulis* (King bolete) and the occasional *Polyozellus multiplex* (blue chanterelle) in this same forest habitat, which could support additional mushroom harvests from these stands (Tedder et al. 2000). The results of the study would suggest there are opportunities for the co-management of timber and mushroom resources but also potential conflicts depending on the rotation age of the second-growth stands.

For most attributes, the chanterelle sites fit the CWHwh1/01 concept well, but using herb and shrub indicator species to assess soil nutrient regimes can be problematic under second-growth stands, especially with extensive deer browse (Kayahara and Pearson 1996). For example, the rich-indicator species sword fern (*Polystichum munitum*) was sometimes noted on steeper slopes and on chanterelle sites with very thin humus layers, suggesting perhaps a better than average soil nutrient regime (also noted by Ehlers [2003]). A few plots also had quite high cover of the moss *Kindbergia oregana*, which, based on its distribution in other coastal forest ecosystems, would also indicate slightly richer soils. It is possible that the cover of *K. oregana* and *P. munitum* were temporarily elevated in second-growth stands due to the scalping of forest floors during past logging events, and that over time these species could decline as forest floor depth increases under climax stands. However, in hypermaritime climates, we also expect some beneficial effects of soil disturbance on site productivity when deep mixing of the profile counteracts the strong weathering and podzolization processes that limit phosphorus and cation availability (Kranabetter et al. 2005a). It might, therefore, be acceptable to classify some of these chanterelle sites as transitional to CWHwh1/03 sword fern to reflect richer soil nutrient regimes.

We walked through a few moist, rich sites (CWHwh1/05 and /06) and were unable to find any chanterelles, which would support the mapping of CWHwh1/01 sites as commercial habitat. Further investigations of more contrasting sites and landforms could help refine soil nutrient regimes, which were predominantly ranked medium (to perhaps slightly rich) but might also include poorer soils as described elsewhere in the Pacific Northwest (Pilz et al. 2003). At a microsite level, we often found large mushroom fruitings on the tops of hummocks or on the convex part of a slope, which would suggest that well-drained, moisture-shedding microsites (3 to 3+ moisture regime) were ideal. Therefore, within mesic polygons, separating out moderately well-drained soils or sites with few hummock features might eliminate less productive habitat. This degree of precision in ecosystem mapping was not possible with the air photographs provided, however, and would likely require either field assessments to more closely evaluate site features or air photographs of finer resolution.

None of the described sites were old forests, and the apparent skewed distribution in fruiting to favour immature stands is consistent with other areas in the Pacific Northwest (Ehlers 2003; Dunham et al. 2006). The reduction in fruiting bodies with stand age suggests *C. formosus* is an early-seral species that is displaced to some degree by mid-seral and late-seral ectomycorrhizal fungal species during succession (Kranabetter et al. 2005b; Twieg et al. 2007). As an early-seral species, *C. formosus* would disperse and establish readily after forest harvesting; in fact, some evidence suggests soil disturbances such as broadcast burning further enhances *C. formosus* abundance in young stands (Peterson et al. 2000), perhaps due to the exclusion of other competing early-seral ectomycorrhizal species.

An important issue for forest managers and mushroom pickers is whether declines in fruiting with stand age would eventually render a site noncommercial for *C. formosus* harvests. Research under way on Vancouver Island suggests mushroom harvests could continue well past the anticipated rotation age of 70 years for these stands (T. Ehlers and R. Winder, pers. comm.). However, harvesting second-growth stands during the prime producing years of *C. formosus* could create an immediate conflict between timber and mushroom resources, whereas maintaining some immature stand age classes through time would be in the best interests of mushroom pickers. The mapping exercise demonstrated relatively extensive areas of potential mushroom habitat (21%), comparable in size to select areas with high concentrations of pine mushroom habitat in other parts of the province (Trowbridge 2005; Williams and Reid 2005), and so, perhaps, some land-use objectives could be agreed upon between industry and the public that would maintain a suitable proportion of productive sites. One advantage of the chanterelle habitat type is that individual stands are generally large enough (averaging 10 ha) to facilitate planning of harvesting schedules or leave areas. Commercial thinning of immature stands may also maintain chanterelle harvests while allowing some timber extraction (Pilz et al. 2006).

In conclusion, an inventory of mesic sites in the CWHwh1 approximated the potential commercial habitat for golden chanterelles, and immature second-growth stands within these sites were the best predictor of current commercial picking areas. To more fully understand the potential scope of the resource throughout the islands, further studies could be undertaken to examine the extent of *C. formosus* fruiting in other BEC variants (e.g., CWHwh2 at higher elevations) and stand age classes with the appropriate mesic habitat. General assessments of chanterelle habitat might be possible through existing terrestrial ecosystem maps (e.g., Lewis 2003) or, more approximately, through forest cover polygons, but we would recommend the interpretation and ground-truthing of ecosystems from air photographs for the most precise mapping of habitat. The preliminary assessment of *C. formosus* habitat around Skidegate Lake indicated that relatively large areas of commercial harvests are currently available, which should provide some flexibility in co-managing the land base for timber and mushroom resources.

Acknowledgements

We thank Enrique Sanchez, Chris Johnston, and Tom Johnson of BC Timber Sales for their interest in non-timber forest products of Haida Gwaii and support in undertaking the fieldwork. The mushroom expertise and time provided by Raymond Bishop and William Walker was greatly appreciated. Digitizing of the mapped habitat was provided by Jola Makowska and Sugu Thuraisamy of Infinity-Pacific Stewardship Group Ltd., and funds for the study were provided by BC Timber Sales.

Harvesting second-growth stands during the prime producing years of C. formosus *could create an immediate conflict between timber and mushroom resources, whereas maintaining some immature stand age classes through time would be in the best interests of mushroom pickers.*

References

? *TEST YOUR KNOWLEDGE*
Questions on page 114

Bergemann, S.E. and D.L. Largent. 2000. The site specific variables that correlate with the distribution of the Pacific golden chanterelle, *Cantharellus formosus*. Forest Ecology and Management 130:99–107.

British Columbia Ministry of Environment, Lands, and Parks and British Columbia Ministry of Forests. 1998. Field manual for describing terrestrial ecosystems. BC Ministry of Forests and BC Ministry of Environment, Lands, and Parks, Victoria, BC. Land Management Handbook No. 25.

British Columbia Ministry of Forests. 2000. Cruising manual. BC Ministry of Forests, Revenue Branch, Victoria, BC.

Dunham, S.M., T.E. O'Dell, and R. Molina. 2006. Forest stand age and the occurrence of chanterelle (*Cantharellus*) species in Oregon's central Cascade Mountains. Mycological Research 110:1433–1440.

Ehlers, T. 2003. Non-timber forest product mushrooms of northern Vancouver Island, British Columbia. Tysig Ecological Research, Winlaw, BC. Unpublished report.

Green, R.N. and K. Klinka. 1994. A field guide to site identification and interpretation for the Vancouver Forest Region. BC Ministry of Forests, Victoria, BC. Field Handbook No. 28.

Green, R.N., R.L. Trowbridge, and K. Klinka. 1993. Towards a taxonomic classification of humus forms. Forest Science Monographs 29:1–48.

Haida Gwaii/Queen Charlotte Islands Land Use Plan. 2006. Recommendations report. Integrated Land Management Bureau, Victoria, BC. Unpublished report. ***ilmbwww.gov.bc.ca/slrp/lrmp/nanaimo/qci/plan/landuseplandraft.htm*** (Accessed February 2009).

Howes, D.E. and E. Kenk. 1997. Terrain classification system for British Columbia (version 2). BC Ministry of Environment and BC Ministry of Crown Lands, Victoria, BC.

Kayahara, G.J. and A.F. Pearson. 1996. Relationships between site index, and soil moisture and nutrient regimes for western hemlock and Sitka spruce. BC Ministry of Forests, Research Branch, Victoria, BC. Working Paper No. 17.

Kranabetter, J.M., A. Banner, and A. de Groot. 2005a. An assessment of phosphorus limitations to soil nitrogen availability across forest ecosystems of north coastal British Columbia. Canadian Journal of Forest Research 35:530–540.

Kranabetter, J.M., J. Friesen, S. Gamiet, and P. Kroeger. 2005b. Ectomycorrhizal mushroom distribution by stand age in western hemlock–lodgepole pine forests of northwest British Columbia. Canadian Journal of Forest Research 35:1527–1539.

Kranabetter, J.M., R. Trowbridge, A. Macadam, D. McLennan, and J. Friesen. 2002. Ecological descriptions of pine mushroom (*Tricholoma magnivelare*) habitat and estimates of its extent in northwestern British Columbia. Forest Ecology and Management 158:249–261.

Lewis, T. 2003. The ecosystems of Block 6, Tree-Farm License 25, Queen Charlotte Islands, British Columbia, 2nd edition. Western Forest Products, Duncan, BC. Unpublished report.

Peterson, M.J., R. Outerbridge, and J. Dennis. 2000. Chanterelle productivity on burned and unburned regeneration sites in the vicinity of Skidegate Lake on Moresby Island. South Moresby Forest Replacement Account. Canadian Forest Service and BC Ministry of Forests, Victoria, BC. ***www.smfra.ca/fileadmin/smfra/home/Chanterelle.pdf*** (Accessed February 2009).

Pilz, D., L. Norvell, E. Danell, and R. Molina. 2003. Ecology and management of commercially harvested chanterelle mushrooms. US Department of Agriculture Forest Service, Portland, Oreg. General Technical Report PNW-576.

Pilz, D., R. Molina, and J. Mayo. 2006. Effects of thinning young forests on chanterelle mushroom production. Journal of Forestry 104:9–14.

Pojar, J., K. Klinka, and D.V. Meidinger. 1987. Biogeoclimatic ecosystem classification in British Columbia. Forest Ecology and Management 22:119–154.

Pojar, J. and A. Mackinnon. 1994. Plants of coastal British Columbia. BC Ministry of Forests, Victoria, BC. and Lone Pine Publishing, Edmonton, Alta.

Soil Classification Working Group. 1998. The Canadian system of soil classification. 3rd edition. Agriculture and Agri-Food Canada Publication No. 1646 (revised).

Tedder, S., D. Mitchell, and R. Farran. 2000. Seeing the forest beneath the trees: The social and economic potential of non-timber forest products and services in the Queen Charlotte Islands/Haida Gwaii. South Moresby Forest Replacement Account. BC Ministry of Forests, Research Branch, Victoria, BC. ***www.smfra.ca/fileadmin/smfra/home/ntfp.pdf*** (Accessed February 2009).

Trowbridge, R. 2005. High value pine mushroom habitat: Mapping methodology and results for the Cranberry Timber Supply Area. BC Ministry of Forests, Skeena-Stikine District, BC. Unpublished report.

Twieg, B.D., D.M. Durall, and S.W. Simard. 2007. Ectomycorrhizal fungal succession in mixed temperate forests. New Phytologist 176:437–447.

Williams, H. and H. Reid. 2005. Blackwater pine mushroom habitat mapping. BC Ministry of Forests, Squamish District, BC. Unpublished report.

ARTICLE RECEIVED: **February 8, 2008**
ARTICLE ACCEPTED: **December 7, 2008**

Research Report

Changes in riparian area structure, channel hydraulics, and sediment yield following loss of beaver dams

Kim C. Green[1] and Cherie J. Westbrook[2]

Abstract

Channel structure, riparian zone structure, and sediment transport capacity were investigated for Sandown Creek, a stream in the East Kootenay region of British Columbia where beaver dams were removed in the late 1980s to "improve" fish passage and flood conveyance. A series of historical aerial photographs taken over a 36-year period between 1968 and 2004 recorded the physical changes to a 3-km section of the stream valley following removal of 18 beaver dams. In the 16 years following beaver dam removal, channel pattern changed from a multi-thread to single-thread form. The riparian area structure also changed from 69% open areas and 9% beaver ponds to 90% closed vegetation. The change in channel structure in Sandown Creek resulted in an estimated 5-times increase in the mean flow velocity and an additional 648 m^3 of sediment available for transport. These findings provide the empirical data needed to verify long-standing assumptions about the ability of beaver ponds to effectively trap sediment and reduce bankfull flow velocity. The results of this study also underscore the speed and magnitude of alterations in the channel and riparian area structure in response to beaver loss in British Columbia's mountain valleys.

While the physical removal of beavers and beaver dams may be a practice of the past, wildland managers may still be inadvertently compromising the sustainability of beavers and associated wetlands in many areas of British Columbia by failing to adequately manage riparian areas to maintain beaver habitat.

KEYWORDS: *beaver dams, channel hydraulics, dam removal, flow velocity, mountain stream, riparian area structure, sediment yield, wetlands.*

Contact Information

1 PhD Candidate, Department of Forest Resource Management, University of British Columbia, 2424 Main Mall, Vancouver, BC V6T 1Z4 Email: apexgeo.kg@telus.net

2 Assistant Professor of Hydrology, Department of Geography and Centre for Hydrology, University of Saskatchewan, 117 Science Place, Saskatoon, SK S7N 5A5. Email: cherie.westbrook@usask.ca

Green, K.C. and C.J. Westbrook. 2009. Changes in riparian area structure, channel hydraulics, and sediment yield following loss of beaver dams. *BC Journal of Ecosystems and Management* 10(1):68–79.

Introduction

Within the ecology community, beaver (*Castor canadensis*) are widely known to have dramatic effects on the hydrology, geomorphology, and ecology of riverine systems. By building dams, beaver form upstream ponds that increase water storage in stream channels; decrease stream velocity; elevate the local water table; trap nutrients and sediments, which reduces downstream turbidity and improves water quality; increase riparian vegetation diversity; and create and maintain riparian wetlands (Naiman et al. 1988; Gurnell 1998; Butler and Malanson 2005; Rosell et al. 2005). Despite their critical role in ecosystems, few studies have actually quantitatively described the influence of beaver dams on streamflow, sediment yield, channel hydraulics, and riparian structure, particularly across the breadth of the beaver's geographic range. The lack of quantitative research on the importance of beaver dams in the creation and maintenance of wetlands in many parts of British Columbia makes the beaver vulnerable to direct and indirect impacts from forestry activities, cattle grazing, as well as other development activities that can compromise the sustainability of beavers and their habitat (Ott and Johnson 2000; BC Ministry of Environment, Lands, and Parks 2001).

The beaver population in North America was estimated to have been between 60 and 400 million prior to the arrival of European settlers (Naiman et al. 1986). Beaver habitat covered most of the continent ranging from northern Mexico to the Arctic and from the Pacific to Atlantic oceans (Jenkins and Busher 1979). Intense trapping and habitat destruction through draining of wetlands for settlements and agriculture resulted in a rapid decline of beaver to near extinction by the early 1900s (Naiman et al. 1986). Conservation efforts have allowed beaver to recover to about 10% of their original population size across most of their original range (Naiman et al. 1986).

In several regions of North America, such as British Columbia, beaver dams were routinely destroyed up until the late 1980s as they were believed to be a barrier to fish migration. Dam removal in Sandown Creek in the late 1980s provided an opportunity to examine the resulting changes to the fluvial landscape. The objective of this study was to assess long-term landscape alteration by beaver. Specifically, we determined the effects of beaver dam removal on: (1) riparian structure, (2) channel hydraulics, and (3) sediment yield in a British Columbia stream where beaver dams were removed to "improve" fish passage. We used GIS coupled with historical aerial photography and field surveys as a means of evaluating changes to landscape and stream channel structure over a 36-year period. Further, published empirical models were used in combination with field studies and GIS methods to estimate temporal changes in sediment yield.

Despite their critical role in ecosystems, few studies have actually quantitatively described the influence of beaver dams on streamflow, sediment yield, channel hydraulics, and riparian structure, particularly across the breadth of the beaver's geographic range.

Methods

Study area

The study was conducted along a 3-km reach of Sandown Creek, which drains a 72-km^2 area in the eastern Purcell Mountains directly west of the Rocky Mountain trench in southeastern British Columbia (Figure 1). Approximately 18 beaver dams were removed from this stream reach in the late 1980s in an effort to improve fish passage to Copper Lake. Currently, the stream reach has a bankfull width of 4–6 m, an average gradient of 0.01 m/m, and a riffle-pool morphology. The floodplain is 50–100 m wide and averages about 1.1 m in elevation above the channel bottom. Fine-textured glaciofluvial and glaciolacustrine sediment underlies the main valley of Sandown Creek from Copper Lake to the confluence with Skookumchuck Creek.

Sandown Creek drains an area with a semi-arid climate. November, December, and June tend to be the wettest months of the year. The long-term mean annual precipitation is 660 mm recorded at Environment Canada's Kimberley, BC station (No. 1154203), 40 km southwest of Sandown Creek. Over half of the total annual precipitation falls as snow between the months of November and March. Mean monthly temperatures range from a low of −8.6°C in January to a high of 17.4°C in July. Peak flows in Sandown Creek occur in response to snowmelt from May to late June and average 2.65 m^3/s based on long-term gauging in nearby Mather Creek.

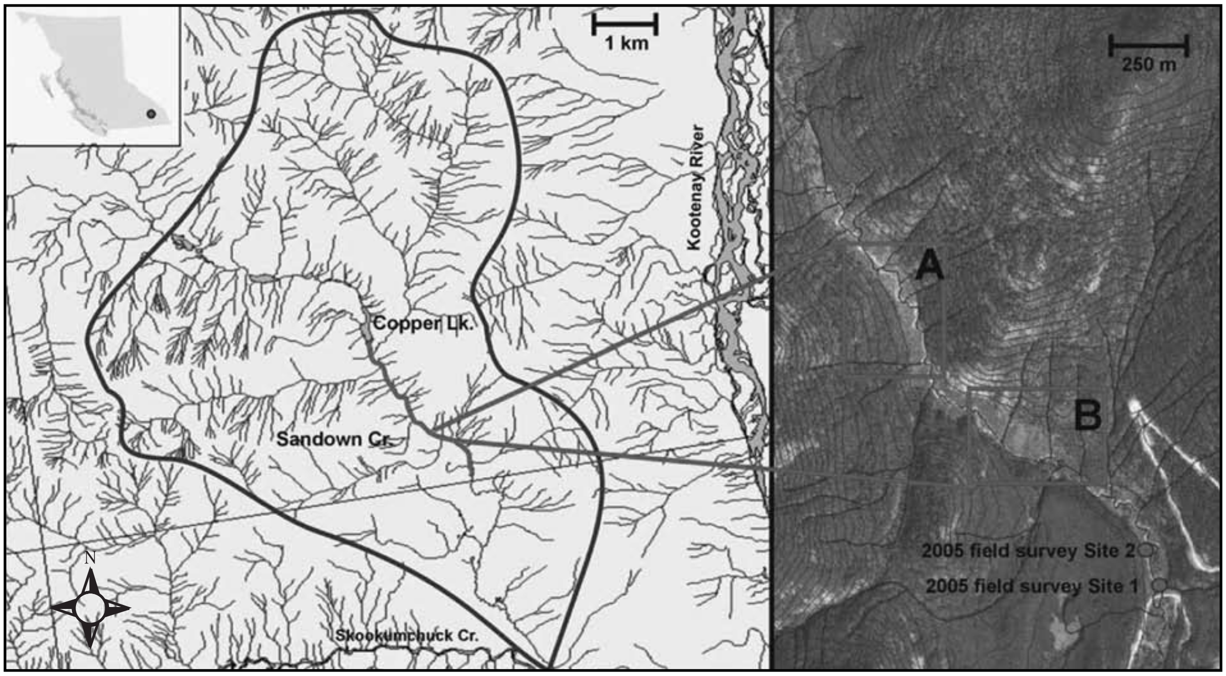


FIGURE 1. Location of Sandown Creek with the bold channel section showing the 3-km reach included in this study. The enlarged orthophoto shows the locations of study areas A and B and the 2005 field survey sites 1 and 2.
* See page 79 endnote re: colour version.

Riparian area structure

Two channel segments (Areas A and B in Figure 1), totalling 1 km of stream length and 13 ha of floodplain area, were selected for a detailed investigation of temporal and spatial changes in beaver pond sites and floodplain vegetation. Aerial photography was obtained for six different years spanning 1968–2004 (Figures 2 and 3). Three photographs covered the 20-year period before the dams were removed (1968, 1975, and 1988), and three photographs covered the 16 years following dam removal (1995, 1997, and 2004). For the analysis, five of the aerial photographs (1995 photo was excluded due to poor resolution) at nominal scales of between 1:15 000 and 1:20 000 were scanned and enlarged to a scale of 1:5000 so that individual shrubs, trees, and dams were clearly visible. Locations of beaver dams and the extent of each land cover type, including beaver pond, open vegetation (sedges and grasses), and closed vegetation (shrubs and trees), were delineated on each photograph by hand. A digital planimeter was used to determine the total area of each land cover type on each of the five photographs in both study areas.

Channel hydraulics

The change in mean velocity and cross-sectional stream power of the bankfull flow was estimated for a 500-m channel section in Area A by using channel surveys, air photo analysis, and Manning's equation to compare the hydraulic geometry of the channel with and without the dams. The historical air photographs provided a visual record of the change in channel form following removal of the beaver dams. Area A was chosen for this analysis because of the relative ease of measurements.

Bankfull flow or discharge (Q_b) in cubic metres per second is related to channel cross-sectional area (A) (m^2) and average velocity (v) (m/s) by:

$$Q_b = A \times v \quad [1]$$

Equation 1 is also equivalent to:

$$Q_b = w \times d \times v \quad [2]$$

where w is bankfull channel width (m), and d is average bankfull channel depth (m). The influence of the dams on channel hydraulic geometry can be determined by assuming that Q_b is equivalent with dams (Q_{bD}) and without dams (Q_{bND}). This is a reasonable assumption because, in the 1988 photo, the 3-km section of Sandown Creek below Copper Lake was occupied by beaver dams and accounted for an area of 0.35 km^2 or just less than 1% of the 45.6 km^2 total catchment area; in other words, an area too small to influence the flow regime of the catchment (Novitzki 1979, 1985). Therefore, if Q_{bD} is equivalent to Q_{bND} then:

$$w_D d_D v_D = w_{ND} d_{ND} v_{ND} \quad [3]$$

such that changes in the cross-sectional area of the bankfull channel will affect the stream mean velocity.

The effect of dam removal on stream mean velocity was estimated using Manning's equation. Manning's equation relates velocity (v) (m/s) to channel geometry (Henderson 1966):

$$v = \frac{R^{2/3} S^{1/2}}{n} = \frac{\left\{\frac{A}{P}\right\}^{2/3} S^{1/2}}{n} \quad [4]$$

where R is hydraulic radius (m), S is the surface slope of the water (m/m), and n is Manning's roughness coefficient, a dimensionless value that accounts for the roughness of the channel bed and banks, and ranges from 0.025 to over 0.15 in natural alluvial channels (Henderson 1966; Acrement and Schneider 1989). The hydraulic radius is also equal to the cross-sectional area, A, divided by the wetted perimeter ($P = w + 2d$).

Manning's n is estimated using the method outlined in Acrement and Schneider (1989) where total n is calculated in an additive manner such that:

$$n = (n_b + n_1 + n_2 + n_3 + n_4)m \quad [5]$$

where n_b = base n value; n_1 = addition for surface irregularities; n_2 = addition for variation in channel cross-section; n_3 = addition for obstructions; n_4 = addition for vegetation; and m = ratio for meandering.

Stream power (Ω) (W/m) is defined by Bagnold (1977) as the energy available in flowing water to do work such as transporting sediment and eroding channel boundaries. The effect of dam removal on stream power per unit length of channel is expressed as:

$$\Omega = \gamma QS \quad [6]$$

where γ is the specific weight of water (N/m^3), Q is bankfull flow or discharge (m^3/s), and S is the surface slope of the stream water (m/m). The influence of the beaver dam removal on cross-sectional stream power (ω) (W/m^2) was calculated as:

$$\omega = \gamma v d S \quad [7]$$

where v is stream velocity and d is depth.

The mean cross-sectional area of the bankfull channel with the beaver dams was calculated from the mean width of all the beaver dams in Area A multiplied by a mean depth of 0.6 m, which is consistent with the mean height of beaver dams in a similar physiographic setting in Glacier National Park, Montana (Meentemeyer and Butler 1999). Dam widths were measured by hand on the 1988 air photograph enlarged to a scale of 1:2000. While the beaver dams were intact, stream velocity and cross-sectional stream power were determined using Equations 4 and 6, respectively, with mean surface water slope along the 500-m channel length calculated as 0.0028 m/m, assuming an average valley slope of 0.016 m/m and a dam height of 0.6 m. Valley slope was determined using GIS and a 25-m resolution digital elevation model (DEM) for the 3-km reach below Copper Lake.

Following removal of the dams, the mean cross-sectional area and wetted perimeter of the bankfull channel were determined using data from 2005 field surveys at Sites 1 and 2 (Figure 1; Table 1).

TABLE 1. Channel structure based on the 2005 survey data from field sites 1 and 2.

	Station no.		
	1	**2**	**Mean**
Stream gradient[a] (%)	< 2	< 2	
Bankfull width (m)	5.2	4.5	4.9
Bankfull depth (m)	0.28	0.35	0.33
D_{50}[b] (mm)	10	15	12.5
D_{90} (mm)	35	30	32.5

[a] Channel gradient was measured with a hand-held clinometer with an accuracy of ± 2%. Gradients less than 2% (0.02 m/m) are reported as < 2.

[b] Particle-size distribution was estimated using the Wolman pebble count method traversing from bank top to thalweg. D50 means that 50% of particles were smaller than or equal to 10 and 15 mm at stations 1 and 2, respectively.

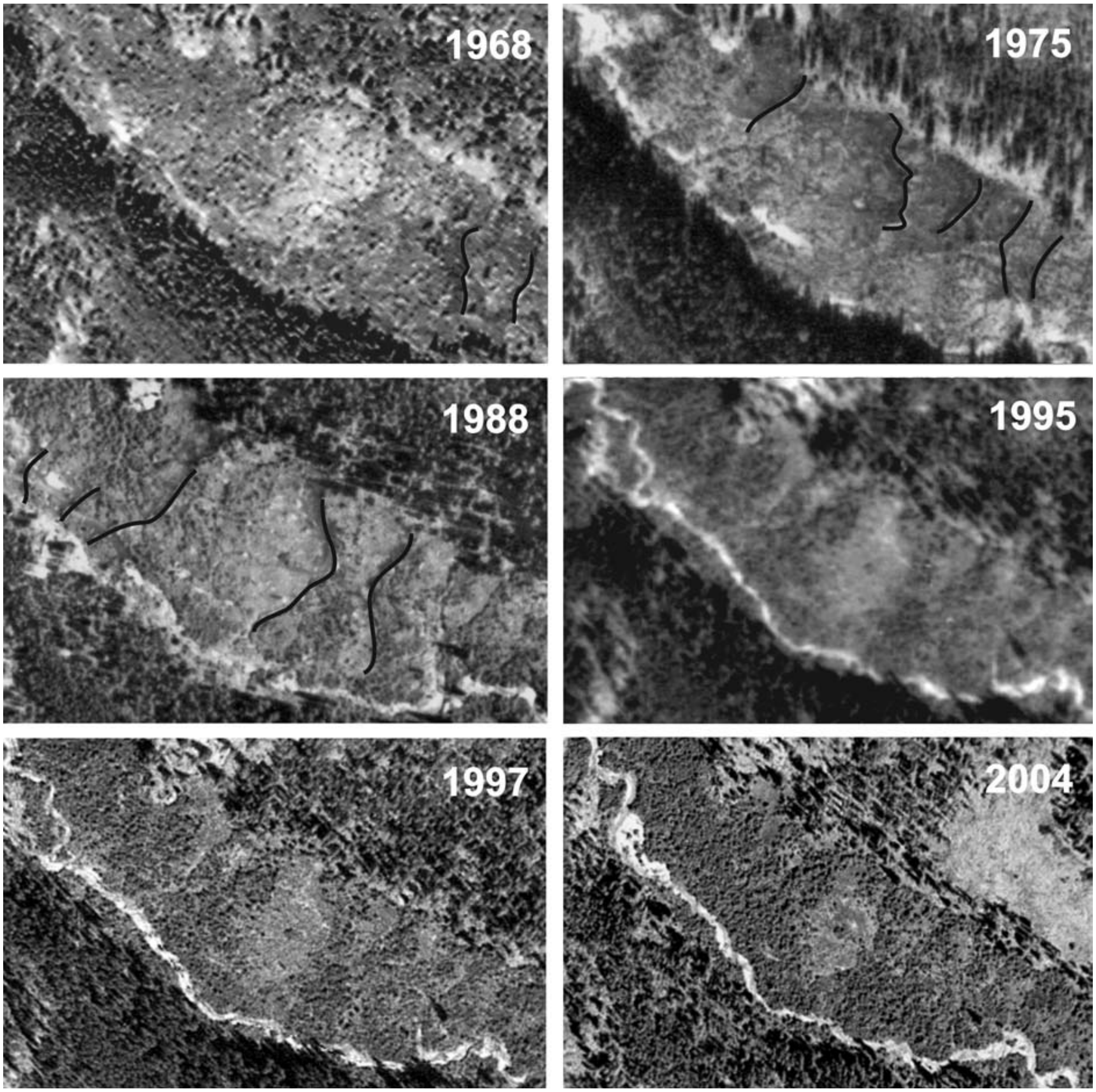


FIGURE 2. A series of six air photographs from Area B (scale approximately 1:10 000) spanning 36 years and documenting the physical changes to the channel and floodplain following removal of the beaver dams in the late 1980s. Black lines highlight beaver dams that contain ponds. The greatest change in channel and floodplain structure occured between 1988 and 1995. Higher-resolution air photos were used in the actual analysis. * See page 79 endnote re: colour version.

For Sandown Creek, which has a width that is much greater than its depth, *R* is approximately equal to stream depth, *d*. Bankfull width was measured where well-defined, vegetated banks confined the channel. Bankfull depth was measured at the thalweg, which was the deepest point across the channel cross-section. For average velocity and cross-sectional stream power calculations, the mean surface slope was equivalent to the average valley slope of 0.016 m/m.

Sediment yield

Two methods were used to estimate the total amount of sediment stored behind the 18 dams that were present in 1988 along the 3-km channel section below

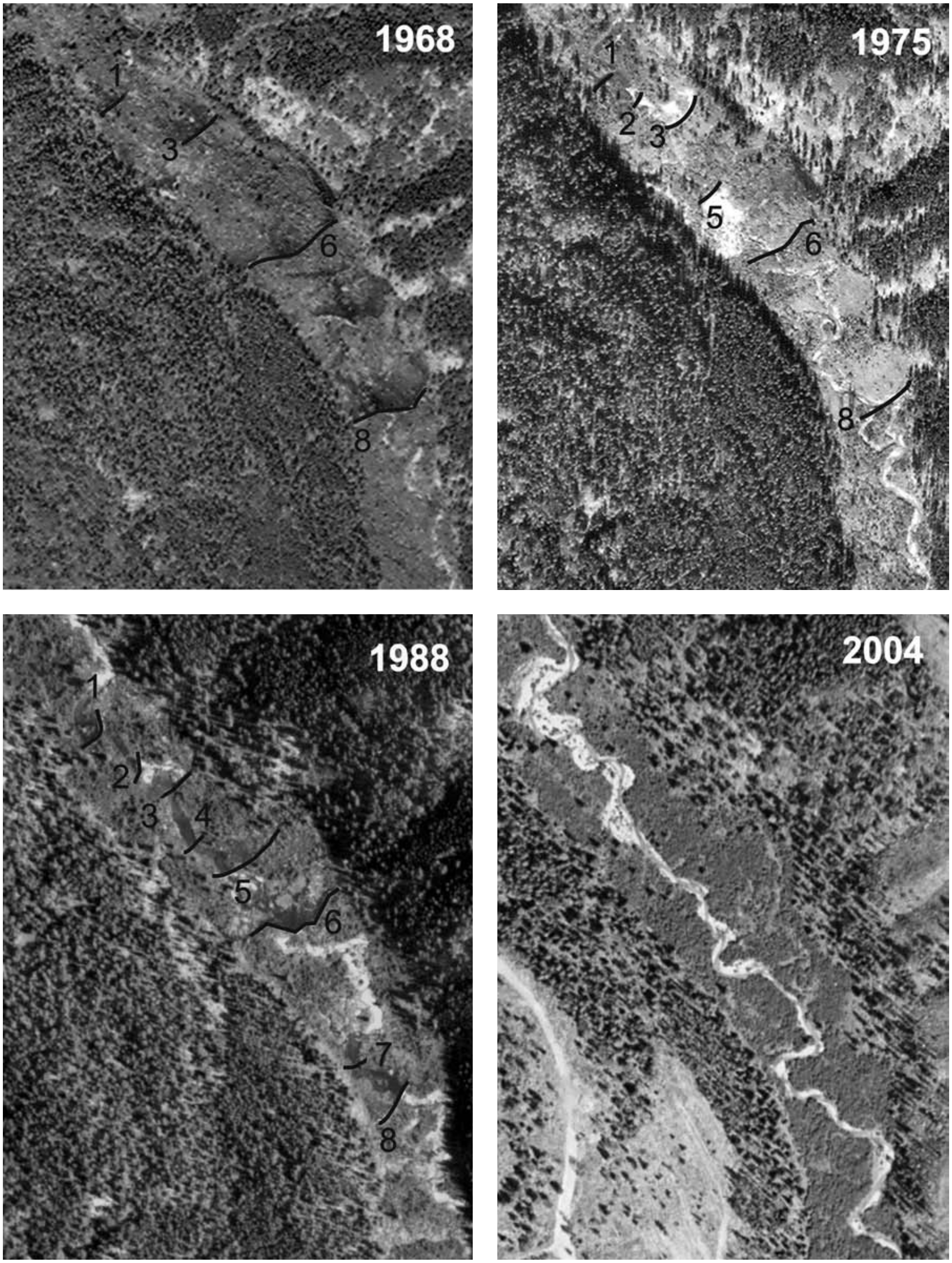


FIGURE 3. Historical air photographs for Area A (scale approximately 1:10 000) indicate that dams 1, 3, 6, and 8 were present from 1968 to 1988. Dams 2 and 5 were evident in the 1975 photo. Dams 4 and 7 were only evident in the 1988 photo. None of the dams in the 1975 photo contained water, and dams 2 and 5 appeared to have released sediment. The 1997 air photograph was included in the riparian structure analysis, but is not shown in this figure.
* See page 79 endnote re: colour version.

Copper Lake. Estimates were based on the eight beaver dams in the 500-m channel section of Area A. For the first method, sedimentation rate was set at 3.7 cm per year, which is consistent with sedimentation rates for beaver ponds from similar physiographic settings (Butler and Malanson 1995). In addition, historical air photographs and peak flow data from the nearby long-term hydrometric station at Mather Creek were used to determine the age and disturbance history of the dams. Mather Creek is 20 km south of Sandown Creek and has a similar basin geology, topography, and climate.

For the second method, the total volume of sediment stored in the 500-m channel of Area A was estimated by applying the regression equation developed for Glacier National Park, Montana, a site with a similar physiographic setting to Sandown Creek. This equation relates total volume of sediment (S_d) to pond area (A_p) for an estimation of cubic metres of sediment per pond (Butler and Malanson 1995):

$$S_d = -84.082 + 0.62502A_p \qquad [8]$$

The pond areas associated with the eight beaver dams in Area A were measured with a digital planimeter on the 1988 air photograph enlarged to 1:2000.

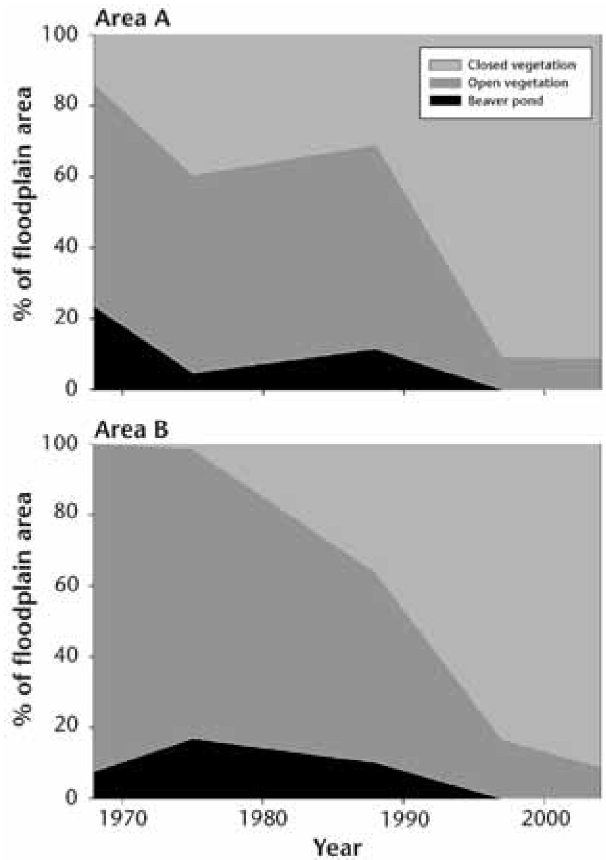


FIGURE 4. Changes in riparian area structure in Areas A and B over a 36-year period. Beaver dams were removed in the late 1980s.

Results

Riparian area structure

Following beaver dam removal, the floodplain of Sandown Creek below Copper Lake was converted from a wide wetland area with ponds, open vegetation, and a multi-thread channel pattern to a single-thread channel with dense shrub cover. Historical air photographs from Area B indicated this conversion occurred over a very short time period between 1988 and 1995 (Figure 2). The floodplain in Areas A and B was occupied predominantely by open vegetation (69%) and beaver ponds (9%) during the 20 years preceding dam removal (Figure 4). In the 16 years following removal of the dams, the open areas were replaced by dense vegetation consisting of willows and coniferous saplings. No beaver ponds were present in the 1997 or 2004 air photographs, and less than 10% of the floodplain riparian area consisted of open vegetation areas of sedges and grasses (Figure 4).

Channel hydraulic geometry

Several methods were used to determine the influence of the beaver dams on channel hydraulic geometry (Table 3). Obvious changes in channel form, including a decrease in average channel width and a loss of beaver ponds, were apparent through visual inspection of the historical air photographs from Areas A and B (Figures 2 and 3). A comparison of the hydraulic geometry of the channel in Area A with and without the beaver dams indicated that dam removal decreased average cross-sectional area of bankfull flows by over 12 times (Table 2). The loss of beaver dams also resulted in a substantial decrease in Manning's roughness coefficient from 0.176 to 0.053. The combined effect of reduced cross-sectional area and reduced roughness coefficient translated into a 5-times increase in mean bankfull stream velocity and a 12-times increase in cross-sectional stream power. In other words, relative to current channel conditions, beaver dams likely reduced the mean velocity of bankfull discharge by approximately 81% and reduced average cross-sectional stream power by up to 92%.

TABLE 2. Influence of beaver dams on Sandown Creek channel hydraulics in Area A.

Channel hydraulic parameter	Dams present	Dams absent
Bankfull cross sectional area (m^2)	20.4	1.7
Manning's roughness coefficient, n	0.176	0.053
Stream velocity at bankfull (m/s)	0.221	1.14
Stream power (W/m^2)	0.43	5.46

Sediment yield

The eight beaver dams present in the 1988 aerial photograph of Area A ranged from 9 to 81 m wide and 23 to 53 m long (Table 3). The dams had a cumulative pond length of 320 m and an estimated mean surface water gradient of 0.0028 m/m. The historical air photographs showed that dams 1, 3, 6, and 8 were present from 1968 to 1988 (Figure 3). Dams 2 and 5 were evident on the 1975 air photograph, whereas dams 4 and 7 were only present on the 1988 air photograph. None of the dams contained water in the 1975 air photograph.

The Log Pearson III flood frequency analysis of annual peak flows for nearby Mather Creek (Water Survey of Canada Station 08NG076) indicated that a flood with a return interval of 8 years occurred in June 1974. Detailed analysis of the historical air photographs determined that only some of the dams in Sandown Creek failed in response to the 1974 flood. All the dams in Area A emptied of water, but only dams 2 and 5, which were the most recently constructed, appeared to have failed and released sediment. None of the peak flows recorded on Mather Creek between 1975 and 1988 had a return interval greater than 8 years. Based on the air photographs and flood history, dams 1, 3, 6, and 8 were approximately 20 years old; dams 2 and 5 were roughly 12 years old, assuming they had been repaired within 2 years of the 1974 flood; and dams 4 and 7 were estimated to be 2 years old (Table 3).

Using an average sedimentation rate of 3.7 cm per year (Butler and Malanson 1995), 406 m^3 of sediment was estimated to be stored behind the eight beaver dams in Area A in 1988 (Table 3). However, if all the dams present in 1975 released their sediment during the 1974 flood, then the total volume of sediment stored by the dams in 1988 would be reduced to 283 m^3 or 35 m^3 per dam averaged over eight dams. If the pond area regression method (Equation 8) was used to compute the volume of sediment, a total of 290 m^3 (36 m^3 per pond) was available for transport in 1988 along the 500-m section of Sandown Creek in Area A.

Eighteen beaver ponds were visible in the 1988 air photographs along the 3-km stretch of Sandown Creek below Copper Lake. Using a mean sediment volume of 36 m^3 per pond, the total volume of sediment available for transport was roughly 648 m^3 or approximately 22 cm of sediment if distributed evenly along the 3 km length of channel.

Discussion

The aerial photograph analysis showed that beaver are important agents of stream ecosystem change as they affect riparian structure and channel hydraulic properties. Removal of beaver dams in Sandown Creek has resulted in a change in riparian vegetation from a variety of vegetative cover types to low riparian complexity comprised almost exclusively of dense shrubs and conifers. Dam removal also changed channel structure from multi-thread channels and ponds with high complexity to a meandering single-thread channel with no ponds. These changes resulted in a 5-times increase in stream cross-sectional velocity and a 12-times increase in stream power. The decrease in stream power associated with the presence of beaver dams was estimated to have resulted in the accumulation of over 600 m^3 of sediment or roughly 22 cm of sediment along a 3-km section of Sandown Creek.

Beaver may influence 20–40% of the total length of North American headwater streams (Naiman and Melillo 1984), and their dams are thought to be important structural elements within the channel because they create steps in the elevational profile (Gurnell 1998). The pools created upstream of dams cause stream water to flow via new pathways around dams and across forested riparian areas, which increases the amount of open canopy (Hammerson 1994). Since beaver dams contribute to the formation of multi-thread channel patterns (Woo and Waddington 1990; Westbrook et al. 2006) and cause channel avulsions (Cooper et al. 2005), one would expect that removal of beaver dams would cause the channel pattern to revert to a single-thread and allow the riparian forest to grow. Indeed, observations at Sandown Creek provided support for this hypothesis. Within 16 years, Sandown Creek changed from a wide multi-thread

TABLE 3. Estimates of available sediment stored in beaver ponds on a 500-m reach of Sandown Creek in Area A.

	Dam no.									
	1	2	3	4	5	6	7	8	Total (to nearest m^3)	Avg. m^3 per pond
Dam age (yrs)	20	12	20	2	12	20	2	20		
Dam width (m)	30	12	28	9	53	81	9	48		
Pond length (m)	44	48	23	53	28	51	25	48		
Pond area (m^2)	99	405	388	502	952	1482	291	1109		
DEPOSITION RATE METHOD										
Sediment depth (m)[a]	0.74	0.44	0.74	0.07	0.44	0.74	0.07	0.74		
Sediment volume (m^3)	81.4	53.3	42.5	9.8	31.1	94.4	4.6	88.8	406	51
REGRESSION METHOD										
Sediment volume (m^3)	478	169	158	230	511	842	98	609		
Sediment depth (m)	0.53	0.42	0.41	0.46	0.54	0.57	0.34	0.55		
Channel length (m)	33	26	26	29	34	36	21	34		
Sediment volume in channel (m^3)	44.2	27.2	26.2	32.7	45	50.5	17.7	47.1	291	36

[a] Sediment accumulated in beaver pond during dam life.

channel to a single-thread channel following beaver dam removal. Also, shrubs invaded the riparian area following dam removal, changing the vegetation cover from predominantly open to predominantly closed. However, the observations from Sandown Creek contrasted with those reported in the literature where most researchers found that beaver-affected areas persist as grass- and sedge-dominated open areas for decades to centuries (Ruedemann and Schoonmaker 1938; Ives 1942; Johnston and Naiman 1987). The succession sequence is frequently stalled because shrubs and trees seldom invade riparian areas affected by beaver activities (McMaster and McMaster 2000). Potential causes for this may be higher shrub production when beaver are present (Neff 1957; Baker and Hill 2003), or a lack of ectomycorrhizal fungi on conifer species due to the fatal effects of prolonged flooding on fungi survival (Terwilliger and Pastor 1999). The processes driving rapid shrub and tree invasion in Sandown Creek require further investigation, but may be associated with post-dam groundwater dynamics in the relatively high-gradient mountain valleys of western North America.

Several studies have determined that the primary influence of beaver dams during peak flow periods is reduced flow velocity (Novitzki 1978, 1985; Johnston and Naiman 1987; Woo and Waddington 1990; Devito and Dillon 1993; Hillman 1998; Meentemeyer and Butler 1999). Similar to jams of large woody debris, beaver dams typically form a series of step-pools along the length of a stream (Naiman et al. 1988; Butler and Malanson 1995). Observations of the hydraulic influence of large woody debris jams demonstrated that resistance associated with jams decreases with increasing flow depth as the jams become submerged by rising peak flows (Shields and Gipple 1995). However, well-maintained beaver dams generally extend up to or beyond the height of the adjacent floodplain, and discharge peak flows uniformly over the top of the dam so that the effect of beaver dams as roughness elements is maintained during peak flow periods (Woo and Waddington 1990; Gipple 1995).

Beaver dams have been reported to reduce flow velocity by up to 100% during low-flow periods, depending on their age, state of repair, and number in sequence along the stream channel (Burns and McDonnell 1998; Meentemeyer and Butler 1999). The calculations from Sandown Creek suggested that functioning beaver dams likely reduced the mean velocity of bankfull discharge by approximately 81%. Increases in bankfull width at the dams enable greater discharges to be transported in the channel before the floodwaters overtop the stream banks. This means that the removal of beaver dams in Sandown Creek either severed or greatly reduced the hydrologic connection between the stream and the riparian zone. Hydrological consequences of this disconnection include lowered water tables and decreased soil moisture in the riparian zone (Cooke and Reeves 1976). Ecological changes include a vegetation shift from riparian species to more xeric species and a decrease in the width of the riparian zone (Bryan 1928; Hendrickson and Minckley 1984).

Beaver dams have a substantial impact on sediment transport rates in a watershed, and act as long-term storage areas for both suspended and bedload sediment. Reported rates of sediment deposition behind beaver dams range from 2.5 cm per year in low relief areas of the Canadian Shield to upwards of 27.9 cm per year in the mountainous areas of Glacier National Park, Montana (Devito and Dillon 1993; Butler and Malanson 1995). Although some study models suggest gradual pond infilling and the eventual formation of meadows, a more likely process is periodic beaver dam failure associated with basin flooding and at least partial release of stored sediment, especially in higher-energy mountainous environments (Butler and Malanson 2005). Our analyses for Sandown Creek revealed that some of the beaver dams on a 1-km reach of Sandown Creek failed in response to a flood that had an 8-year return interval. However, only two dams appeared to release substantial volumes of sediment. Our observations also suggested that sediment transport and storage dynamics in streams with beaver dams were complex. During large-magnitude floods, beaver dam failure can result in extensive disturbance to channel banks and portions of the adjacent riparian area, and can cause scour and/or aggradation below the washed-out dam. Smaller magnitude floods that cause limited dam failures likely result in local channel aggradation and degradation as sediment is redistributed through the channel network (Kondolf et al. 1991; Hillman 1998). Where dams have failed, stream base levels drop and the channel creates an incision in the fine sediments stored behind the dams (Fouty 2003).

Management implications

Beaver dams are important hydrogeomorphic structures that can influence channel and floodplain structure, channel hydraulics, and sediment budgets of watersheds. The disappearance of beavers and beaver dams from Sandown Creek in southeastern British Columbia has resulted in substantial increases in flow velocity, increased sediment yield, and decreased wetland area, which, in turn, has caused channel entrenchment, bank erosion, and increased rates of sediment transport along the lower reaches of Sandown Creek.

Although the importance of beaver activities on the fluvial environment has been widely recognized in the ecology literature, beavers and their dams were still being destroyed in British Columbia during the late 1980s to improve flood conveyance and fish passage. Numerous studies from North America and Europe have since established the beneficial function of beaver ponds for many aquatic species including fish (Snodgrass and Meffe 1998; Schlosser and Kallemeyn 2000; Pollock et al. 2004). However, many fluvial systems across British Columbia remain in a degraded state due to the removal of beavers and their dams. While riparian management zones are a legislated requirement along fish-bearing streams (BC Ministry of Forests and Range 1995), there are no guidance documents or legislation available to British Columbians that recognize the importance of managing or enhancing beaver habitat to preserve wetlands in many parts of the province. This study was motivated by the desire to improve our understanding of the importance of beavers in a healthy, functioning ecosystem.

Acknowledgements

Tembec, Inc. is graciously acknowledged for their support during the initial field assessment of Sandown Creek. Bruce Pope, RPF, of Tembec is also thanked for his assistance in filling in some of the data gaps for this study. The detailed review and comments provided by one anonymous reviewer were greatly appreciated. This project was completed as part of the course requirements for Geography 503, University of British Columbia, and, for this reason, we thank Marwan Hassan, PhD, and Rob Millar, PhD, PEng, who provided the incentive and the inspiration for this project. Finally, thanks to the beavers that once inhabited Sandown Creek and whose past engineering efforts remain a legacy to teach us the importance of responsible environmental stewardship.

References

? TEST YOUR KNOWLEDGE
Questions on page 114

Acrement, G.J. and V.R. Schneider. 1989. Guide for selection of Manning's roughness coefficients for natural channels and flood plains. US Geological Survey, Washington, DC. Water-Resource Paper 2339.

Bagnold, R.A. 1977. Bed load transport by natural rivers. Water Resources Research 13:303–312.

Baker, B.W. and E.P. Hill. 2003. Beaver (*Castor canadensis*). *In* Wild mammals of North America: Biology, management, and conservation, 2nd edition. G.A. Feldhamer, B.C. Thompson, and J.A. Chapman (editors). The Johns Hopkins University Press, Baltimore, Md.

British Columbia Ministry of Environment, Lands and Parks. 2001. Beaver management guidelines, draft version. BC Ministry of Environment, Lands and Parks, Vancouver Island Region, BC. ***wlapwww.gov.bc.ca/vir/pa/Beaver-Guide.pdf***

British Columbia Ministry of Forests. 1995. Riparian management area guidebook. BC Ministry of Forests, Forest Practices Branch, Victoria, BC.

Bryan, J. 1928. Change in plant associations by change in ground water levels. Ecology 9:474–478.

Burns, D.A. and J.J. McDonnell. 1998. Effects of a beaver pond on runoff processes: Comparison of two headwater catchments. Journal of Hydrology 205:248–264.

Butler, D.R. and G.P. Malanson. 1995. Sedimentation rates and patterns in beaver ponds in a mountain environment. Geomorphology 13:255–269.

__________. 2005. The geomorphic influences of beaver dams and failures of beaver dams. Geomorphology 71:48–60.

Cooke, R.U. and R.W. Reeves. 1976. Arroyos and environmental change in the American Southwest. Oxford Clarendon Press, Gloucestershire, UK.

Cooper, D.J., J. Dickens, N. Thompson Hobbs, L. Christensen, and L. Landrum. 2005. Hydrologic, geomorphic and climatic processes controlling willow establishment in a montane ecosystem. Hydrological Processes 20:1845–1864.

Devito, K.J. and P.J. Dillon. 1993. Importance of runoff and winter anoxia to the P and N dynamics of a beaver pond. Canadian Journal of Fisheries and Aquatic Science 50:2222–2233.

Fouty, S.C. 2003. Current and historic stream channel response to changes in cattle and elk grazing pressure and beaver activity. PhD thesis. University of Oregon, Eugene, Oreg.

Gipple, C.J. 1995. Environmental hydraulics of large wood debris in streams and rivers. Journal of Environmental Engineering 121:388–395.

Gurnell, A.M. 1998. The hydrogeomorphological effects of beaver dam-building activity. Progress in Physical Geography 22:167–189.

Hammerson, G.A. 1994. Beaver (*Castor canadensis*): Ecosystem alterations, management, and monitoring. Natural Areas Journal 14:44–57.

Henderson, F.M. 1966. Open channel flow. MacMillan Publishing Co., New York, NY.

Hendrickson, D.A. and W.L. Minckley. 1984. Cienegas: Vanishing climax communities of the American Southwest. Desert Plants 6:131–175.

Hillman, G.R. 1998. Flood wave attenuation by a wetland following a beaver dam failure on a second order boreal stream. Wetlands 18:21–34.

Ives, R.J. 1942. The beaver-meadow complex. Journal of Geomorphology 5:191–203.

Jenkins, S.H. and P.E. Busher. 1979. *Castor canadensis*. Mammalian Species 120:1–8.

Johnston, C.A. and R.J. Naiman. 1987. Boundary dynamics at the aquatic terrestrial interface: The influence of beaver and geomorphology. Landscape Ecology 1:47–57.

Kondolf, G.M., G.F. Cada, M.J. Sale, and T. Felando. 1991. Distribution and stability of potential salmonid spawning gravels in steep boulder-bed streams of the western Sierra Nevada. Transactions of the American Fisheries Society 120:177–186.

McMaster, R.T. and N.D. McMaster. 2000. Vascular flora of beaver wetlands in western Massachusetts. Rhodora 102:175–197.

Meentemeyer, R.K. and D.R. Butler. 1999. Hydrogeomorphic effects of beaver dams in Glacier National Park, Montana. Physical Geography 20:436–446.

Naiman, R.J. and J.M. Melillo. 1984. Nitrogen budget of a subarctic stream altered by beaver (*Castor canadensis*). Oecologia 62:150–155.

Naiman, R.J., J. Melillo, and J. Hobbie. 1986. Ecosystem alteration of boreal forest streams by beaver (*Castor canadensis*). Ecology 67:1254–1269.

Naiman, R.J., C.A. Johnston, and J.C. Kelly. 1988. Alteration of North American streams by beaver. Bioscience 38:753–762.

Neff, D.J. 1957. Ecological effects of beaver habitat abandonment in the Colorado Rockies. Journal of Wildlife Management 21:80–84.

Novitzki, R.P. 1979. Hydrologic characteristics of Wisconsin's wetlands and their influence on floods, stream flow and sediment. *In* Wetland functions and values: The state of our understanding. P.E. Greeson, J.R. Clark, and J.E. Clark (editors). American Water Resources Association, Minneapolis, Minn.

Novitzki, R.P. 1985. The effects of lakes and wetlands on flood flows and base flows in selected northern and eastern States. *In* Proceedings of the Conference on Wetlands of the Chesapeake. Environmental Law Institute, Easton, Md.

Ott, G.D. and D.W. Johnson. 2000. Beaver influence on fisheries habitat: Livestock interactions. A research review paper. Twisp, Wash. Unpublished report. ***www.okanogan1.com/ecology/beaver/index.htm***

Pollock, M.M., G.R. Pess, T.J. Beechie, and D.R. Montgomery. 2004. The importance of beaver ponds to Coho salmon production in the Stillaguamish River basin, Washington, USA. North American Journal of Fisheries Management 24:749–760.

Rosell, F., O. Bozser, P. Collen, and H. Parker. 2005. Ecological impact of beavers *Castor fiber* and *Castor canadensis* and their ability to modify ecosystems. Mammal Review 35:248–276.

Ruedemann, R. and W.J. Schoonmaker. 1938. Beaver-dams as geologic agents. Science 88:523–525.

Schlosser, I.J. and L.W. Kallemeyn. 2000. Spatial variation in fish assemblages across a beaver influenced successional landscape. Ecology 81:1371–1382.

Shields, F.D. and C.J. Gipple. 1995. Prediction of effects of woody debris removal on flow resistance. Journal of Hydraulic Engineering 121:341–354.

Snodgrass, J.W. and G.K. Meffe. 1998. The influence of beavers on stream fish assemblages: Effects of pond age and watershed position. Ecology 79:928–942.

Terwilliger, J. and J. Pastor. 1999. Small mammals, ectomycorrhizae, and conifer succession in beaver meadows. OIKOS 85:83–94.

Westbrook, C. J., D. J. Cooper, and B.W. Baker. 2006. Beaver dams and overbank floods influence groundwater–surface water interactions of a Rocky Mountain riparian area. Water Resources Research 42:W06404, doi:10.1029/2005WR004560.

Woo, M.K. and J.M. Waddington. 1990. Effects of beaver dams on subarctic wetland hydrology. Arctic 43:223–230.

ARTICLE RECEIVED: **April 23, 2007**
ARTICLE ACCEPTED: **December 23, 2008**

* Figures 1, 2, and 3 are available in colour in the online version of this article at: ***www.forrex.org/publications/jem/ISS50/vol10_no1_art7.pdf***

Research Report

Using the low-level aerial survey method to identify Marbled Murrelet nesting habitat

F. Louise Waterhouse[1], Alan E. Burger[2], David B. Lank[3], Peter K. Ott[4], Elsie A. Krebs[5], and Nadine Parker[6]

Abstract

Identifying and managing nesting habitat for the threatened Marbled Murrelet (*Brachyramphus marmoratus*) is difficult because it nests secretively, high in the canopies of large, old conifers of the Pacific Northwest. In British Columbia, low-level surveying from a helicopter is now a recommended standard method of assessing forested landscapes for key microhabitat features—such as availability of potential platforms and developed moss pads for nests, foliage cover above the nest, and accessibility—that are not distinguishable on air photos, satellite images, or forest cover maps. Using a sample of 111 nest sites and 139 random sites within forests greater than 140 years old and distributed across three study areas in south coastal British Columbia, we confirmed the effectiveness of the aerial survey method for classifying overall habitat quality of murrelet nesting habitat. The minimum map units were 3-ha patches. Overall, 40% of the 111 nest sites were in patches classed as Very High, 36% were in High, 15% were in Moderate, 6% were in Low, and 3% were in Very Low. Our ranking of habitat quality was most strongly influenced by estimates of platform availability and moss development. Using an information-theoretic approach, we identified that the Resource Selection Function scores of nest patches improved as elevation decreased, slope grade increased, and the proportion of emergent and canopy trees with mossy pads increased. We also confirmed that study area location affected the strength of model application. Our findings support the potential utility of the low-level aerial survey method for identifying or confirming Marbled Murrelet nesting habitat for land-management purposes.

KEYWORDS: *aerial survey,* Brachyramphus marmoratus*, classification, habitat quality, Marbled Murrelet, nesting habitat assessment, survey methods.*

Contact Information

1 Research Wildlife Ecologist, British Columbia Ministry of Forests and Range, Coast Forest Region, 2100 Labieux Road, Nanaimo, BC V9T 6E9. Email: Louise.Waterhouse@gov.bc.ca

2 Research Associate, Department of Biology, University of Victoria, Victoria, BC V8W 3N5 Email: aburger@uvic.ca

3 Centre for Wildlife Ecology, Simon Fraser University, 8888 University Drive, Burnaby, BC V5A 1S6. Email: dlank@sfu.ca

4 Strategic Analysis Group, Research Branch, British Columbia Ministry of Forests and Range, 1st Floor, 722 Johnson Street, Victoria, BC V8W 1N1. Email: Peter.Ott@gov.bc.ca

5 Centre for Wildlife Ecology, Simon Fraser University, 8888 University Drive, Burnaby, BC V5A 1S6, and Canadian Wildlife Service, Environment Canada, 5421 Robertson Road, Delta, BC V4K 3N2. Email: Elsie.Krebs@ec.gc.ca

6 30 23rd Avenue East, Vancouver, BC V5V 1W9. Email: nadineparker@mac.com

JEM — Volume 10, Number 1

Waterhouse, F.L., A.E. Burger, D.B. Lank, P.K. Ott, E.A. Krebs, and N. Parker. 2009. Using the low-level aerial survey method to identify Marbled Murrelet nesting habitat. *BC Journal of Ecosystems and Management* 10(1):80–96.

Introduction

The Marbled Murrelet (*Brachyramphus marmoratus*) is a small seabird (Family *Alcidae*) found in nearshore waters of the Pacific Northwest. Throughout most of their range, murrelets typically nest on thick mossy pads that have developed on large branches of older trees (Hamer and Nelson 1995; Nelson 1997; Manley 1999; Nelson and Wilson 2002). In British Columbia, forests less than 140 years old support few nesting murrelets, because these forests lack suitable canopy structures for nests. Most nest sites are found in forests greater than 250 years old (Burger 2002; Waterhouse et al. 2004). The declining areas of coastal old-growth forest in British Columbia has led to the listing of Marbled Murrelets as Threatened by the Committee on the Status of Endangered Wildlife in Canada (2000) and to efforts to manage their nesting habitat (CMMRT 2003).

Effective habitat management that is compatible with other forest resource use requires reliable mapping of the forest habitat in which murrelets are most likely to nest (British Columbia Ministry of Water, Land and Air Protection 2004). Studies at nest sites indicate that suitable nesting habitat generally includes: large, old trees; suitable platforms for nests on limbs or deformities within the canopy; some degree of foliage cover over the nest; and canopy gaps that allow flying murrelets to access nest sites (Nelson 1997; Burger 2002; CMMRT 2003). Not all large, old trees provide the necessary canopy structure that allows nesting. Consequently, habitat suitability mapping cannot rely solely on stand age and tree size as shown in forest cover mapping or air photo interpretation. Furthermore, a key requirement, potential nest platforms (defined as limbs or deformities > 15 cm in diameter, including epiphyte cover) are not visible in air photos and are not included in forest cover or other available Geographic Information System (GIS) resources (e.g., CMMRT 2003; Donaldson 2004; Waterhouse et al. 2008). Established methods used to assess canopy platforms involve ground-based observers (e.g., Manley 1999; Rodway and Regehr 2002; Burger and Bahn 2004), but these methods are both labour-intensive and biased by site accessibility (Bradley 2002; Bradley et al. 2004). Therefore, low-level aerial surveys using helicopters provide an alternative method for assessing forest canopy structures and for efficiently classifying and mapping potential murrelet habitat-nesting areas (Burger et al. 2004).

Our study tested the application of the low-level survey method in two regions of southern British Columbia, the Sunshine Coast and the west coast of Vancouver Island, and used nest sites previously located with radio-telemetry.

Based on field testing and consultation with practitioners, standard methods for low-level surveys were developed (Burger et al. 2004) using environmental variables known to be linked to murrelet habitat requirements (Ralph et al. 1995; Nelson 1997; Burger 2002; CMMRT 2003). Briefly, the assessment ranks a range of canopy and topographic parameters, then provides a subjective ranking of the overall habitat quality using a six-class ranking system (Nil through Very High) (details in "Methods" section). Aerial surveys are usually undertaken in conjunction with other habitat-assessment methods, such as air photo interpretation or habitat algorithms, and are used either to confirm the quality of a specific forest area for murrelet management or to produce maps of habitat quality that will assist in management planning (Burger 2004). Our study tested the application of the low-level survey method in two regions of southern British Columbia, the Sunshine Coast and the west coast of Vancouver Island, and used nest sites previously located with radio-telemetry (Bradley 2002; Bradley et al. 2004; McFarlane Tranquilla et al. 2005).

Our study had three objectives. First, we tested whether nest sites could be effectively distinguished within the greater than 140-year-old forest (mature and old) by comparing habitat at nests with habitat at randomly selected points within the same landscapes. The assumption was that habitat murrelets actually use would best reflect the desirable qualities for nesting. (Cody 1985; Martin 1992). We inferred selectivity by murrelets for (or against) habitat of a particular class if nest sites occurred more frequently (or less frequently) within the class relative to the randomly selected sites (Jones 2001; Manly et al. 2002). These comparisons were made at two spatial scales: within patches (radius 100 m around the selected point or nest), and within the larger stand of similar forest surrounding the patch. Second, by comparing the habitat quality classes assigned to patches and stands, we examined whether the area of mapping unit would affect our ranking of habitat quality class, and if so, what implications this might have for describing and managing nesting habitat. Third, we evaluated the relationships between assessments made of the individually assessed environmental variables (e.g., tree size, moss development, and platform availability) and the overall habitat quality class for each site. This also allowed us to determine whether all assessed variables, or a subset of these, best predicted habitat suitability for nest sites.

Study areas

We analyzed data from three study areas: Desolation Sound and Toba Inlet, adjacent to each other on the Sunshine Coast (50°50' N, 124°40' W), and Clayoquot Sound on the west coast of Vancouver Island (49°12' N, 126°06' W). The Sunshine Coast region is characterized by three biogeoclimatic zones: Coastal Douglas-fir (0–600 m elevation), Coastal Western Hemlock (0–1000 m), and Mountain Hemlock (usually >1000 m) (Meidinger and Pojar 1991). Forests at lower elevations are dominated by Douglas-fir (*Pseudotsuga menziesii*), western hemlock (*Tsuga heterophylla*), and lesser amounts of western redcedar (*Thuja plicata*). Amabilis fir (*Abies amabilis*) becomes common at moister sites and with increasing elevation. The forest transitions into yellow-cedar (*Chamaecyparis nootkatensis*) and mountain hemlock (*Tsuga mertensiana*) in the Mountain Hemlock zone (Green and Klinka 1994). Forests on the Sunshine Coast are fragmented by mountainous topography, including steep cliffs and avalanche chutes (Zharikov et al. 2006), ongoing forest harvesting activities that date back to the early 1900s, fire disturbance (particularly in drier ecosystems), and some wind disturbance.

Clayoquot Sound is dominated by the wetter variants of the Coastal Western Hemlock and Mountain Hemlock zones. Sitka spruce (*Picea sitchensis*) is often found in wet sites of coastal floodplains. The windward hypermaritime variants of the outer coast of Clayoquot Sound commonly have bog forests and include a mixture of western hemlock, redcedar and yellow-cedar, amabilis fir, and small amounts of lodgepole pine (*Pinus contorta*) (Green and Klinka 1994). Forests in Clayoquot Sound are relatively continuous and uniform, except in the southwest portion of the study area, which is fragmented by forest harvesting, and in the northeast portion of the study area, which is mountainous.

Methods

Sampling

We used a two-sample design (i.e., use versus random). We evaluated habitat using 100 m radius plots centred on the sites defined as the patches. Nests were located by tracking radio-tagged murrelets on the Sunshine Coast from 1998 to 2001, and in Clayoquot Sound from 2000 to 2002 (Bradley et al. 2004; Zharikov et al. 2006). Nest samples from different years were combined on the assumption that habitat selection at the scale we tested was not detectably affected by inter-annual variations of other factors (e.g., food availability, climate; but see McFarlane Tranquilla et al. 2005). We used only nests at sites in forests older than 140-years and thus excluded 11 nests found in forest classed as less than 140 years old and six potential cliff nests (e.g., Bradley and Cooke 2001) for which platform structure assessments are not appropriate.

We compared known nest sites with sites at randomly located points in greater than 140-year-old-forest of each study area. We defined Study Area using a minimum convex polygon that encompassed all nests, plus a 5-km buffer. The buffer was approximately double the mean distance between the annual samples of known nests within the study areas (Zharikov et al. 2006). Inclusion of the buffer ensured that we could obtain a sample of random points that was at least equal to the number of nests.

We maintained a minimum spacing of 600 m between random points and ensured representation across the landscape and elevational gradient (Waterhouse et al. 2008). Elevation was calculated from a digital elevation model (Integrated Land Management Bureau 2007), and we retained it as an explanatory variable for the statistical analyses.

Aerial observations and habitat assessments

We used a Bell Jet Ranger helicopter and followed the methods of Burger et al. (2004). Flight routes were planned using GPS, a 1:85 000 topographic map, and 1:20 000 forest cover maps. Before data collection at a site, we confirmed GPS locations on pre-marked air photos. Sites were tested blind; that is, observers did not know whether the site was a nest or random point.

TABLE 1. Description of environmental variables and habitat quality classification used to assess nest and random patches by the low-level aerial survey method (adapted from Burger et al. 2004).

Variables	Description	Classes[a]
Large Trees[a]	% of canopy trees > 28 m tall	**Very High**, 51–100% **High**, 26–50% **Moderate**, 6–25%
Trees with Platforms[a]	% of canopy and emergent trees with potential nest platforms	**Low**, 1–5% **Very Low**, ~1%
Moss Development[a]	% of canopy and emergent trees with obvious mossy pads on limbs	**Nil**
Canopy Closure	% cover of overstorey canopy based on vertical projection of crowns on the ground, using the recommendations from the Canadian Marbled Murrelet Recovery Team (2003)	**Most Likely**, 40–60% **Moderately Likely**, 30 or 70% **Least Likely**, < 30%, > 70%
Vertical Complexity[b]	Vertical complexity and gappiness is subjectively ranked from least to highest, approximately matching the criteria used in air photo assessments of murrelet habitat	**Very High to Low**
Topographic Complexity[c]	Topographic features providing gaps and complexity to the forest (e.g., large boulders, rocky outcrops) ranked by subjective assessment	**Very High to Low**
Slope Grade	Steepness of slope grade at site	**Flat and gentle** **Moderate** **Steep**
Slope Position	Position on macroslope (slope assessed based on natural topographic breaks)	**Low and Valley Bottom** **Mid** **Upper and Ridge**
Patch Habitat Quality	Overall habitat quality ranked as a qualitative assessment considering occurrence and amount of all variables within the 100 m radius patch	**Very High**, 51–100% **High**, 26–50% **Moderate**, 6–25%
Stand Habitat Quality	As above, but overall habitat quality ranking of the stand (which varies in area) surrounding and including the 100 m radius patch.	**Low**, 1–5% **Very Low**, ~1% **Nil**

[a] Mod–Low refers to pooled Moderate, Low, and Very Low (~1–25% where applicable) for analysis (refer to Figure 1).

[b] Very High: Very non-uniform (> 40% difference leading trees and average canopy, very irregular canopy created by emergent trees, gaps, fallen trees); High: Non-uniform (31–40% height difference; canopy gaps often visible due to past disturbance; irregular canopy created by emergent trees, gaps, fallen trees); Moderate: Moderately uniform (21–30% height difference, some canopy gaps visible, evidence of past disturbance, a few emergent trees and obvious gaps); Low: Uniform (11–20% height difference, few canopy gaps visible, little or no evidence of disturbance, no emergent trees).

[c] A subjective assessment based on the effect of stand-level topography (e.g., slope, small rocky outcrops, avalanche chutes, large boulders) in creating small gaps and creating a complex canopy structure.

At each patch, the helicopter circled for 3–5 minutes. If patches or stands included young forest greater than or equal to 140 years old, or non-forested areas, the assessment was applied only to those portions of forest greater than 140 years old.

We classed environmental variables of patches using standard aerial survey criteria (Table 1; Burger et al. 2004). These variables are thought to describe habitat structure associated with cover (Canopy Closure, Vertical Complexity, and Slope Position, i.e., exposure), access into the stand (Vertical Complexity, Topographic Complexity, and Slope Grade), and nest platform availability for Marbled Murrelets (Large Trees, Trees with Platforms, Moss Development, and Slope Position, i.e., site productivity). After taking into consideration the classes of all the other parameters, we finally assessed the overall habitat quality of the patch (Patch Habitat Quality). Without making detailed assessments of each canopy parameter, we also subjectively classed the overall habitat quality of the stand surrounding the patch (Stand Habitat Quality). Stands included forest with relatively uniform age, species composition, and structure of trees, but were variable in area. Also, stands were broadly equivalent to polygons mapped for forest cover from air photos (Resource Inventory Committee 2002).

Data analysis

Statistical procedures used SAS 9.1 (SAS Institute Inc. 2003). Significance was evaluated using $\alpha = 0.10$, unless otherwise specified. We used a larger than customary level of significance to reduce the likelihood of a Type II error (i.e., not detecting real differences), which we felt could pose more risk to murrelet management than the occurrence of a Type I error. Using a suite of regression tools, we screened each variable and subsequently pooled classes of some variables to provide adequate sample sizes for analyses and pooled data among study areas where no effect was indicated (see methods in Waterhouse et al. 2008).

Determining habitat quality of nest patches and stands

We used a log-linear model (Agresti 1996) to determine if habitat quality differed according to Site Type (nest versus random point). This was done for both patches (Patch Type effect) and stands (Stand Type effect). From these models, we generated the predicted probabilities (Prob) that an observation belonging to one of the Site Types (nest or random point) would fall into any one of the habitat quality classes (e.g., Very Low through Very High).

Assessing habitat quality of patches compared to stands

To determine if overall habitat quality substantially differed depending on the area of forest classed, we used the Kappa statistic (κ) (Cohen 1960) to measure agreement between matched pairs of patch and stand (pooled nest and random samples: $n = 249$); full agreement equals 1 from a possible range of 0 to 1. Next, for those sites for which the habitat class of the patch differed from that assigned to the surrounding stand, we tested if the lack of agreement occurred more often between matched pairs at nest sites than between those at random sites (Chi-square test). We hypothesized that a lack of agreement would be greater for nest sites than for random sites if nesting murrelets selected smaller patches of higher-quality habitat within poorer-quality stands.

Determining relationships of environmental variables to patch habitat quality

To examine relationships between the environmental variables and the final habitat quality class of patch we used Spearman rank correlations (r_s) and the Mantel–Haenszel Chi-square test between ordinal variables (Mantel and Haenszel 1959).

Predicting nest patch habitat using resource selection functions

We determined which combination of environmental variables were the best predictors of nest patches using Akaike's Information Criterion adjusted for small samples (AIC_c) and Akaike weights (ω) to select logistic regression models (multiple or single) that best predicted Patch Type under our use–availability design (Burnham and Anderson 2002). We interpreted these models as Resource Selection Functions (Manly et al. 2002) that are proportional to the true probability of predicting Patch Type (i.e., nest patch). Please see Appendix for modelling details. We considered all variables identified a priori for field testing (Table 1) and included Study Area, Elevation, and any significant interactions indicated by the individual univariate analyses of the variables during screening. We reduced the potential for multicollinearity by excluding those variables highly associated based on Spearman rank correlations (if $P \leq 0.01$ and $r_s \geq 0.7$; Myers 1986), and retaining only the variable that best explained the differences between Patch Type.

Categorical predictors were parameterized using indicator or dummy variables that can take on values of 1 or 0 (Myers 1986, pp. 87–94). All but the final level of a predictor were assigned a dummy variable, so that the parameter estimate for each dummy variable conveyed the difference in the effect of a level compared to the effect of the final level. During model selection, all dummy variables of a categorical predictor were either kept in or dropped from the model. If the dummy variables associated with an interaction were included, then the dummy variables associated with both main effects were also included in the model. The "best" model had the minimum AIC_c and highest weight, and models that differed from it by less than 2 units in AIC_c scores were considered to have similar predictive ability (Burnham and Anderson 2002). Akaike weights were interpreted as approximate probabilities of the model, being the "best" from among those models examined (Anderson et al. 2000).

We initially assessed the "best" models based on the non-significant Hosmer and Lemeshow (2000) goodness-of-fit tests. Only then did we further examine fit of the "best" model in two phases. We used K-fold cross-validation (Boyce et al. 2002; Lillesand et al. 2004; see methods used Waterhouse et al. 2008) to assess the performance of each model for predicting Patch Type, where a strong positive Spearman rank correlation coefficient (r_s) between the predicted Resource Selection Function (categorized into bins) and the relative frequency of nests indicates good predictive performance (Boyce et al. 2002). Then, we determined the deviance reduction (ΔD) associated with each predictor variable by using (Chi-square) likelihood ratio tests (McCullagh and Nelder 1989; Guisan and Zimmermann 2000).

Results

Habitat quality of nest patches and stands

In the three study areas, we assessed 250 sites composed of 111 nest sites and 139 random sites (Table 2). We found that both nest and random patches centred on these sites (Patch Habitat Quality) and the stands surrounding the patches (Stand Habitat Quality) were distributed across five habitat quality classes (Figures 1a and 1b). Following pre-screening tests, we combined the Moderate, Low, and Very Low classes (hereafter Mod–Low) for testing habitat quality of patches and stands. Due to an interaction between Study Area and Patch Type (χ^2= 6.23, P = 0.04), we tested Patch Type separately by Study Area; whereas we pooled study areas for testing Stand Type due to non-significant differences (Study Area χ^2 = 1.60, P = 0.45; Study Area × Stand Type χ^2 = 2.09, P = 0.35).

Our tests of Patch Type (nests versus random) were significant for Desolation Sound (χ^2 = 4.88, P = 0.03) and Toba Inlet (χ^2 = 9.22, P < 0.01), but non-significant for Clayoquot Sound (χ^2 = 0.22, P = 0.64). Most nests in all the Study Areas were classed Very High and High (approximately 70–80 %; Figure 1a). In Desolation Sound and Toba Inlet, nest patches, when compared to random patches, respectively occurred 1.6 and 3 times more often than expected in Very High quality habitat and similarly less often than expected in the Mod–Low

TABLE 2. Area, forest cover, and sample sizes for the three study areas.

Study Area	Total area (ha)	Forest > 140 years old (% of area)	Type of site: Nest (no. of sites)	Type of site: Random (no. of sites)
Clayoquot Sound	1.82×10^5	53	31[a]	42
Desolation Sound	2.44×10^5	12	58	63[a]
Toba Inlet	1.89×10^5	20	22	34
Total patches			111	139

[a] One nest site and one random site were dropped for most analyses due to missing data.

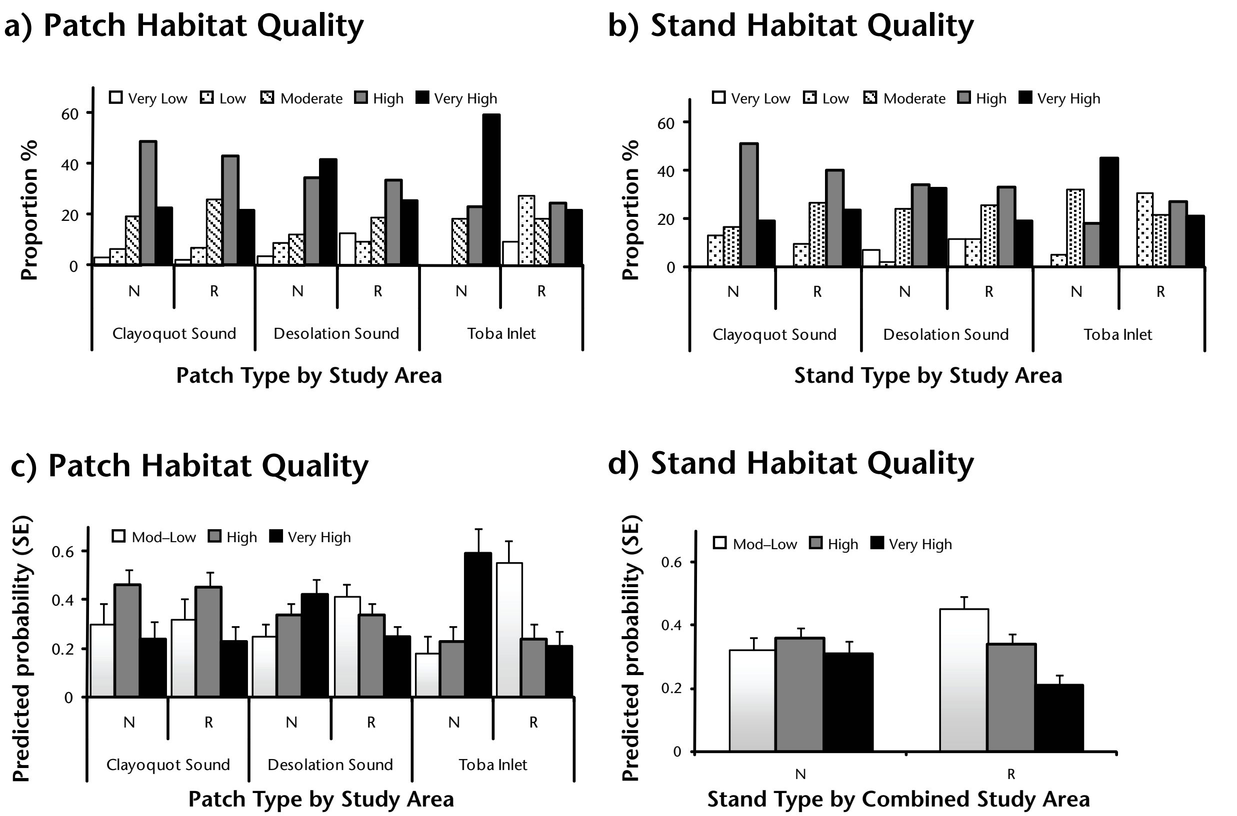


FIGURE 1. Proportions (%) by variable classes of nest (N) patches and of random (R) patches in each Study Area for Patch Habitat Quality (a) and Stand Habitat Quality (b) contrasted to the predicted probabilities and standard errors (SE) by variable classes (but using the combined Mod–Low as per Table 1) produced from reduced statistical models for Patch Habitat Quality (c) by Study Area and Stand Habitat Quality (d) for combined Study Areas.

habitat. (Figure 1c). For Stand Type, most nest stands (60–70 %) were also classed Very High or High (Figure 1b). Using the pooled Study Areas, our results were consistent with the Patch analysis ($\chi^2 = 5.13$, $P = 0.02$, Figures 1b, 1d); nest stands were 1.5 times more likely to be classed Very High than were random stands (Figure 1d), whereas those classed Mod–Low were similarly avoided (used 1.4 times less; Figure 1d).

Habitat quality of patches compared to stands

The habitat quality classes assigned to the patch and its surrounding stand were usually identical (75% of nest patches, $n = 111$; 73% of random patches, $n = 138$; 74% for pooled data, $n = 249$ with $\kappa = 0.65$, SE = 0.04). For those pairs that did not match ($n = 65$; 28 nest sites and 37 random sites) the difference was only one class, except for one pair with a larger difference. We found that significantly ($\chi^2 = 7.67$, $P < 0.01$) more of the nest patches were within stands assigned a lower habitat quality class (23/28; 82%) rather than a higher class (18%) compared to the random patches, which were as likely to be assigned a higher (18/37; 47%) or lower (53%) quality class than the surrounding stand.

Relationships of environmental variables to patch habitat quality

To examine relationships between the overall habitat quality and the environmental variables assessed at each patch, we pooled data from study areas. Overall patch habitat quality was strongly positively correlated with the occurrence of large trees, trees with platforms, and

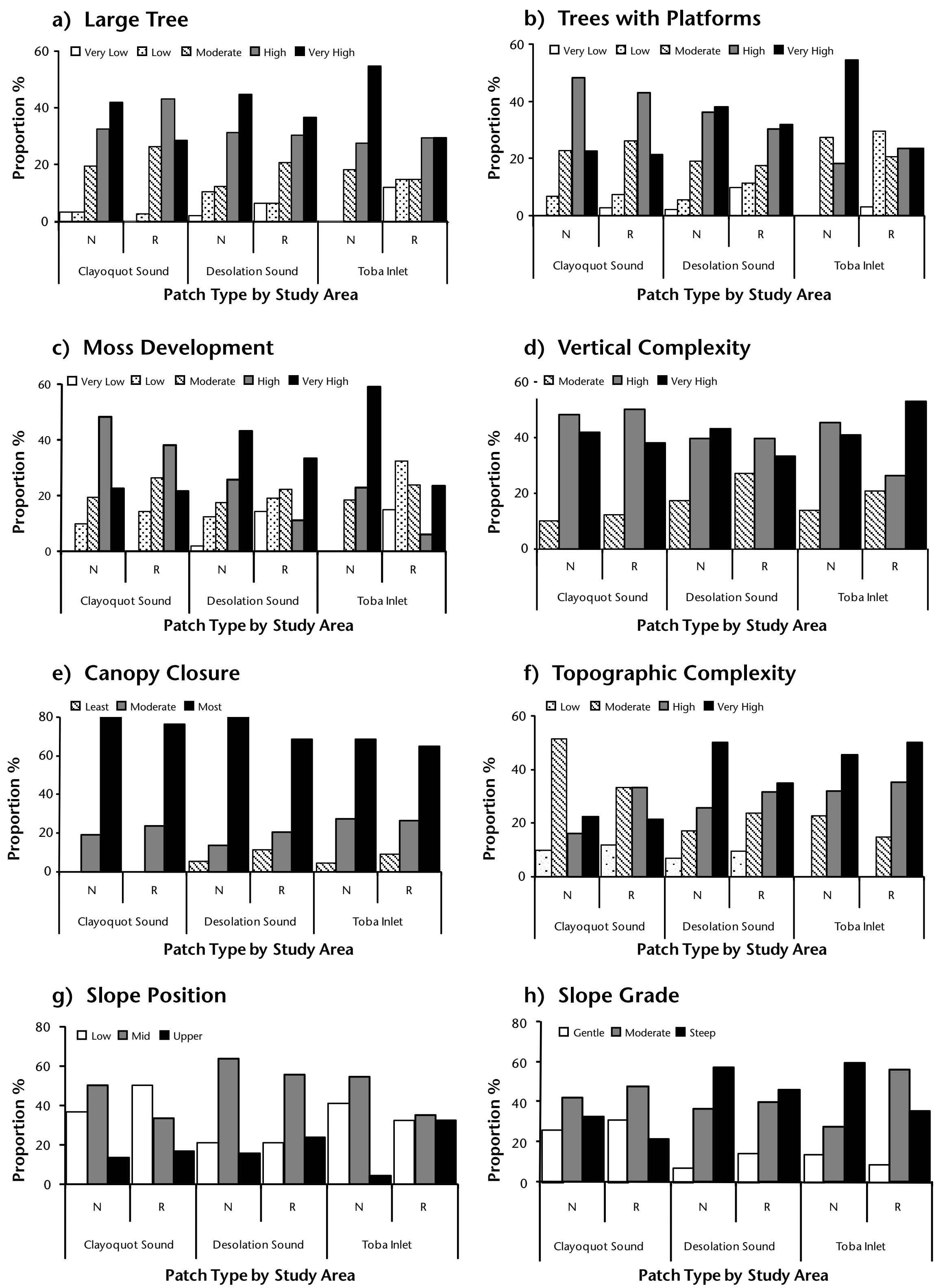


FIGURE 2. For each Study Area, proportions (%) of nest (N) patches and of random (R) patches by class for Large Trees, Trees with Platforms, Moss Development, Vertical Complexity, Canopy Closure, Topographic Complexity, Slope Position, and Slope Grade. Proportions of classes sum to 100% for each variable.

moss development (for each comparison: Spearman rank correlation, $n = 248$, $r_s = 0.75–0.91$, $P < 0.01$). Patch Habitat Quality was moderately correlated with vertical complexity (positive), slope position (negative), and elevation (negative) ($n = 248$, $r_s = 0.32–0.46$, $P < 0.01$), and weakly correlated with slope grade (negative) and topographic complexity (positive) ($n = 248$, $r_s < 0.21$, $P < 0.01$).

Predicting nest patch habitat using resource selection functions

In the greater than 140-year-old forest, we found that both nest and random patches fell within most of the possible classes of each environmental variable (Figure 2). Exceptions were that no patches were classed Nil for any variable, and no patches were classed Very Low for Topographic Complexity or as Low or Very Low for Vertical Complexity.

For model building, we excluded canopy closure as a candidate variable because most samples fell into the Most Likely class (Figure 2). We tested, separately, Large Trees, Trees with Platforms, and Moss Development because Spearman correlations suggested multicollinearity ($n = 250$, $r_s > 0.72$, $P < 0.01$). For the AIC_c analysis using Moss Development, Platform Trees, and Large Trees, following pre-screening, we combined the three lower classes into one (Mod–Low).

First, we tested models containing Moss Development, retaining Study Area because it had a significant effect on this variable ($\chi^2 = 19.55$, $P < 0.01$). We additionally retained all other variables including Elevation (thus the significant interaction term Study Area × Elevation), because the Spearman correlations among them were either significant but weaker (range $n = 248$ to 250, range $r_s = 0.13$ to 0.51, $P < 0.05$) or were not significant ($P > 0.05$ for Vertical Complexity and Slope Position, Vertical Complexity and Elevation). The analysis produced 160 models of which two appeared "best" for predicting nest patches (Table 3). Model 1 included Study Area, Moss Development, Slope Grade, Elevation, and Study Area × Elevation interaction. Model 2, which had a similar predictability (Δ $AIC_c < 2$), included these same variables plus Topographic Complexity. Only Vertical Complexity and Slope Position were excluded from the top models. Both models had reasonable fit based on a non-significant Hosmer and Lemeshow Goodness of Fit statistics (i.e., $P > 0.10$).

TABLE 3. Resource Selection Functions that predict Patch Type developed by using Akaike's Information Criterion adjusted for small samples (AIC_c) and weighting (ω_i). Top models were selected based on ΔAIC_c, with two top models identified using Moss Development.

Model	Variables	No. of variables (K)	AIC_c	ω_i
Model 1	Study Area Moss Development Slope Grade Elevation Study Area × Elevation	10	310.17	0.25
Model 2	Study Area Moss Development Slope Grade Elevation Study Area × Elevation Topographic Complexity	13	311.57	0.16
Model 3	Moss Development Slope Grade Elevation	6	313.14	0.08

The likelihood parameter estimates for Model 1 (Table 4) provided us with the influence of each variable on the Resource Selection Function score, which is proportional to the probability of nest patch use. The model yielded higher Resource Selection Function scores (assuming elevation is zero) at Toba Inlet than at Desolation Sound, and produced the lowest scores at Clayoquot Sound (Study Area effect). These scores: (1) increased if moss development was classed High or Very High (Moss Development effect); (2) decreased as elevation increased (Elevation effect); (3) declined most steeply with elevation in Toba Inlet and least steeply in Clayoquot Sound (Study Area × Elevation interaction); and (4) increased as slope gradient increased, where steep slopes were more likely and gentle slopes were least likely to have nest patches than were moderate slopes (Slope Gradient effect).

Model 2 had a similar interpretation, but the additional estimates from including Topographic Complexity were not significant. The estimates were difficult to interpret because nests were best predicted to occur in patches with Very High and Moderate complexities, followed by patches with Low complexity, and were least likely to occur in patches of High complexity. We therefore deemed Model 2 unreliable and focused further only on Model 1.

For Model 1 we used the K-fold cross-validation and confirmed that it had good predictive capacity ($r_s = 0.84$, $n = 10$, $P < 0.001$). We also determined that all variables included in Model 1 contributed significantly to explaining the deviance in the model (i.e., $P < 0.02$); the greatest change in deviance was explained by Elevation ($\Delta D = 20.57$), followed by Slope Grade ($\Delta D = 12.06$), Study Area × Elevation ($\Delta D = 9.13$), Moss Development ($\Delta D = 7.52$), and then Study Area ($\Delta D = 7.13$).

Next, we re-ran the AIC_c analysis using Trees with Platforms instead of Moss Development. We found that Trees with Platforms was retained as an explanatory variable in one of four top models only if Study Area, for which we had detected a significant pre-screening effect ($\chi^2 = 8.96$, $P < 0.06$), was excluded. Otherwise,

TABLE 4. Statistically significant predictions derived from the top-ranked binary logistic regression model (Model 1, Table 3) for separating Patch Type (nests versus random patches). Significance of the overall model was based on the reduction in deviance between an intercept-only model and a model with all predictor variables included ($\chi2 = 53.88$, df = 9, $P < 0.0001$). All tests of variables or interactions shown here are based on 1 degree of freedom ($n = 248$).

Variable	Parameter estimate	Standard error	Likelihood ratio χ^2	P
Intercept	3.265	1.072	N/A	N/A
Moss Development				
Very High	0.564	0.379	2.22	0.14
High	1.064	0.377	8.22	0.004
Study Area				
Clayoquot Sound	−2.724	1.119	6.99	0.008
Desolation Sound	−2.244	1.083	4.98	0.0256
Elevation	−0.005	0.002	20.55	< 0.001
Elevation × Study Area				
Clayoquot Sound	0.004	0.001	7.50	0.006
Desolation Sound	0.004	0.001	7.99	0.005
Slope Grade				
Gentle	−1.435	0.472	.82	0.002
Moderate	−0.867	0.335	6.97	0.008

Trees with Platforms was not retained. Lastly we re-ran the analyses using Large Trees, for which the Study Area effect was non-significant ($\chi^2 = 0.80$, $P = 0.67$), and we found it was retained in two of five top models. Consistent with the AIC_c analysis for Moss Development, our analyses using Trees with Platforms and Large Trees also retained various combinations of these variables in the top models: Elevation, Slope Grade, Topographic Complexity, but also Vertical Complexity in the Large Tree AIC_c analysis.

Discussion

Classifying habitat quality

In support of using the low-level aerial survey method to assess Marbled Murrelet habitat, we found that murrelets selected nesting habitats in higher-quality classes and avoided those in lower-quality classes. This was found for both patches (100 m around nests) and the larger surrounding stands (usually tens or up to low hundreds of hectares). Overall, 40% of the 111 nest sites were in patches classed as Very High, 36% were in High, 15% were in Moderate, 6% were in Low, and 3% were in Very Low. Because we were comparing sites at nests with sites at random points within greater than 140-year-old forest, some proportion of the random sites also occurred in suitable nest habitat. Consequently, the differences between nest and random patches were less striking than expected; this is a common problem when comparing used habitat with random (Jones 2001; Manly et al. 2002). The small differences between nest and random patches (or stands) in the predicted probabilities of habitat quality (Figure 1c and 1d) and the considerable proportion of nests (24%) in patches classed as Mod–Low suggest that the classification's effectiveness for distinguishing all nest patches has limitations in the greater than 140-year-old forest stratum.

The aerial survey classification's greatest value for wildlife managers may be in its use to quantitatively rank and classify the potential value of one area relative to another, rather than to provide a threshold to identify suitable nesting habitat within the older forest stratum. The challenge in this application is that, given the lack of known relationships between habitat quality and occupancy or nest density (Burger 2004; Burger and Waterhouse 2009), we do not know to what extent one class supports higher densities of nesting murrelets than another class.

The low-level aerial survey method provided a regionally consistent method for identifying Marbled Murrelet nesting habitat in south coastal British Columbia. Despite some differences among study areas—that is, nesting habitat was more effectively distinguished on the Sunshine Coast (Desolation Sound and Toba Inlet) than on the west coast of Vancouver Island (Clayoquot Sound)—nest habitat patches had many similar characteristics among the regions based on those variables assessed by the aerial survey method. We suspect that nest patch selectivity was more easily detected on the Sunshine Coast because availability of suitable habitat is reduced there owing to historic disturbance and to effects of topography and elevation (Zharikov et al. 2006); that is, it is less likely on the Sunshine Coast that random points would fall within suitable habitat. In comparison, Clayoquot Sound has experienced far less habitat loss from logging and has more uniform coverage of suitable forest (Zharikov et al. 2006); consequently a higher proportion of random points might fall within suitable nesting habitat, thereby minimizing the differences between nests and random points.

Aerial assessments of habitat quality were sensitive to the area of forest assessed, even though agreement was high between the classes assigned to pairs of patch and forest stand (74% of these pairs had identical habitat quality class). Information can be lost as minimum mapping units increase in area (i.e., the grain at which the element is assessed increases) (Fassnacht et al. 2006), as shown by our comparison between smaller patches contained within often larger stands. Our result was of particular importance because we showed that, where there were differences between the habitat quality of the patch and surrounding stand at nest sites, the nests were disproportionately found in patches of habitat classed higher for habitat quality. Murrelets are likely selecting higher-quality patches for nesting within the overall forest matrix (Nelson and Wilson 2002). The minimum mapping unit currently applied for producing aerial survey habitat maps for murrelets in British Columbia is approximately 3 ha, with maps produced to 1:20 000 scale (Sue McDonald, Western Forest Products, pers. comm., November 2008). Based on our testing using 3-ha patches, if inventory sampling is applied uniformly during low-level flights, 3 ha should be adequate for identifying patches of higher-quality habitat.

Interpreting the Classification

Murrelets, as most other animals, likely exploit a wider range of habitats by using patches with a range of habitat characteristics (Guénette and Villard 2004). By broadly distributing themselves for nesting across the landscape, murrelets can perhaps better respond to factors such as the distribution of marine prey and predators. Research has shown that considering combinations of both structural and topographic variables improves the probability of detecting that a patch has nesting habitat value for murrelets (Bahn and Newsom 2002a, 2002b; Nelson et al. 2006; Zharikov et al. 2006). The habitat quality classification is intended to incorporate assessments of multiple forest structural and topographic variables (Burger 2004). Yet, the assessment of overall habitat quality made from the helicopter was, in practice, weighted by a few key forest structural features. The strong positive intercorrelations between the habitat quality classification and forest structure variables suggested that the final assigned habitat quality class was dependent on tree size, platform availability, and moss development while little weighting was attributable to topographic variables.

In contrast to the habitat quality classification, the Resource Selection Functions suggested that murrelet nest habitat was best distinguished from available habitat using topographic variables as well as forest structural variables. Moss Development, Slope Grade, and Elevation proved the best predictors of murrelet nesting habitat following our analysis approach using AIC_c. Mossy platforms are key forest structural features for supporting the nest (Nelson 1997; Burger 2002) and can be distinguished within the greater than 140-year-old forest by using aerial surveys. Although strongly intercorrelated, Large Trees and Trees with Platforms were less reliable predictors of murrelet nest habitat than Moss Development in the Resource Selection Functions. Slope Grade, retained as an aerial estimate of topography, is thought to describe site accessibility where steeper slopes may enhance a murrelet's ability to access stands by exposing entryways into the canopy (Bradley 2002). Although the best-fit models did not retain Slope Position, we suggest it may be beneficial to record this variable during aerial surveys because it may be help to eliminate stands on ridge tops that can be exposed to wind disturbance and are therefore less suitable for murrelets (Meyer et al. 2002, 2004). Elevation may influence murrelets' nest-site selectivity because low-elevation forests are often more productive (have larger trees) and are often closer to foraging areas used by murrelets (Burger 2002; Meyer et al. 2004; Nelson et al. 2006; Zharikov et al. 2006). More importantly, the model explained in part how nest patches may occur across a range of elevations and slopes where murrelets are able to access and use higher-elevation habitats or steeper slopes if platforms with moss pads are available.

We found only weak evidence that Topographic Complexity and Vertical Complexity, as assessed in aerial surveys, helped to predict murrelet nesting habitat. Their effectiveness for distinguishing habitat may be reduced if there is site-to-site variation in how murrelets discriminate stand access. Vertical Complexity can alternatively be assessed on air photos (Waterhouse 2002, 2008; Donaldson 2004). Canopy Closure, based on the lack of variability in our data, may not prove as useful a variable to collect during aerial surveys in the greater than 140-year-old forest stratum. In immature forests (< 140 years old), however, closed and uniform canopies might preclude murrelets from accessing canopy limbs (Waterhouse et al. 2002).

Conclusions and management implications

Low-level aerial surveys enable biologists to identify likely nesting habitat for Marbled Murrelets, as they focus on key habitat features (platforms and moss development) not discernable using lower-resolution tools such as aerial photographs or satellite images. When combined with knowledge of site topography, estimating availability of mossy platforms may prove one of the most useful indicators of the aerial survey. Aerial surveys can be used to rapidly classify and map large areas of forest, including forest with poor access for ground observers. If applied with a fine-scale resolution of approximately 3 ha, small patches of suitable habitat within a larger matrix of less suitable forest can be detected, and hence improve the accuracy of the classification. This information can be used to help identify candidate areas that meet habitat management objectives for nesting murrelets (e.g., Wildlife Habitat Areas; British Columbia Ministry of Water, Land and Air Protection 2004).

Our selectivity analysis supports the idea of focusing management for nesting murrelets on habitats classed Very High or High in aerial surveys. However, such higher-quality habitats might not be frequently found in some landscapes and a proportion of murrelets (approximately 25% in this study) do nest in some lower-quality habitats.

Low-level aerial surveys enable biologists to identify likely nesting habitat for Marbled Murrelets, as they focus on key habitat features (platforms and moss development) not discernable using lower-resolution tools such as aerial photographs or satellite images.

Consequently, wildlife managers may need to consider using lower-quality habitats (particularly those classified Moderate) to meet habitat management objectives. In such cases, and depending on management objectives, other methods could be applied to show evidence of murrelet use of these lower-quality habitats (e.g., radar or audiovisual surveys).

At the practical level, the current discrete six-class classification (Burger et al. 2004) could be replaced by the less subjective predictive Resource Selection Functions (i.e., producing continuous relative probabilities) (Boyce et al. 2002; Manly et al. 2002; Boyce 2006). We are cautious in overly interpreting our current Resource Selection Function results because our testing may be considered borderline exploratory, where the variables were selected a priori but the relationship between them was unknown. Further development of Resource Selection Functions would enable biologists to integrate stand-level metrics collected during aerial surveys with other stand and landscape metrics that relate to habitat selectivity (Bahn and Newsom 2002a, 2002b; Meyer et al. 2004; Zharikov et al. 2006). Such an approach could also help account for hierarchal or multistage habitat selection (Johnson 1980; Orians and Wittenberger 1991; Manly et al. 2002), which may be used by the Marbled Murrelet (Manley 1999; Meyer 2007).

Acknowledgements

This project used locations of Marbled Murrelet nests determined by Fred Cooke's research group at the Centre for Wildlife Ecology, Simon Fraser University, from 1998 to 2002. We thank Russ Bradley, Glen Keddie, Lynn Lougheed, Conrad Theissen, and Yuri Zharikov for helping us co-ordinate and work with the nest information. The aerial assessments were conducted by Alan Burger and Louise Waterhouse, with navigation by Nadine Parker and E&B Helicopters, Campbell River. Financial and logistical support for the current project was provided by the British Columbia Ministry of Forests and Range, the Forest Science Program of the Forest Investment Account, Western Forest Products Inc., Weyerhaeuser Company Limited, the Natural Sciences and Engineering Research Council of Canada (NSERC), and Simon Fraser University's Centre for Wildlife Ecology. Air photos were provided by International Forest Products Ltd. (Gerry Sommers and Wayne Wall) and Weyerhaeuser Company Limited (Gary Purpor), and maps were provided by the British Columbia Ministry of Agriculture and Lands. Preliminary editing was done by Kathi Hagan. The interpretations contained in this report do not necessarily reflect the opinions of the aforementioned organizations or people. Thank you also to the anonymous reviewers and editor Susan Thorne.

References

? TEST YOUR KNOWLEDGE Questions on page 115

Agresti, A. 1996. An introduction to categorical data analysis. John Wiley and Sons, New York, NY.

Anderson, D.R., K.P. Burnham, and W.L. Thompson. 2000. Null hypothesis testing: Problems, prevalence, and an alternative. Journal of Wildlife Management 64:912–923.

Bahn, V. and D.N. Newsom. 2002a. Can marbled murrelet use of nesting habitat be predicted from mapped forest characteristics? *In* Multi-Scale studies of populations, distribution and habitat associations of Marbled Murrelets in Clayoquot Sound, British Columbia. A.E. Burger and T.A. Chatwin (editors). British Columbia Ministry of Water, Land and Air Protection, Victoria, BC.

________ 2002b. Habitat suitability mapping for Marbled Murrelets in Clayoquot Sound. *In* Multi-Scale studies of populations, distribution and habitat associations of Marbled Murrelets in Clayoquot Sound, British Columbia. A.E. Burger and T.A. Chatwin (editors). British Columbia Ministry of Water, Land and Air Protection, Victoria, BC.

Boyce, M.S. 2006. Scale for resource selection functions. Diversity and Distributions 12:269–276.

Boyce, M.S., P.R. Vernier, S.E. Nielsen, and F.K.A. Schmiegelow. 2002. Evaluating resource selection functions. Ecological Modelling 157:281–300.

Bradley, R.W. 2002. Breeding ecology of radio-marked Marbled Murrelets (*Brachyramphus marmoratus*) in Desolation Sound, British Columbia. MSc thesis, Simon Fraser University, Burnaby, BC.

Bradley, R.W. and F. Cooke. 2001. Cliff and deciduous tree nests of Marbled Murrelets in southwestern British Columbia. Northwestern Naturalist 82:52–57.

Bradley R.W., F. Cooke, L.W. Lougheed, and W.S. Boyd. 2004. Inferring breeding success through radiotelemetry in the Marbled Murrelet. Journal of Wildlife Management 68:318–331.

British Columbia Ministry of Water, Land and Air Protection. 2004. Identified wildlife management strategy. Environmental Stewardship Division, Victoria, BC. ***www.env.gov.bc.ca/wld/frpa/iwms/index.html*** (Accessed June 2007).

Burger, A.E. 2002. Conservation assessment of Marbled Murrelets in British Columbia: Review of the biology, populations, habitat associations, and conservation. Canadian Wildlife Service, Pacific and Yukon Region, Delta, BC. Technical Report Series No. 387. ***www.sfu.ca/biology/wildberg/bertram/mamurt/PartA.pdf*** (Accessed June 2007).

Burger, A.E. 2004. Part one: General introduction. *In* Standard methods for identifying and ranking nesting habitat of Marbled Murrelets (*Brachyramphus marmoratus*) in British Columbia using air photo interpretation and low-level aerial surveys. A.E. Burger (editor). British Columbia Ministry of Water, Land and Air Protection, Biodiversity Branch, Victoria, BC. ***wlapwww.gov.bc.ca/wld/documents/fia_docs/mamu_standard.pdf*** (Accessed June 2007).

Burger, A.E. and V. Bahn. 2004. Inland habitat associations of Marbled Murrelets on southwest Vancouver Island, British Columbia. Journal of Field Ornithology 75:53–66.

Burger, A.E., B.R. Smart, L.K. Blight, and J. Hobbs, 2004. Part three: Low-level aerial survey methods. *In* Standard methods for identifying and ranking nesting habitat of Marbled Murrelets (*Brachyramphus marmoratus*) in British Columbia using air photo interpretation and low-level aerial surveys. A.E. Burger (editor). British Columbia Ministry of Water, Land and Air Protection, Biodiversity Branch, Victoria, BC. ***wlapwww.gov.bc.ca/wld/documents/fia_docs/mamu_standard.pdf*** (Accessed June 2007).

Burger, A.E. and F. L. Waterhouse. 2009. Relationships between habitat area, habitat quality, and populations of nesting Marbled Murrelets. BC Journal of Ecosystems and Management 10(1):101–112. ***www.forrex.org/publications/jem/ISS50/vol10_no1_art10.pdf***

Burnham, K.P. and D.R. Anderson. 2002. Model selection and multimodel inference: A practical information-theoretic approach. Springer-Verlag, NY.

(CMMRT) Canadian Marbled Murrelet Recovery Team. 2003. Marbled Murrelet conservation assessment 2003, part B: Marbled Murrelet recovery team advisory document on conservation and management. Canadian Wildlife Service, Pacific and Yukon Region, Delta, BC. Canadian Marbled Murrelet Recovery Team Working Document No. 1. ***www.sfu.ca/biology/wildberg/bertram/mamurt/PartB.pdf*** (Accessed June 2007).

Cody, M.L. 1985. Habitat selection in birds. Academic Press, Inc., Orlando, Fla.

Cohen, J. 1960. A coefficient of agreement for nominal scales. Educational and Psychological Measurement 20:37–46.

Committee on the Status of Endangered Wildlife in Canada, Government of Canada. 2000. Marbled Murrelet. ***www.cosewic.gc.ca/eng/sct1/searchdetail_e.cfm?id=39&StartRow=1&boxStatus=All&box|Taxonomic=All&location=All&change=All&board=All&commonName=marbled%20murrelet&scienceName=&returnFlag=0&Page=1*** (Accessed June 2007).

Donaldson, A. 2004. Part two: Air photo interpretation. *In* Standard methods for identifying and ranking nesting habitat of Marbled Murrelets (*Brachyramphus marmoratus*) in British Columbia using air photo interpretation and low-level aerial surveys. A.E. Burger (editor). British Columbia Ministry of Water, Land and Air Protection, Biodiversity Branch, Victoria, BC. ***http://wlapwww.gov.bc.ca/wld/documents/fia_docs/mamu_standard.pdf*** (Accessed June 2007).

Fassnacht, K.S., W.B. Cohen, and T.A. Spies. 2006. Key issues in making and using satellite-based maps in ecology: A primer. Forest Ecology and Management 222:167–181.

Green, R.N. and K. Klinka. 1994. A field guide to site identification and interpretation for the Vancouver Forest Region. British Columbia Ministry of Forests, Research Branch, Victoria, BC. Land Management Handbook No. 28.

Guénette, J-S. and M-A. Villard. 2004. Do empirical thresholds truly reflect species tolerance to habitat alteration? Ecological Bulletins 51:163–171.

Guisan, A. and N.E. Zimmermann. 2000. Predictive habitat distribution models in ecology. Ecological Modelling 135:147–186.

Hamer, T.E. and S.K. Nelson. 1995. Characteristics of Marbled Murrelet nest trees and nesting stands. *In* Ecology and conservation of the Marbled Murrelet. C.J. Ralph, G.L. Hunt, Jr., M.G. Raphael, and J.F. Piatt (editors). US Department of Agriculture Forest Service Pacific Southwest Research Station, Albany, Calif. General Technical Report PSW-GTR-152.

Hosmer, D.W. and S. Lemeshow. 2000. Applied logistic regression. John Wiley and Sons, Inc., New York, NY.

Integrated Land Management Bureau. 2007. Digital Elevation Model. GeoBC. Base mapping and Geomatic Services. ***ilmbwww.gov.bc.ca/bmgs/*** (Accessed March 2009).

Johnson, D. 1980. The comparison of usage and availability measurements for evaluating resource preference. Ecology 61:65–71.

Jones, J. 2001. Habitat selection studies in avian ecology: A critical review. Auk 118:557–562.

Keating, K.A. and S. Cherry. 2004. Use and interpretation of logistic regression in habitat-selection studies. Journal of Wildlife Management 68:774–789.

Lillesand, T.M., R.W. Kiefer, and J.W. Chipman. 2004. Remote sensing and image interpretation. John Wiley and Sons, New York, NY.

Manley, I.A. 1999. Behaviour and habitat selection of Marbled Murrelets nesting on the Sunshine Coast. MSc thesis, Department of Biological Sciences, Simon Fraser University, Burnaby, BC.

Manly, B., L. McDonald, D.L. Thomas, T.L. McDonald, and W.P. Erickson. 2002. Resource selection by animals. Kluwer Academic Publishers, Maine.

Mantel, N. and W. Haenszel. 1959. Statistical aspects of the analysis of data from retrospective studies of disease. Journal of the National Cancer Institute 22:719–748.

Martin, T.E. 1992. Breeding productivity considerations: What are the appropriate habitat features for management. *In* Ecology and conservation of neotropical migrant landbirds. J.M. Hagen, and D.W. Johnson (editors). Smithsonian Institute Press, Washington, DC.

McFarlane Tranquilla, L., N.R. Parker, R.W. Bradley, D.B. Lank, E.A. Krebs, L. Lougheed, and C. Lougheed. 2005. Breeding chronology of Marbled Murrelets varies between coastal and inshore sites in southern British Columbia. Journal of Field Ornithology 76:357–367.

McCullagh, P. and J.A. Nelder. 1989. Generalized linear models, 2nd edition. Chapman and Hall, New York, NY.

Meidinger, D. and J. Pojar. (editors). 1991. Ecosystems of British Columbia. British Columbia Ministry of Forests, Research Branch, Victoria, BC. Special Report Series No. 6. ***www.for.gov.bc.ca/hfd/pubs/Docs/Srs/SRseries.htm*** (Accessed June 2007)

Meyer, C. B. 2007. Does scale matter in predicting species distributions? Case study with the Marbled Murrelet. Ecological Applications 17:1474–1483.

Meyer, C.B., S.L. Miller, and C.J. Ralph. 2002. Multi-scale landscape and seascape patterns associated with marbled murrelet nesting areas on the U.S. west coast. Landscape Ecology 17:95–115.

Meyer, C.B., S.L. Miller, and C.J. Ralph. 2004. Stand-scale habitat associations across a large geographic region of an old-growth specialist, the Marbled Murrelet. Wilson Bulletin 116:197–286.

Myers, R.H. 1986. Classical and modern regression with applications. Duxbury Press, Boston, Mass.

Nelson, S.K. 1997. Marbled Murrelet (*Brachyramphus marmoratus*). *In* The birds of North America. A. Poole and F. Gill (editors). Academy of Natural Sciences, Philadelphia, PA, and American Ornithologists Union, Washington, DC.

Nelson, S.K. and A.K. Wilson. 2002. Marbled Murrelet habitat characteristics on state lands in western Oregon. *In* Final report. Oregon Cooperative Fish and Wildlife Research Unit, Oregon State University, Department of Fisheries and Wildlife, Corvallis, Oreg.

Nelson, S.K., M.H. Huff, S.L. Miller, and M.G. Raphael. 2006. Chapter 2: Marbled Murrelet biology: Habitat relations and populations. *In* Northwest forest plan: the first 10 years (1994–2003): Status and trends of populations and nesting habitat for the Marbled Murrelet. M.H. Huff, M.G. Raphael, S.L. Miller, S.K. Nelson, and J. Baldwin (editors). US Department Agriculture Forest Service, Pacific Northwest Research Station, Portland, Oreg. General Technical Report PNW-GTR-650.

Orians, G.H. and J.F. Wittenberger. 1991. Spatial and temporal scales in habitat selection. American Naturalist 137:S29–S49.

Ralph, C.J., G.L. Hunt, M.G. Raphael, and J.F. Piatt. 1995. Ecology and conservation of the Marbled Murrelet: An overview. *In* Ecology and conservation of the Marbled Murrelet. C.J. Ralph, G.L., Jr. Hunt, M.G. Raphael, J.F. Piatt (tech. editors). US Department of Agriculture, Forest Service, Pacific Southwest Research Station, Albany, Calif. General Technical Report PSW-152.

Resource Inventory Committee. 2002. Photo interpretation procedures V2.4. British Columbia Ministry of Sustainable Resource Management, Terrestrial Information Branch, Victoria, BC. ***www.for.gov.bc.ca/hts/vri/standards/index.html*** (Accessed June 2007).

Rodway, M.S. and H.M. Regehr. 2002. Inland activity and forest structural characteristics as indicators of Marbled Murrelet nesting habitat in Clayoquot Sound. *In* Multi-scale studies of populations, distribution and habitat associations of Marbled Murrelets in Clayoquot Sound, British Columbia. A.E. Burger and T.A. Chatwin (editors). British Columbia Ministry of Water, Land and Air Protection, Victoria, BC.

SAS Institute Inc. 2003. SAS OnlineDoc® 9.1. SAS Institute Inc., Cary, NC.

Waterhouse, F.L., R. Bradley, J. Markila, F. Cooke, and L. Lougheed. 2002. Use of airphotos to identify, describe, and manage forest structure of Marbled Murrelet nesting habitat at a coastal British Columbia site. British Columbia Ministry of Forests, Coast Forest Region, Research Section, Nanaimo, BC. Technical Report No. TR-016. ***www.for.gov.bc.ca/rco/research/wildlifereports/tr016.pdf*** (Accessed June 2007).

Waterhouse, F.L., A. Donaldson, and D.B. Lank. 2004. Using airphotos to interpret marbled murrelet nesting habitat in British Columbia: Application of a preliminary classification scheme. British Columbia Ministry of Forests, Coast Forest Region, Research Section, Nanaimo, BC. Technical Report No. TR-029 Wildlife. ***www.for.gov.bc.ca/rco/research/Mamu%5Ctr029.pdf*** (Accessed June 2007).

Waterhouse, F.L., A. Donaldson, D.B. Lank, P.K. Ott, and E.A. Krebs. 2008. Using air photos to interpret quality of Marbled Murrelet nesting habitat in south coastal British Columbia. BC Journal of Ecosystems and Management 9(1):17–37. ***www.forrex.org/publications/jem/ISS47/vol9_no1_art3.pdf***

Zharikov, Y., D.B. Lank, D.B., F. Huettmann, R.W. Bradley, N. Parker, P.P.W. Yen, L.A. McFarlane Tranquilla, and F. Cooke. 2006. Habitat selection and breeding success in a forest-nesting Alcid, the Marbled Murrelet, in two landscapes with different degrees of forest fragmentation. Landscape Ecology 21:107–120.

ARTICLE RECEIVED: **September 4, 2007**
ARTICLE ACCEPTED: **January 12, 2009**

Appendix A

Using logistic regression to estimate a Resource Selection Function when the data consists of two samples: One of used and one of available sites

Following along the lines of Keating and Cherry (2004) and Manly et al. (2002):

$$P(\text{site has a nest} \mid \text{site is among the type types of samples drawn}, \mathbf{x}) = \frac{\frac{P_u}{P_a} P(\text{site has a nest} \mid \mathbf{x})}{1 + \frac{P_u}{P_a} P(\text{site has a nest} \mid \mathbf{x})}$$

where P_u and P_a are the sampling inclusion probabilities for the used and available sites respectively and $\mathbf{x}$ is a vector of explanatory environmental variables.

If we assume that the resource selection probability function has the form , where for all , then

$P(\text{site has a nest} \mid \mathbf{x}) = \exp(\boldsymbol{\beta}^{\mathrm{T}} \mathbf{x})$, where $\boldsymbol{\beta}^{\mathrm{T}} \mathbf{x} \leq 0$ for all $\mathbf{x}$, then

$$P(\text{site has a nest} \mid \text{site is among the two types of samples drawn}, \mathbf{x}) = \frac{\exp(\boldsymbol{\beta}^{*T}\mathbf{x})}{1+ \exp(\boldsymbol{\beta}^{*T}\mathbf{x})}$$

the first element of $\boldsymbol{\beta}^*$ is $\beta_0 + \log(\frac{P_u}{P_a})$.

Keating and Cherry (2004) show that one way to ensure $\boldsymbol{\beta}^{\mathrm{T}} \mathbf{x} \leq 0$ for all $\mathbf{x}$ is for $P(\text{site has a nest}) \leq \frac{n_u}{n_a \exp(\boldsymbol{\beta}^{*T}\mathbf{x})}$

for all $\mathbf{x}$ in the population (where n_u and n_a are the size of the used and available samples, respectively).

Under these conditions, a logistic regression fit to the use-availability data (i.e., the dependent variable is coded as 1 when the site is used an 0 when the site it is available, along with the vector of explanatory variables) will be able to recover either: (1) the assumed resource selection probability function when P_u and P_a are known, or (2) a Resource Selection Function proportional to it when P_u and P_a and are unknown.

Extension Note

British Columbia's Forests

White Pine Blister Rust Forest Health Stand Establishment Decision Aid

Stefan Zeglen[1], Richard Hunt[2], and Michelle Cleary[3]

Introduction

White pine blister rust (*Cronartium ribicola*) is an introduced disease affecting five-needle pines throughout North America. Like other non-native pests, its impact on the native hosts has been dramatic, decimating species such as western white pine in both number and distribution. Because of its prevalence, white pines have been removed from commercial forestry consideration in most areas. This is unfortunate as western white pine is an excellent substitute for Douglas-fir in areas prone to laminated root disease. It can also command a premium price. To mitigate disease impact and permit management, a good understanding of the biology of *C. ribicola* is necessary.

The Stand Establishment Decision Aid (SEDA) format has been used to extend information on various vegetation and forest health concerns in British Columbia. This decision aid summarizes information that relates current management regimes to the spread and effects of white pine blister rust. The first page provides general information, hazard ratings for the biogeoclimatic zones and subzones of British Columbia, and biological considerations for white pine blister rust. The second page outlines the implications to silviculture and the various techniques used to manage the disease. This page also includes a resource and reference list to provide readers with more detailed information. Reference material that is not available online can be ordered through libraries or the Queen's Printer at: ***www.qp.gov.bc.ca***

? *Test Your Knowledge*
Questions on page 115

Acknowledgements

The preparation and publication of this decision aid was supported by the British Columbia Ministry of Forests and Range through the Forest Investment Account–Forest Science Program and by the Canadian Forest Service.

KEYWORDS: Cronartium ribicola*, forest health, forest management, pine stem rust management,* Ribes *spp., white pine blister rust.*

Contact Information

1 Forest Pathologist, British Columbia Ministry of Forests and Range, Coast Forest Region, 2100 Labieux Road, Nanaimo, BC V9T 6E9. Email: Stefan.Zeglen@gov.bc.ca
2 Research Scientist (retired), Canadian Forest Service, Pacific Forestry Centre, 506 West Burnside Road, Victoria, BC V8Z 1M5.
3 Forest Pathologist, British Columbia Ministry of Forests and Range, Southern Interior Forest Region, 515 Columbia Street, Kamloops, BC V2C 2T7. Email: Michelle.Cleary@gov.bc.ca

ARTICLE RECEIVED: **June 7, 2007**
ARTICLE ACCEPTED: **February 5, 2009**

Zeglen, S., R. Hunt, and M. Cleary. 2009. British Columbia's forests: White Pine Blister Rust Forest Health Stand Establishment Decision Aid. *BC Journal of Ecosystems and Management* 10(1):97–100.

White Pine Blister Rust

Norm Alexander

Infected western white pine displaying streaming pitch from a canker and multiple branch flagging.

General information

- White pine blister rust (WPBR) is caused by *Cronartium ribicola*, a non-native fungus that is an obligate parasite and requires a live host to survive and reproduce.
- First reported in 1854 on eastern white pine (*P. strobus*) planted in Estonia, WPBR spread across Europe in about 40 years. It likely originated in Asia, although an exact location is not known.
- Introduced on eastern white pine seedlings into western North America (Vancouver, BC) and possibly other locations before 1915, WPBR appeared earlier (1906) in eastern North America, also via shipments of seedlings from Europe.
- Because of the effect of WPBR on eastern white pines, the *Plant Quarantine Act* was passed in 1912; Quarantine Number 1 prohibited the importation of 5-needle pines to the United States and Canada.
- The western North American distribution ranges from British Columbia in the north (on whitebark pine) to South Dakota in the east (on limber pine), and to New Mexico (on southwestern pine) and California (on sugar pine) in the south. The disease has not yet been reported in Mexico. Western white pine is affected throughout all of its range.

Host information

Highly Susceptible: Western white pine (*Pinus monticola*), whitebark pine (*P. albicaulis*), limber pine (*P. flexilis*), and all other five-needle pines native to North America.

Immune: Non-five-needle pines and other trees.

Hazard rating

- Hazard rating is high throughout British Columbia (based on Pine Stem Rust Management Guidebook).
- Biogeoclimatic zone has no known effect on hazard rating. Hazard rating declines at elevations above 1000 m on the Coast. The steeper the slope, the higher cankers are found in the crowns, particularly on trees not selected for resistance. On such sites, consider early harvesting.

Susceptible stand characteristics

- Stands containing highly susceptible pine species (e.g., wild western white pine).
- Presence of *Ribes* species (the alternate host) in proximity (within 30 m) to susceptible species greatly increases the hazard of infection.
- In northern Idaho, some *Pedicularis* (lousewort) and *Castilleja* (paintbrush) species are confirmed alternate hosts. The impact of these hosts on the disease needs further evaluation.

Signs and symptoms

- **Symptoms:** swelling of infected tissues forming fusiform cankers often with streaming pitch, roughened bark on old (often dead) cankers, and necrotic foliage on cankered branches (so-called "red flagging").
- **Signs:** pyncial droplets forming around canker margins, orangish bark, orange aeciospores in ruptured blisters in spring, and uredial and telial structures on foliage of the alternate host.
- Diamond-shaped stem cankers expand annually, growing faster vertically than horizontally. Death occurs when secondary organisms (other fungi and insects) invade cankers, often through aecial ruptures.
- Cankers within 30 cm of stem can spread mycelia into the stem; those more than 60 cm away never infect the stem.

Life cycle

- *Cronartium ribicola* is a heteroecious, macrocyclic rust that requires two hosts and has five spore stages: pycnial and aecial on *Pinus*, and uredinial, telial, and basidial on the alternate host (see Figure 1).
- Given proper moisture and temperature conditions, infection on the pine host commences with the transfer of basidiospores to foliage and subsequent germination. The fungus enters through stomata and begins to colonize leaf tissue, often creating distinct yellow to red infection spots or bands.
- Successful infections eventually grow into the branch (or stem if infected needle is directly attached) beginning a latent period in which fungal development continues with no evident outward symptoms.
- Infected tissues swell to create a visible canker from which blisters containing orange aeciospores appear. Wind-dispersed in spring, these spores are relatively durable, travelling several kilometres to colonize an alternate host. Often, the infected needle remains attached to the canker long after other foliage has died.
- Aecia invade the leaves of the alternate host (again through the stomata); pustules form shortly after releasing short-lived urediospores that spread to adjacent foliage and intensify the disease over the summer.
- From these pustules, telia develop as hairlike columns which remain in place on the leaf underside.
- Each teliospore germinates, producing four, wind-dispersed basidiospores that travel back to a pine host, completing the asexual cycle in the late summer/fall. Life-cycle timing is delayed at higher elevations.
- Sexual reproduction occurs by transfer of pycniospores (spermatia) exuded as a sticky mass at the canker margin often a year before aecia development. Flies attracted to exudate act as vectors.

White Pine Blister Rust

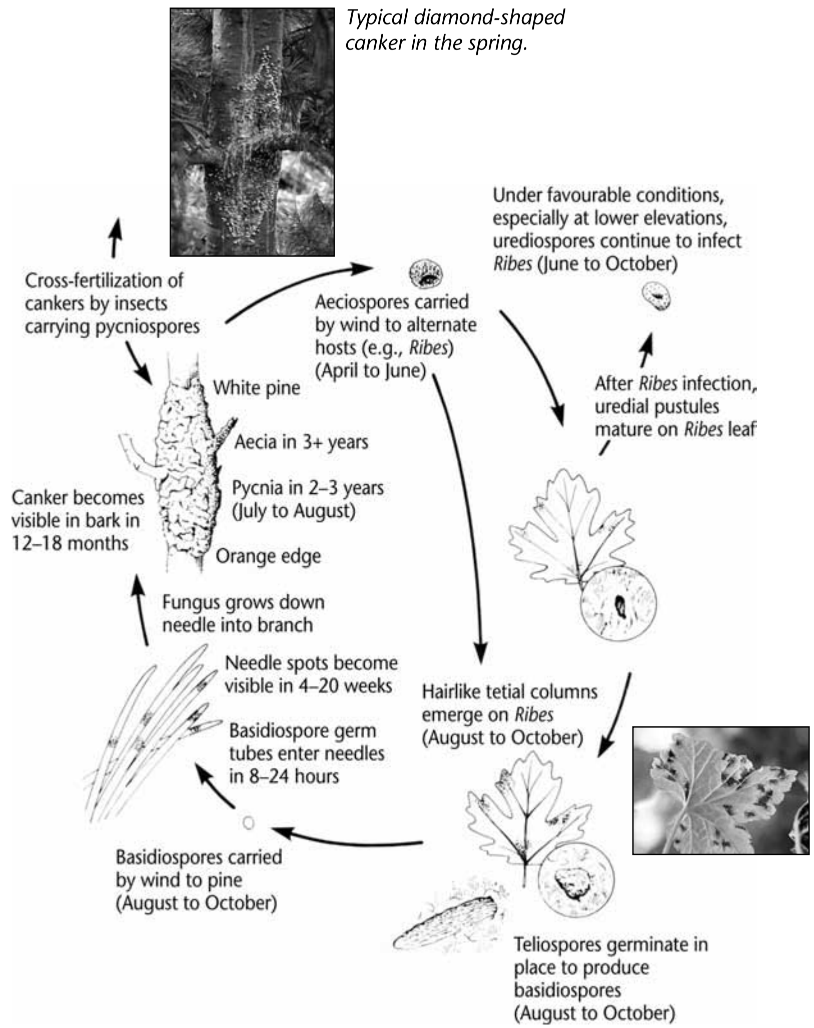


FIGURE 1. *Life cycle of white pine blister rust (Source: Canadian Forest Service; Richard Hunt photo, top).*

Disease management

For managing rust-susceptible white pine stands, the following actions are recommended to meet stocking standards.

Harvesting and site preparation

- Harvesting practices greatly affect the ability of *Ribes* spp. to regenerate. Winter logging reduces ground disturbance and provides a less inviting seedbed. Low volume removals retain canopy thus maintaining low light levels, which reduces seed germination.
- Although the use of fire for site preparation was previously advocated to reduce seedbanking, this method's effectiveness is quite inconsistent; partial disturbance may increase *Ribes* seed germination.
- If possible, threatened whitebark and limber pines should not be cut during harvesting operations to retain the genetic diversity of these species.

Alternate host eradication

- Up to the 1970s, the Americans conducted a massive *Ribes* eradication program that largely failed in the West due to the extreme difficulty of eliminating them. However, local eradication can be very effective.
- In some areas, currants are a popular crop, but their cultivation may increase the local rust hazard. Generally, black currants (*Ribes nigrum*) are very susceptible to WPBR, while red currants are less so. Rust-resistant, commercial black currant cultivars frequently show poor yields and a susceptibility to powdery mildew. Several resistant, ornamental currants are available.

Regeneration/establishment

GENETIC RESISTANCE

- In British Columbia, resistant western white pines have been sought for 25 years. Resistant selections: (1) have slowly growing small cankers (possibly conferred by "polygenes"); or (2) have developmental disease resistance (conferred by age and elevation); or (3) are "totally clean" (conferred by a single dominant, or major, gene).
- Seed orchards are composed of the first two types; coastal orchards have coastal selections and interior orchards have interior and Idaho selections. Resistant seed is available.
- Pollen from major gene resistant (Cr2) trees identified in the Cascade Range is used in coastal seed orchards to produce 50–100% "clean" seedlings that still retain superior growth characteristics. This seed should be used for coastal reforestation. Above 1000 m, use resistant stock from an interior or Idaho orchard. In the Interior, use only material from British Columbia or Idaho orchards (65% or better canker-free).

White Pine Blister Rust

SEEDLING PROTECTORS

- Enclosed seedling protectors, which physically block spores from susceptible foliage during the early growing years, show promise. Tests continue.

Stand tending

CANKER EXCISING

- As canker excision is time consuming, it should be restricted to high-value trees in parks or highly visible locations. Remove the live bark and cambial tissue surrounding the margin of a stem canker at least 5 cm past the leading side edge and 20 cm past the top and bottom edge of those that have not spread more than halfway around the stem. Moistening bark will help to define the canker boundary.

THINNING AND PRUNING STANDS

- Thinning non-resistant pine protects uninfected trees and culls infected ones. However, thinning without pruning increases WPBR infections because as thinning increases, airflow and spore circulation increases. Retain about 700 stems per hectare.
- Lower branch pruning reduces the incidence of WPBR. Over 85% of infections occur in the first 2 m; therefore, early removal of susceptible foliage reduces the number of fatal infections. Pruning should not be required when regenerating with resistant stock.
- Currently, a two-lift system is recommended. Conduct the first pruning when average stand height reaches 1–2 m, removing up to 50% (Interior) or 65% (Coast) of the live crown (leave at least three live whorls). Conduct the second pruning when trees reach 4–5 m, removing at least 50% of the live crown. To ensure wood quality in the first log, an optional third lift is possible.
- Consider autumn pruning to lessen tree damage due to bark stripping. Trimmed boughs are a non-timber forest product providing revenue if sold as ornamental floral greens. Ensure that pickers do not leave long branch stubs.
- Free-growing damage criteria state that trees with stem or branch infections less than 60 cm from the bole are unacceptable.

BIOLOGICAL CONTROL

- Other fungi will parasitize cankers and compete with WPBR. Purple mould (*Tuberculina maxima*) is associated with declining or inactive cankers; however, neither this nor other fungi have been used successfully as a biological control.

FUNGICIDES

- Although several chemicals offer prophylactic protection or kill established cankers, most provide limited or ineffective protection. However, triadimefon (not registered in Canada) provides some protection to nursery stock and seedlings when applied during planting.

Other effects and associations

- Mountain pine beetle may prefer trees with stem cankers; old basal cankers may contain decay.
- Resin-producing basal stem cankers might be confused with symptoms of Armillaria root disease.

Resource and reference list

Allen, E., D. Morrison, and G. Wallis. 1996. Common tree diseases of British Columbia. Canadian Forest Service, Pacific Forestry Centre, Victoria, BC. ***www.pfc.forestry.ca/diseases/CTD/index_e.html*** (Accessed February 2009).

British Columbia Ministry of Forests and BC Ministry of Environment, Lands and Parks. 1996. Pine stem rust management guidebook. Forest Practices Code, Victoria, BC. ***www.for.gov.bc.ca/tasb/legsregs/fpc/fpcguide/pinestem/pine-toc.htm*** (Accessed February 2009).

Hummer, K.E. and R.A. Sniezko. 2000. Introduction: *Ribes*, pines, and white pine blister rust. HortTechnology 10:514.

Hunt, R.S. 2003. White pine blister rust. Recent Research Developments in Mycology 1:73–85.

_______. 2006. Blister-rust-resistant western white pines for British Columbia. Canadian Forest Service, Pacific Forestry Centre, Victoria, BC. Information Report BC-X-397.

Hansen, E.M. and K.J. Lewis. 1997. Compendium of conifer diseases. APS, St. Paul, Minn.

Henigman, J., T. Ebata, E. Allen, J. Westfall, and A. Pollard. 2001. Field guide to forest damage in British Columbia. 2nd ed. Canadian Forest Service and BC Ministry of Forests, Victoria, BC. FRDA II Rep. No. 17.

Maloy, O.C. 1997. White pine blister rust control in North America: A case history. Annual Review of Phytopathology 35:87–109.

Schnepf, C.C. and J.W. Schwandt. 2006. Pruning western white pine. University of Idaho, Pacific Northwest Extension Publication PNW-584.

Zambino, P.J. [2009]. *Ribes* species: Biology, pathology, and implications for management of white pine blister rust. Forest Pathology. In press.

Zeglen, S., J. Pronos, and H. Merler. [2009]. Silvicultural management of five-needle pines in western North America. Forest Pathology. In press.

Discussion Paper

Relationships between habitat area, habitat quality, and populations of nesting Marbled Murrelets

Alan E. Burger[1] and F. Louise Waterhouse[2]

Abstract

We review relationships between the area and quality of apparently suitable nesting habitat (as defined by canopy structure) and the population size of Marbled Murrelets (*Brachyramphus marmoratus*) which such habitat might support. This information is important to manage the old seral forest nesting habitat of this threatened seabird. Studies at different spatial scales indicate that linear relationships provide good, biologically feasible fits between murrelet counts and areas of apparently suitable habitat when the effects of habitat quality are unknown. A large-scale analysis across Washington, Oregon, and California showed a strong linear relationship between murrelet numbers and area of habitat within large conservation regions. Seven separate watershed-level radar studies (six in British Columbia and one in Washington) support a linear relationship and also indicate that when logging reduces habitat, the murrelets do not aggregate in the remaining habitat at higher densities. Tree-climbing studies show similar trends at stand levels: compared to more pristine habitat, nest densities were not higher in remnant old-growth patches in depleted, highly fragmented areas. Do murrelets nest at higher densities in higher-quality habitat? The sparse information on this topic suggests a correspondence between nest locations and habitat quality as assessed by algorithms, air photo interpretation, and low-level aerial surveys. Most nests (92% and 86% in pooled data from aerial surveys or air photo interpretation, respectively) were found in habitat rated as Moderate, High, or Very High, and few (8% and 14%, respectively) in those rated Low, Very Low, or Nil. The relationship between perceived quality and the likelihood of nesting is, however, non-linear and it is premature to assume that murrelet nest densities will be significantly higher within the upper ranks of suitable habitat assessed from forest features.

KEYWORDS: Brachyramphus marmoratus, *habitat assessment, habitat management, habitat quality, Marbled Murrelet, nesting habitat, population–habitat relationships.*

Contact Information

1 Associate Professor (Adjunct), Department of Biology, University of Victoria, PO Box 3020, Stn CSC, Victoria, BC V8W 3N5. Email: aburger@uvic.ca

2 Research Wildlife Habitat Ecologist, Coast Forest Region, BC Ministry of Forests and Range, 2100 Labieux Road, Nanaimo, BC V9T 6E9. Email: Louise.Waterhouse@gov.bc.ca

***JEM* — VOLUME 10, NUMBER 1**

Burger, A.E. and F.L. Waterhouse. 2009. Relationships between habitat area, habitat quality, and populations of nesting Marbled Murrelets. *BC Journal of Ecosystems and Management* 10(1):101–112.

Introduction

The issue of "how much habitat is enough?" frequently arises when land managers consider maintaining wildlife habitat (Tear et al. 2005). In British Columbia, this dilemma is a regular problem, both in large-scale strategic plans such as regional land use planning, and in finer-scale planning for landscape units or watersheds. It is important to know whether a consistent relationship exists between the amount (area) of apparently suitable habitat and the number of target animals likely to use this habitat. This information can then be applied, either to determine the habitat area needed to maintain a desired wildlife population, or to estimate the number of animals likely supported by a specific area of habitat. In this paper, we assess the relationships between expected populations of nesting Marbled Murrelets (*Brachyramphus marmoratus*) and the area and quality of suitable nesting habitat in British Columbia's forests. Marbled Murrelets are listed as "Threatened" in Canada. In British Columbia, they are "red-listed" and designated as an "identified species" under the *Forest and Range Practices Act* (Canadian Marbled Murrelet Recovery Team 2003; Identified Wildlife Management Strategy 2004). Loss of nesting habitat in old seral forest is the main threat affecting this enigmatic seabird (Burger 2002; Piatt et al. 2006). This review provides a timely response to issues facing government agencies, the forest industry, and other stakeholders in planning policies, management strategies, and operational plans that involve Marbled Murrelet nesting habitat in British Columbia's old forests.

Forest managers dealing with Marbled Murrelets raise two important questions:

1. Is there a linear relationship between the expected numbers of breeding murrelets and the area of suitable nesting habitat?
2. Can murrelets be expected to nest at higher densities in better-quality habitat?

In research and strategic planning for murrelets, the measure of population is the number of birds (including breeders, failed breeders, and non-breeders) that might fly into a watershed or be counted on the ocean (e.g., Burger 2002; Piatt et al. 2006). The exact relationship between the number of nests and the number of birds entering a watershed is not known (Burger 2001; Peery et al. 2004).

It is important to know whether a consistent relationship exists between the amount of apparently suitable habitat and the number of target animals likely to use this habitat.

Background

The biology and conservation issues of Marbled Murrelets are well covered in recent reviews (Ralph et al. 1995; Burger 2002; McShane et al. 2004; Piatt et al. 2006). Apart from a negligible number (~3%) of nests located on cliff-ledges or in old deciduous trees, murrelets in British Columbia require old seral conifers (generally > 200 years old) to nest, and most nests have been found within 30 km of the sea (Burger 2002). A guideline document focusing on maintenance and restoration of forest nesting habitat outlined the intent of the Canadian Marbled Murrelet Recovery Team (CMMRT) (Canadian Marbled Murrelet Recovery Team 2003). The recovery team's recommendations helped develop a habitat algorithm currently used to map habitat across coastal British Columbia (see "Murrelet Habitat Mapping Algorithm" below).

Murrelet Habitat Mapping Algorithm

The Canadian Marbled Murrelet Recovery Team (2003) algorithm as used for mapping murrelet habitat in coastal British Columbia (e.g., Chatwin and Mather 2007) includes:

- Stands with age classes 8 (141–250 years) or 9 (250+ years) that have height class 4 (28.5 m) or greater.
- Elevations of 0–900 m, except in the North and Central Mainland Coast conservation regions where 600 m is the highest elevation and 500 m in the Haida Gwaii (Queen Charlotte Islands) region.

Based on the recovery team's guidelines (Canadian Marbled Murrelet Recovery Team 2003) and other products from the Marbled Murrelet Conservation Assessment (Burger 2002; Steventon et al. 2003, 2007), the provincial government published guidelines in the Identified Wildlife Management Strategy (IWMS) under the *Forest and Range Practices Act*. The IWMS accounts and measures for Marbled Murrelets focuses on maintaining nesting habitat within forests on Crown land (Identified Wildlife Management Strategy 2004). All of these conservation initiatives and management measures deal with maintaining likely areas of suitable nesting habitat. It is therefore important to know the relationships between habitat area and numbers of birds using the habitat.

Relationship between murrelet numbers and habitat area

Here we address the question: Is there a linear relationship between the expected numbers of breeding murrelets and the area of suitable nesting habitat? Issues of habitat quality are discussed later.

Evidence from a large-scale regional analysis

At a regional spatial scale, Raphael (2006) compared availability of inland nesting habitat and at-sea counts of Marbled Murrelets across conservation zones in Washington, Oregon, and California. He found a highly significant ($R^2 = 0.88$) positive linear relationship between murrelet numbers and area of forest habitat across nine large latitudinal segments. He concluded that the amount of nesting habitat likely sets carrying capacity, and suggested that murrelet population size would likely be reduced as habitat is lost because the birds did not aggregate in remaining suitable habitat at higher densities.

Evidence at watershed scales from radar studies

The use of high-frequency marine radar has become a standard protocol for counting Marbled Murrelets (Manley 2006), and is often used to estimate the number of murrelets entering watersheds as they fly in from the sea (Burger 2001; Cooper et al. 2001). Although the proportion of murrelets detected with radar varies according to the radar location, topography, tilt of the radar antenna, and flight paths, several studies show that radar is the most reliable method to assess local murrelet populations during the breeding season and to track changes in these populations (Arcese et al. 2005; Bigger et al. 2006; Cooper et al. 2006). Radar counts of murrelets entering watersheds include some proportion of non-breeding or failed breeders, and the exact relationship between the number of birds counted with radar and the number of nests within the watershed is not known (Burger 2001; Peery et al. 2004).

Seven separate watershed-level radar studies (six in British Columbia and one in Washington) examined the relationships between murrelet counts and habitat areas. These studies defined habitat in different ways—some used the CMMRT algorithm, but others not. Nesting density will obviously be affected by how areas of habitat are defined, but here we are interested in the nature of the census–habitat relationship and not the exact predictive equations. All seven studies indicate that linear relationships between murrelet counts and habitat areas provide a good, biologically feasible fit to the data (Table 1). Two analyses specifically testing for linearity in the trends showed that linear regressions generally were the best fit; when more complex power, quadratic, and cubic functions fit the data better, the differences were marginal and the predicted lines were close to linear (Burger et al. 2004, 2006). Several studies showed a wide scatter of points leading to relatively low predictability of the regressions, but these studies usually had low sampling (mainland British Columbia; Burger et al. 2004), problems in defining the catchment area (southwestern Vancouver Island; Burger et al. 2006), or included factors such as commuting distance which affected the murrelet densities (mainland British Columbia; Burger et al. 2004). Regional differences in the regression slopes, and hence densities (birds per hectare of habitat), suggest that a single uniform nesting density for murrelets does not exist across British Columbia (e.g., densities were lower on the mainland than on southwestern Vancouver Island; Burger et al. 2004). These regional differences might be due to variance in the distribution and quality of forest habitat, or at-sea foraging conditions (Burger et al. 2004; Ronconi 2008).

Evidence at the stand level from telemetry and tree-climbing studies

Radio-telemetry (catching murrelets at sea, attaching small radio transmitters, and tracking them back to nest sites) is the most effective tool for locating murrelet nests and hence for determining the habitat relationships of actual nest sites (Bradley 2002; Waterhouse et al. 2007,

TABLE 1. Is there a linear relationship between numbers of breeding Marbled Murrelets and area of suitable nesting habitat? Evidence from a comparison of radar counts of murrelets entering defined catchments with the areas of likely suitable habitat within those catchments.

Study area and reference	Sample effort	Conclusions
Clayoquot Sound, British Columbia (Burger 2001)	Radar counts in 18 watersheds over 3 years	Significant positive linear relationship between radar counts and areas of low-elevation mature forest. Logged watersheds had lower than expected counts based on original forest area. Where logging removed suitable habitat, the murrelets were not aggregated in the remaining habitat at higher densities.
Olympic Peninsula, Washington (Raphael et al. 2002)	Radar counts in 10 watersheds over 3 years	Significant positive linear correlations between murrelet counts and core areas of late-seral forest. Additional negative effects of amount of forest edge and isolation of forest patches.
Comparison of five regional studies (two on southwest Vancouver Island and three on the British Columbia mainland; Burger et al. 2004)[a]	Variable effort in each study (1–3 years of surveys and 18–25 watersheds per study). Pooled data covered >18 000 birds at 101 watersheds (> 2 million ha)	Both linear and non-linear (power curves) equations showed significant regressions between murrelet counts and habitat area. Linear regressions were the best predictor for the west Vancouver Island data; power curves best fit the mainland data (but shape of power curves was near-linear). Slopes of relationships indicated higher densities for west Vancouver Island than the British Columbia mainland. Watersheds at the heads of long inlets or fjords had fewer murrelets than expected.
Southwest Vancouver Island – south of Clayoquot Sound (Burger et al. 2006)	Radar counts at 25 watersheds over 4 years	Significant positive linear relationship between radar counts and areas of likely habitat. Complex quadratic and cubic equations gave marginally better fits than linear regression, but all regression lines were close to linear in shape.

[a] This analysis includes the Clayoquot Sound study (Burger 2001), which is also treated separately here to highlight some analyses not included in the pooled data (Burger et al. 2004).

2008, 2009). Locating nests with telemetry provides no data on the density of nests or the shape of the relationship between number of nests and habitat area; this is because only a fraction of the existing nests can be located by telemetry in any breeding season. The telemetry data, however, do suggest that nests are widely separated: distances between active nests of tagged birds averaged 4.6 ± 4.0 (SD) km in Desolation Sound and 6.6 ± 4.2 km in Clayoquot Sound (Zharikov et al. 2007).

Three studies in British Columbia estimated nest densities by climbing randomly selected trees within selected habitat types (reviewed by Conroy et al. 2002). Nest depressions remain visible for several years after use and therefore the density of all visible nests overestimates the density of nests active within a breeding season. The density of visible nests in fragmented habitat on the Sunshine Coast was 0.3–0.7 nests per hectare (mean and SD not available), which was similar to densities of visible nests in more pristine habitat in Clayoquot Sound (mean 0.53 ± 0.24 [SD], 95% confidence limits, 0.05–1.0 nests per hectare) and Carmanah-Walbran (0.60 ± 0.35, 95% confidence limits, 0.25–0.95 nests per hectare). Conroy et al. (2002) interpreted this as evidence that murrelet nests were not aggregated in remaining patches at higher densities in the highly logged and fragmented landscape (Desolation Sound).

Summary

Overall, statistically significant and relatively consistent evidence at a range of spatial scales (regional, watershed, and stand) shows that murrelets nest at low densities in suitable habitat, that populations usually exhibit a significant positive and linear relationship with available area of suitable habitat, and that in areas of reduced or fragmented habitat murrelets do not aggregate in the remaining habitat at higher densities. As most of the tests were correlations, inferring causal relationships should be done with caution. Nevertheless, there is good support for a linear relationship between the number of breeding murrelets and the area of suitable nesting habitat, although the slope of the relationship (number of birds per hectare added) may vary regionally.

Relationship between nesting density and habitat quality

The relationship between nesting density and habitat quality is an important issue in British Columbia. By focusing on higher-quality habitats, it may be possible to reduce the forest area set aside to manage murrelets, and thereby reduce impacts on timber supply. The implication is that higher-quality habitat has a higher probability of use and will support a higher density of nesting murrelets. Currently, the CMMRT algorithm provides no opportunity to rank habitat by quality, but more refined habitat ranking could provide opportunities for wildlife managers to offset habitat area with habitat quality, minimizing economic impacts for the timber industry.

It is not clear what constitutes high-quality nesting habitat for Marbled Murrelets. The essential requisites for nesting appear to be: tall trees, which facilitate entry and exit for birds of low maneuverability in flight; broad limbs or deformities, which provide platforms for nests (usually with epiphyte cover); and forest canopy gaps, which provide access (Burger 2002; Canadian Marbled Murrelet Recovery Team 2003; Identified Wildlife Management Strategy 2004). Several algorithms developed in British Columbia and the United States predict or rank habitat suitability for nesting murrelets with mixed success (reviewed by Tripp 2001, Burger 2002). New methods for ranking murrelet habitat based on air photo interpretation and low-level aerial surveys have been developed (Burger [editor] 2004; Table 2) and are widely applied in British Columbia by government ministries and the forest industry. These methods show some promise in identifying most of the known nest sites (Waterhouse et al. 2008, 2009), but no studies have compared such habitat rankings with actual densities of nesting murrelets. A study comparing radar counts with habitat rankings at the watershed level is under way (D. Lank, Simon Fraser University, pers. comm.).

Do murrelets nest at higher densities in higher-quality habitat?

Nest density might vary with habitat quality in several ways. Four likely options are provided by the Linear, Neutral, Threshold, and Modified Threshold models (see Figure 1 for details). These options can be regarded as competing hypotheses for comparison with available data, and we envisage them as applying to habitat use at a range of spatial scales from small patches (1–3 ha) to watersheds.

TABLE 2. Ranking system used in the protocols for air photo interpretation and aerial surveys of Marbled Murrelet habitat (see Burger [editor, 2004] for further details).

Rank	Habitat value	General description of habitat quality	% assessed area with habitat feature present
1	Very High	Key habitat features present in abundance; nesting highly likely	50–100
2	High	Key habitat features common and widespread; nesting likely	25–50
3	Moderate	Key habitat features present but uncommon and patchy; nesting likely but at moderate to low densities	6–25
4	Low	Key habitat features all evident but patchy and sparse; nesting possible but unlikely or at very low density	2–5
5	Very Low	Key habitat features sparse and all may not be present; nesting highly unlikely	~ 1
6	Nil	All key habitat features absent; nesting impossible (e.g., bogs, bare rock)	0

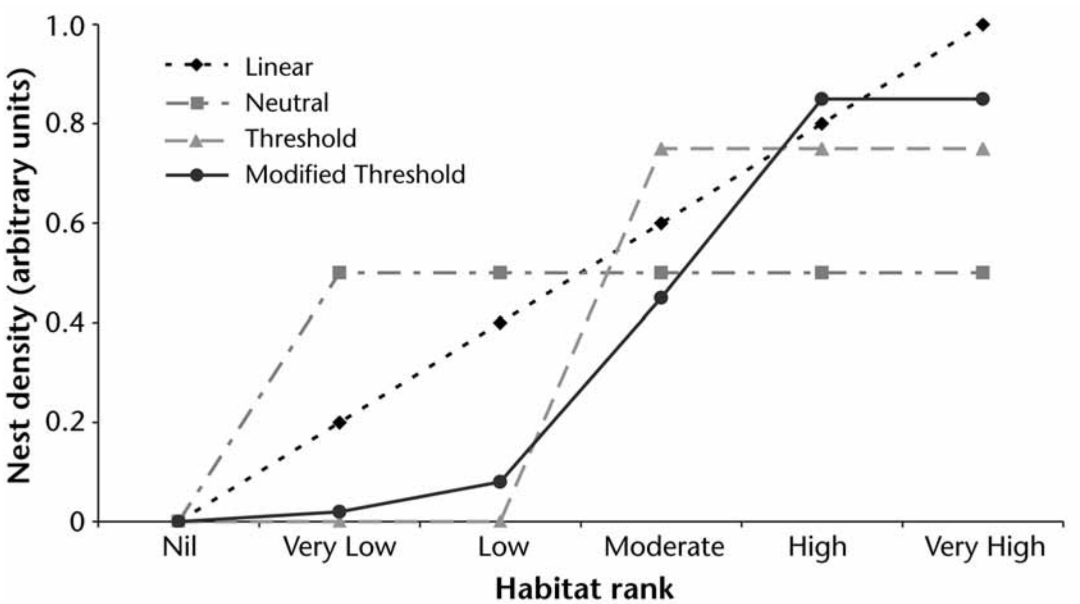


FIGURE 1. Four possible ways in which nest density of Marbled Murrelets might vary with habitat quality as ranked by air photographs or aerial surveys in British Columbia. All options assume no nesting in the Nil habitat rank. The Linear model assumes a linear trend from zero to maximum density correlated with habitat rank. The Neutral model assumes no effect on nest density by habitat rank above Nil. The Threshold model assumes no nesting in the lowest three ranks, but equal densities in the upper three ranks. The Modified Threshold model assumes a low expectation of nesting in the Low and Very Low ranks, intermediate densities in the Moderate rank, and equal high densities in the High and Very High ranks.

Several studies have compared the distribution of known murrelet nests across the ranks of habitat quality (Table 2) as assessed by air photo interpretation and low-level aerial surveys (Waterhouse et al. 2007, 2008, 2009). Using aerial surveys, 111 nest sites from southern British Columbia (Desolation Sound and Toba Inlet on the southern mainland and Clayoquot Sound on Vancouver Island) were compared with 139 randomly selected points in forests more than 140 years old in the same watersheds. The nest sites occurred more frequently than expected in the higher-ranked categories, with some regional variation evident (Waterhouse et al. 2009). Overall, nest sites were more likely in habitat ranked in aerial surveys as "High" or "Very High" than in the pooled "Moderate–Low" categories. The pooled sample of 118 nest sites (i.e., the 111 from southern British Columbia plus 7 from Haida Gwaii) showed that 92% of nests were found in habitat ranked as "Moderate," "High," or "Very High" by aerial surveys (Figure 2). A similar analysis using air photo interpretation showed that, compared to random sites, forest patches with nests more often ranked high (Very High + High pooled) and less often ranked low (Low + Very Low pooled), but showed no difference for Moderate ranks (Waterhouse et al. 2008). In general, the air photo interpretation analysis tended to rank habitat lower than the low-level aerial surveys, probably because potential nest platforms are not visible on air photos. Nevertheless, 86% of nests were in the upper three air-photo ranks (Figure 2).

Bahn and Lank (in prep.) address the issue of habitat quality in their comparison of actual nest sites in Clayoquot Sound relative to the rankings produced by the Bahn and Newsom (2002) habitat suitability model. Based on the availability of suitable nesting structures, the model did a reasonable job in predicting where the nests might occur. The upper two ranks (Excellent and Good) had twice the probability of nest use compared to the lower two ranks (Low and Suboptimal), but little difference was evident between the use of higher ranks (Excellent vs. Good). Two of the 31 nests (6%) fell within the "Unsuitable" category of the best model. Bahn and Lank (in prep.) suggest that natural selection has not led to strong aggregations of murrelets in nesting

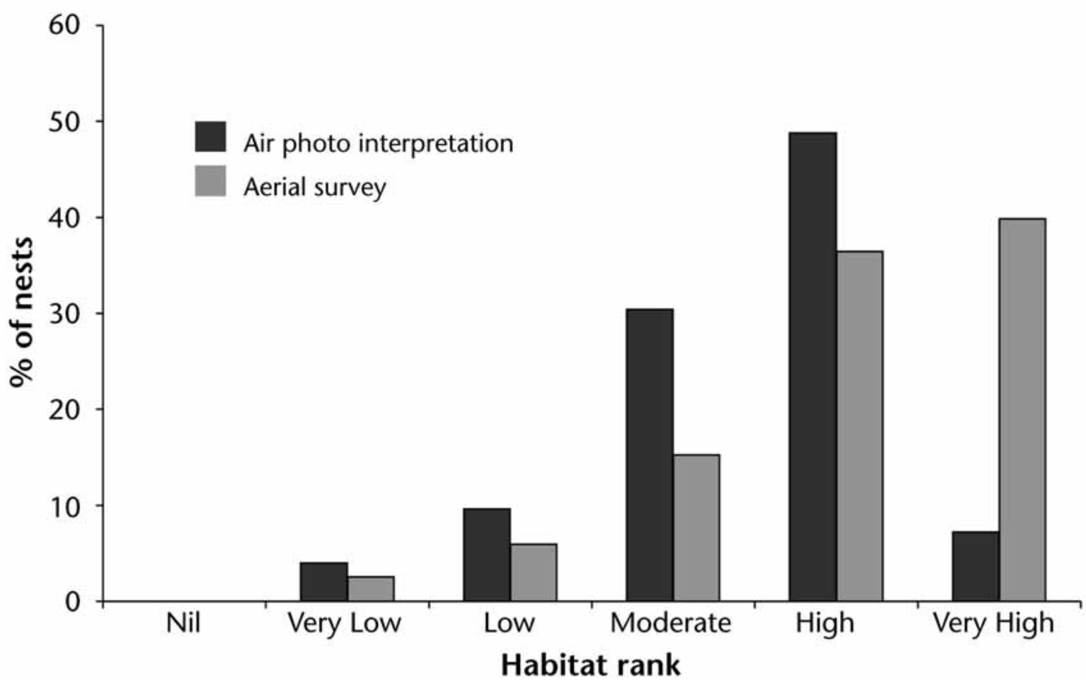


FIGURE 2. Habitat quality of forest patches (~3 ha; 100 m radius) within forests older than 140 years in British Columbia that contained a nest, as assessed by air photo interpretation (*n* = 125 nests) and low-level aerial surveys (*n* = 118 nests). Data from Waterhouse et al. (2007, 2009); see these sources for more detailed comparison between nest sites and randomly selected points in the same watersheds.

habitat which offers the most or best nesting structures. They speculate that murrelets use behavioural strategies to keep nesting densities low overall, perhaps to avoid detection and search image formation by predators. Consequently, murrelets nest at low densities in all habitats; only those habitats failing to support nests at low densities are expected to be identified in such an analysis. They conclude that murrelet modelling should use a constraint approach rather than a correlative one. In other words, managers could assume that few nests might be found in the lowest ranked habitat, but habitats ranked at the high end might not support higher densities than those in the mid-range.

As explained above, telemetry data cannot be used to test density effects. Conroy et al. (2002) compared densities of nests located with randomized tree climbing in habitats ranked as "Excellent," "Good," or "Sub-optimal" using the Bahn and Newsom (2002) habitat suitability model. At the tree-climbing plots, the density of trees with potential nest platforms in the Excellent, Good, and Sub-optimal categories was 30 ± 14, 37 ± 27, and 12 ± 11 trees per hectare, respectively (240, 139, and 88 trees climbed, respectively). From these tree searches, the density of nests active in the year of discovery was 0.11 ± 0.2 nests per hectare in the Excellent category and zero in both the Good and Sub-optimal categories. Although the results seem to indicate higher probability of nesting in higher-ranked habitat, the sample sizes here were unequal and perhaps insufficient to adequately sample the sparse distribution of nests.

Using a combination of forest-cover mapping data and radar counts of murrelets applied to a Bayesian habitat quality model, Steventon (2008) predicted the likely density of breeding murrelets in watersheds on the north coast of British Columbia. He then compared these expected densities with low-level aerial assessments made at 94 sites in the region using the map-based forest cover attributes for each site (Figure 3). The results show a positive correspondence between habitat rank and expected density. Because this approach combines watershed-level counts of murrelets with patch-level helicopter assessments, the comparison is expected to show only broad trends; these data are therefore not strictly comparable with those from actual nest sites (Figure 2). This explains why

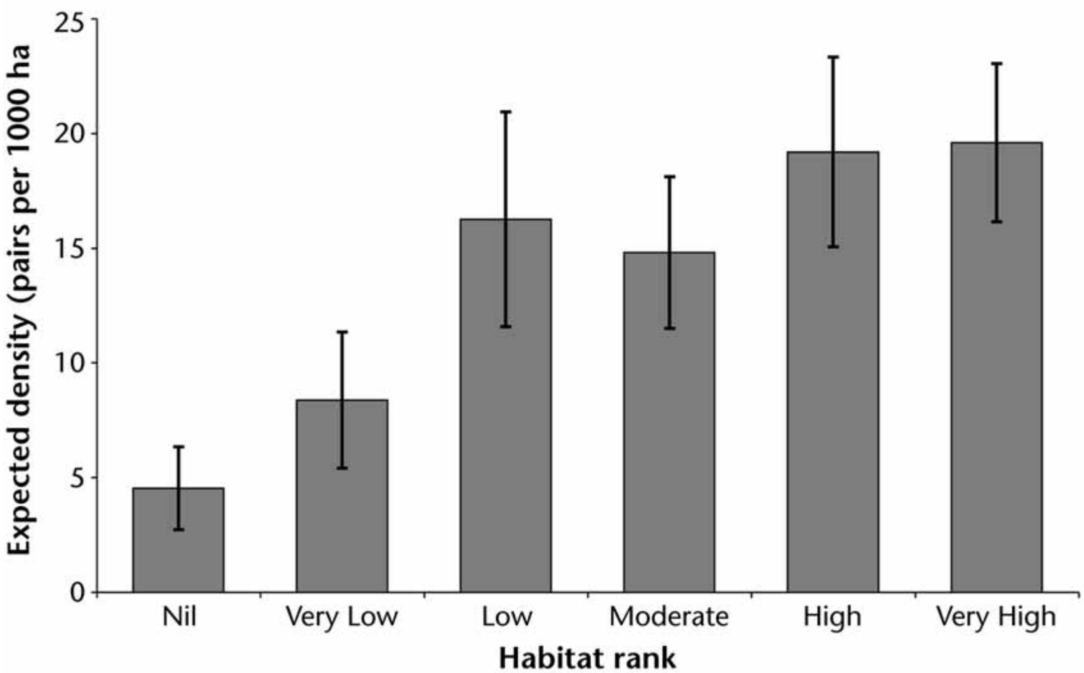


FIGURE 3. Comparison of the predicted nesting density of Marbled Murrelets (± SE), derived from a combination of habitat modelling and radar counts in watersheds on the north coast of British Columbia, relative to the habitat rankings made from low-level aerial surveys (from Steventon 2008). Densities were estimates for each of 94 patches made from the Bayesian habitat quality model incorporating radar counts (see Steventon 2008 for details) and the habitat ranks for each patch followed the six-rank aerial survey classification (see Burger [editor, 2004]).

Steventon's (2008) modelling predicts some nesting even in habitat ranked as "Low" and "Nil," due to averaging of habitat values across watersheds, which most likely also included better-quality habitat.

Summary

Murrelets do appear to preferentially select nest sites that correspond broadly to the mid- and upper-ranks of habitat quality as ranked by habitat suitability models, air photo interpretation, or low-level aerial surveys. However, within the mid- to upper-ranks, the habitat ranking and the likelihood of nesting do not closely correspond. Relative to the four schematic models (Figure 1), the available data show little or no support for the Linear and Neutral models. The Threshold model fails because some nesting does occur in the lower ranks of habitat quality. The best fit to the various data sets is the Modified Threshold model where:

- a few nests are expected in lower-quality habitat;
- intermediate ranks (e.g., "Moderate" in Table 2) show intermediate likelihood of nesting; and
- the upper habitat ranks are most likely to be used for nesting, but no differences are likely within the upper ranks themselves.

Clearly, no simple relationship exists between habitat quality and the expectation of nesting or nest density and this should be the focus of ongoing research.

Conclusions and management implications

A linear relationship is clearly evident between murrelet numbers and habitat area when habitat quality is not known or is averaged across large spatial units. The slope of this relationship, however, appears to vary by geographic location. Several factors might influence this slope including forest habitat quality, marine food availability, and the effects of commuting distance for the murrelets (Burger et al. 2004). The probability of nesting does appear to be affected by habitat quality as assessed by algorithms, air photo interpretation, and low-level aerial surveys. Nest density is likely to be affected by the probability of habitat use, but there is clearly not a simple linear or threshold relationship between habitat quality and nest density. In suitable habitat, the densities of murrelet nests appear low (likely in the range of 1 nest for every 10–40 ha of suitable forest based on radar data; Burger et al. 2004), and are likely similar across the upper ranks of habitat quality. These conclusions are tentative and could change as more information on habitat associations becomes available from radar studies, improved habitat assessment methods, improved habitat modelling, and a better understanding of the behaviour and life history of Marbled Murrelets.

At the strategic level, these tentative conclusions have important implications. The Canadian Marbled Murrelet Recovery Team (2003) recommends that no more than 30% of the suitable nesting habitat, which existed in 2002 across coastal British Columbia, should be lost by 2032 and that the area of suitable habitat should remain stable after 2032. Consequently, 70% of the available habitat suitable for nesting murrelets is needed to support 70% of the existing breeding population, and the amounts of habitat maintained in the six murrelet conservation regions should be proportioned assuming a linear 1:1 population–habitat relationship. In this context, it seems prudent to include as suitable all habitat ranked as "Moderate" through "Very High" by air photo interpretation or low-level aerial surveys, and perhaps assume that a small proportion of nests (about 10% based on the aerial survey and air photo results) might fall within those habitats ranked as "Low" or "Very Low." Aerial surveys could help to confirm nest habitat attributes in areas to be maintained that are ranked "Moderate" by air photo interpretation.

Until the shape of the nest density response to habitat quality is clarified, the prudent operational approach would see the application of the same 1:1 linear relationship in the management of landscape units and watersheds, avoiding assumptions that areas ranked as "High" or "Very High" will support higher densities than those ranked as "Moderate." Nevertheless, habitat quality should be taken into account to avoid inclusion of poor habitat and, if possible, habitat suitability should be confirmed with aerial surveys. Habitat quality and confirmation of habitat suitability might be important when following current forestry regulations and directives that emphasize the maintenance of murrelet habitat within the non-contributing land base rather than within the timber harvesting land base (Forest Practices Board 2008).

Practitioners at both the strategic and operational levels need to better understand the regional relationships between murrelet numbers and habitat area and the regional responses to habitat quality.

Practitioners at both the strategic and operational levels need to better understand the regional relationships between murrelet numbers and habitat area (i.e., the slope of the population–habitat curve) and the regional responses to habitat quality. This knowledge would allow fine-tuning of nest habitat maintenance in each region, which is especially important in those parts of the murrelet's range where habitat is most depleted and management options are limited (e.g., southern mainland and eastern Vancouver Island; see Canadian Marbled Murrelet Recovery Team 2003).

Acknowledgements

Support for this review was provided by the Forest Investment Account–Forest Sciences Program, the BC Forest Practices Board, BC Ministry of Forests and Range, and NSERC Canada. The opinions expressed in this review are not necessarily shared by these organizations. We thank the many murrelet researchers and managers in British Columbia who have discussed these issues over many years, especially D. Heppner, D. Steventon, B. van Drimmelen, and W. Wall who provided comments on earlier drafts. Edits by S. Bannerman improved the paper.

References

? TEST YOUR KNOWLEDGE
Questions on page 115

Arcese P., B. Bertram, A.E. Burger, S. Cullen, J. Deal, J. Gibbs, A. Fall, A. Harfenist, W. Harper, G. Jones, D. Lank, D. Lindsay, I. Manley, E. Selak, S. Runyan, B. Schroeder, C. Staudhamer, D. Steventon, and G. Sutherland. 2005. Monitoring designs to detect population declines and identify their causes in the Marbled Murrelet. Centre for Applied Conservation Research, University of British Columbia, Vancouver BC. Unpublished report.

Bahn, V. and D. Lank. Achieving robust analyses of habitat suitability using an array of advanced techniques illustrated on the Marbled Murrelet (*Brachyramphus marmoratus*). Department of Biological Sciences, Simon Fraser University, Burnaby, BC. In preparation.

Bahn, V. and D. Newsom. 2002. Habitat suitability mapping for Marbled Murrelets in Clayoquot Sound. *In* Multi-scale studies of populations, distribution and habitat associations of Marbled Murrelets in Clayoquot Sound, British Columbia. A.E. Burger and T.A. Chatwin (editors). BC Ministry of Water, Land and Air Protection, Victoria, BC, pp. 101–119. ***wlapwww.gov.bc.ca/wld/documents/techpub/mamuwebs.pdf*** (Accessed February 2009).

Bigger, D., M.Z. Peery, J. Baldwin, S. Chinnici, and S.P. Courtney. 2006. Power to detect trends in marbled murrelet populations using audiovisual and radar surveys. Journal of Wildlife Management 70:492–503.

Bradley, R.W. 2002. Breeding ecology of radio-marked Marbled Murrelets (*Brachyramphus marmoratus*) in Desolation Sound, British Columbia. MSc Thesis. Simon Fraser University, Burnaby, BC.

Burger, A.E. 2001. Using radar to estimate populations and assess habitat associations of Marbled Murrelets. Journal of Wildlife Management 65:696–715.

_______. 2002. Conservation assessment of Marbled Murrelets in British Columbia: Review of the biology, populations, habitat associations, and conservation (Marbled Murrelet Conservation Assessment, Part A). Canadian Wildlife Service, Delta, BC. Technical Report Series No. 387. ***www.sfu.ca/biology/wildberg/bertram/mamurt/links.htm*** (Accessed February 2009).

_______. (editor). 2004. Standard methods for identifying and ranking nesting habitat of Marbled Murrelets (*Brachyramphus marmoratus*) in British Columbia using air photo interpretation and low-level aerial surveys. BC Ministry of Water, Land and Air Protection, Biodiversity Branch, Victoria, BC. ***www.env.gov.bc.ca/wld/documents/fia_docs/mamu_standard.pdf*** (Accessed February 2009).

Burger, A.E., T.A. Chatwin, S.A. Cullen, N.P. Holmes, I.A. Manley, M.H. Mather, B.K. Schroeder, J.D. Steventon, J.E. Duncan, P. Arcese, and E. Selak. 2004. Application of radar surveys in the management of nesting habitat of Marbled Murrelets (*Brachyramphus marmoratus*). Marine Ornithology 32:1–11.

Burger, A.E., R.E. Page, C.J. Conroy, and B.K. Schroeder. 2006. Application of radar counts and forest cover GIS data to assess habitat associations of Marbled Murrelets breeding on southwest Vancouver Island. Department of Biology, University of Victoria, Victoria, BC. Unpublished report.

Chatwin, T.A. and M. Mather. 2007. Background document to accompany B.C. coastal Marbled Murrelet habitat suitability maps. BC Ministry of Environment, Nanaimo, BC. Unpublished report.

Canadian Marbled Murrelet Recovery Team. 2003. Marbled Murrelet Conservation Assessment 2003, Part B – Marbled Murrelet Recovery Team advisory document on conservation and management. Canadian Wildlife Service, Delta, BC. ***www.sfu.ca/biology/wildberg/bertram/mamurt/links.htm*** (Accessed February 2009).

Conroy, C.J., V. Bahn, M.S. Rodway, L. Ainsworth, and D. Newsom. 2002. Estimating nest densities for Marbled Murrelets in three habitat suitability categories in the Ursus Valley, Clayoquot Sound. *In* Multi-scale studies of populations, distribution and habitat associations of Marbled Murrelets in Clayoquot Sound, British Columbia. A.E. Burger and T.A. Chatwin (editors). BC Ministry of Water, Land and Air Protection, Victoria, BC, pp. 121–137. ***wlapwww.gov.bc.ca/wld/documents/techpub/mamuwebs.pdf*** (Accessed February 2009).

Cooper, B.A., M.G. Raphael, and D. Evans Mack. 2001. Radar-based monitoring of marbled murrelets. Condor 103:219–229.

Cooper, B.A., M.G. Raphael, and M.Z. Peery. 2006. Trends in radar-based counts of Marbled Murrelets on the Olympic Peninsula, Washington, 1996–2004. Condor 108:936–947.

Forest Practices Board. 2008. Conservation of Species at Risk under the *Forest and Range Practices Act*: Marbled Murrelets on the Sunshine Coast. British Columbia Forest Practices Board, Victoria, BC. Special Investigation Report FPB/SIR/22. ***www.fpb.gov.bc.ca/special/investigations/SIR22/SIR22.pdf*** (Accessed February 2009).

Identified Wildlife Management Strategy. 2004. Accounts and measures for managing identified wildlife: Marbled Murrelet (*Brachyramphus marmoratus*). BC Ministry of Water, Land and Air

Protection, Biodiversity Branch, Victoria, BC. ***www.env.gov.bc.ca/wld/frpa/iwms/accounts.html*** (Accessed February 2009).

Manley, I. 2006. Inventory methods for Marbled Murrelet radar surveys. Standards for components of British Columbia's biodiversity No. 10a. Resources Information Standards Committee, BC Ministry of Environment, Ecosystems Branch, Victoria, BC. ***ilmbwww.gov.bc.ca/risc/pubs/tebiodiv/index.htm*** (Accessed February 2009).

McShane, C., T. Hamer, H. Carter, G. Swartzman, V. Friesen, D. Ainley, R. Tressler, K. Nelson, A. Burger, L. Spear, T. Monagen, R. Martin, L. Henkel, K. Prindle, C. Strong, and J. Keany. 2004. Evaluation report for the 5-year status review of the Marbled Murrelet in Washington, Oregon, and California. EDAW, Inc., Seattle, Wash. Report to US Fish and Wildlife Service, Region 1 (Portland, Oreg.). ***www.earthjustice.org/library/background/marbled_murrelet_status_review_pdf.html*** (Accessed February 2009).

Peery, M.Z., S.R. Beissinger, S.H. Newman, B.H. Becker, E. Burkett, and T.D. Williams. 2004. Individual and temporal variations in inland flight behavior of Marbled Murrelets: Implications for population monitoring. Condor 106:344–353.

Piatt, J.F., K.J. Kuletz, A.E. Burger, S.A. Hatch, V.L. Friesen, T.P. Birt, M.L. Arimitsu, G.S. Drew, A.M.A. Harding, and K.S. Bixler. 2006. Status review of the Marbled Murrelet (*Brachyramphus marmoratus*) in Alaska and British Columbia. US Geological Survey Open-File Report 2006-1387. ***pubs.usgs.gov/of/2006/1387/*** (Accessed February 2009).

Ralph, C.J., G.L. Hunt Jr., M.G. Raphael, and J.F Piatt (editors). 1995. Ecology and conservation of the Marbled Murrelet in North America. US Department of Agriculture Forest Service, Pacific Southwest Research Station, Albany, Calif. General Technical Report PSW-GTR-152. ***www.fs.fed.us/psw/rsl/projects/wild/gtr152/*** (Accessed February 2009).

Raphael, M.G. 2006. Conservation of the Marbled Murrelet under the Northwest Forest Plan. Conservation Biology 20:297–305.

Raphael, M.G., D. Evans Mack, and B.A. Cooper. 2002. Landscape-scale relationships between abundance of Marbled Murrelets and distribution of nesting habitat. Condor 104:331–342.

Ronconi, R.A. 2008. Patterns and processes of marine habitat selection: Foraging ecology, competition and coexistence among coastal seabirds. PhD dissertation, University of Victoria, Department of Biology, Victoria, BC.

Steventon, J.D. 2008. Conservation of marbled murrelets in British Columbia. *In* Bayesian networks: A practical guide to applications. O. Pourret, P. Naim, and B. Marcot (editors). Wiley and Sons, Chichester, UK. pp. 127–148.

Steventon, J.D., G.D. Sutherland, and P. Arcese. 2003. Long-term risks to Marbled Murrelet (*Brachyramphus marmoratus*) populations: Assessing alternative forest management policies in coastal British Columbia. BC Ministry of Forests, Research Branch, Victoria, BC. Technical Report No. 012. ***www.for.gov.bc.ca/hfd/pubs/Docs/Tr/Tr012.htm*** (Accessed February 2009).

_______. 2007. A population-viability-based risk assessment of Marbled Murrelet nesting habitat policy in British Columbia. Canadian Journal of Forest Research 36:3075–3086.

Tear, T.H., P. Kareiva, P.L. Angermeier, P. Comer, B. Czech, R. Kautz, L. Landon, D. Mehlman, K. Murphy, M. Ruckelshaus, J.M. Scott, and G. Wilhere. 2005. How much is enough? The recurrent problem of setting measurable objectives in conservation. Bioscience 55:835–849.

Tripp, T. 2001. A synopsis of Marbled Murrelet habitat suitability models in BC. Ministry of Water, Land and Air Protection, Habitat Branch, Victoria, BC. Unpublished report.

Waterhouse, F.L., A.E. Burger, A. Cober, A. Donaldson, and P.K. Ott. 2007. Assessing habitat quality of Marbled Murrelet nest sites on the Queen Charlotte Islands/Haida Gwaii, by algorithm, airphoto interpretation, and aerial survey methods. BC Ministry of Forests and Range, Coast Forest Region, Nanaimo, BC. Technical Report TR-035. ***www.for.gov.bc.ca/rco/research/vanpublicat.htm*** (Accessed February 2009).

Waterhouse, F.L., A. Donaldson, D.B. Lank, P.K. Ott, and E.A. Krebs. 2008. Using air photos to interpret quality of Marbled Murrelet nesting habitat in south coastal British Columbia. BC Journal of Ecosystems and Management 9:17–37. ***www.forrex.org/publications/jem/ISS47/vol9_no1_art3.pdf*** (Accessed February 2009).

Waterhouse, F.L., A.E. Burger, D.B. Lank, P.K. Ott, E.A. Krebs, and N. Parker. 2009. Using the low-level aerial survey method to identify Marbled Murrelet nesting habitat. BC Journal of Ecosystems and Management 10(1):80–96. ***www.forrex.org/publications/jem/ISS50/vol10_no1_art8.pdf*** (Accessed February 2009).

Zharikov, Y., D. Lank, and F. Cooke. 2007. Influence of landscape pattern on breeding distribution and success in a threatened Alcid, the marbled murrelet: Model transferability and management implications. Journal of Applied Ecology 44:748–759.

ARTICLE RECEIVED: **October 27, 2008**
ARTICLE ACCEPTED: **February 13, 2009**

Test Your Knowledge . . .

How well can you recall some of the main messages in the preceding articles? Test your knowledge by answering the following questions. Answers appear on page 116.

ARTICLE 1

British Columbia's Northern Interior Forests: Dothistroma Stand Establishment Decision Aid, by Larry McCulloch and Alex Woods

1. New infections are likely to be highest:
   A) In the fall, when it is cool and moist
   B) In the summer during cool dry periods
   C) During warm, humid conditions in the growing season
2. Only the current years' pine needles are susceptible.
   A) True
   B) False
3. The best strategy for avoiding Dothistroma infections on dry sites is to:
   A) Avoid clearcutting
   B) Plant an exotic pine species
   C) Spray the area with copper fungicides
   D) Plant Douglas-fir
   E) Plant a mix of pine, spruce, and Douglas-fir

ARTICLE 2

New methods for assessing Marbled Murrelet nesting habitat: Air photo interpretation and low-level aerial surveys, by Alan E. Burger, F. Louise Waterhouse, Ann Donaldson, Carolyn Whittaker, and David B. Lank

1. Which of the following features important to Marbled Murrelets can be assessed by low-level aerial surveys, but not with air photo interpretation?
   A) Tree height
   B) Canopy complexity
   C) Potential nest platforms
   D) Overall habitat quality
2. Most murrelet nests have been found in habitat patches ranked by air photo interpretation as:
   A) Low to Very High
   B) Moderate to High
   C) Moderate to Very High
   D) High to Very High
3. Because of the high cost of helicopter flights low-level aerial surveys are well-suited for:
   A) Research on actual nest sites found with telemetry
   B) Confirming habitat suitability after application of habitat algorithms
   C) Confirming the suitability of Wildlife Habitat Areas for murrelets
   D) All of the above apply

ARTICLE 3

Profitability of manual brushing in young lodgepole pine plantations, by Christopher Opio, Karima Fredj, and Baotai Wang

1. The break-even relative additional cost (BeRAC) represents:
   A) The critical value that a new treatment's actual relative additional cost (ARAC) should not exceed for the treatment to be profitable.
   B) The critical value that a new treatment's actual relative additional cost (ARAC) should be equal to in order for the treatment to be profitable.
   C) The value of the additional cost of a new treatment relative to the value of a just-established stand.
2. A brushing treatment with an actual relative additional cost (ARAC) equal to 2% can be interpreted as:
   A) The brushing treatment results in an actual additional cost increase of 2% relative to the stand value.
   B) The brushing treatment's actual additional cost represents 2% of the stand value.
   C) The brushing treatment is profitable if its actual relative additional cost represents 2% of the stand value.
3. According to Table 1, a single brushing applied at a radius of 1.25 m when the discount rate is equal to 2%:
   A) Requires at least 2 years of time gain to become profitable.
   B) Is profitable for less than 2 years of time gain.
   C) Is only profitable if the time gain is equal to 2 years.

ARTICLE 4

An overview of the effects of forest management on groundwater hydrology, by Brian D. Smerdon, Todd E. Redding, and Jos Beckers

1. Groundwater is:
   A) Water in the soil
   B) Water in small puddles on the ground surface
   C) Water that occurs within the zone of saturation beneath the Earth's surface
   D) All of the above

2. The proposed hydrogeologic landscapes are based on:
   A) Climate zones
   B) Vegetation zones
   C) Geology
   D) Physiography
   E) All of the above

3. Hypothesized effects of forest harvesting on groundwater in steep, wet coastal environments includes:
   A) Decreased pore water pressures
   B) Increased shallow groundwater flow
   C) A large increase in deep (regional) groundwater flow
   D) Decreased surface runoff

ARTICLE 5

Aerial overview survey of the mountain pine beetle epidemic in British Columbia: Communication of impacts, by Michael A. Wulder, Joanne C. White, Danny Grills, Trisalyn Nelson, Nicholas C. Coops, and Tim Ebata

1. Annual aerial overview surveys in British Columbia:
   A) Are conducted from fixed-wing aircraft and collect data on a variety of forest health concerns
   B) Provide operational data used for harvest planning
   c) Are used to count the number of trees infested with mountain pine beetle

2. Shelf life measures:
   A) The length of time required for mountain pine beetle to successfully attack and kill a host tree
   B) The length of time since attack within which mountain pine beetle killed trees are still economically merchantable
   C) The length of time it takes for the foliage of an attacked tree to turn a characteristic red colour

3. Which two factors have contributed to mountain pine beetle spread?
   A) Warm winter temperatures and urban forests
   B) Fire suppression and several years of favourable climatic conditions
   C) Plantation forestry and fire suppression

ARTICLE 6

Ecological descriptions of Pacific golden chanterelle (*Cantharellus formosus*) habitat and estimates of its extent in Haida Gwaii, by J. Marty Kranabetter, Harry Williams, and Jacques Morin

1. Commercial picking of golden chanterelles on Haida Gwaii typically occurs in:
   A) High-elevation, productive forests of yellow-cedar and mountain hemlock
   B) Open, grassy meadows adjoining coastal beaches
   C) Low-elevation, moderately productive forests of western hemlock and Sitka spruce

2. The yields of golden chanterelles are typically best in:
   A) Old-growth forests with high amounts of coarse woody debris
   B) Second-growth stands of conifers at least 30 years in age
   C) Immediately postharvest on plantations that had been broadcast-burned

3. Golden chanterelles have these habitat attributes because this species is:
   A) An early-seral ectomycorrhizal fungi that colonizes the roots of conifers
   B) A saprophytic fungi utilizing decaying stumps in second-growth stands
   C) A pathogenic fungi that causes root rot in immature conifer trees

ARTICLE 7

Changes in riparian area structure, channel hydraulics, and sediment yield following loss of beaver dams, by Kim C. Green and Cherie J. Westbrook

1. What ecosystem is closely linked to beaver dams in western North America?
2. How do beaver dams influence the velocity of bankfull flows?
3. How does channel pattern change following removal or loss of beaver dams?

ARTICLE 8

Using the low-level aerial survey method to identify Marbled Murrelet nesting habitat, by F. Louise Waterhouse, Alan E. Burger, David B. Lank, Peter K. Ott, Elsie A. Krebs, and Nadine Parker

1. Low-level aerial surveys are most commonly used to assess:
   A) Murrelet nest habitat
   B) Murrelet nests
   C) Habitat with nesting potential for murrelets
2. Low-level aerial surveys can be combined with
   A) Air photo interpretation methods
   B) GIS habitat algorithms mapping
   C) Both of the above
3. One important low-level aerial survey habitat variable for identifying potential nesting habitat is:
   A) Vertical complexity
   B) Moss development
   C) Canopy closure

ARTICLE 9

British Columbia's Forests: White Pine Blister Rust Forest Health Stand Establishment Decision Aid, by Stefan Zeglen, Richard Hunt, and Michelle Cleary

1. From what seed sources should resistant seedlings be grown?
2. Which silviculture treatments are most effective for protecting white pine?
3. How does white pine blister rust differ from pine stem rusts on lodgepole or ponderosa pines?

ARTICLE 10

Relationships between habitat area, habitat quality, and populations of nesting Marbled Murrelets, by Alan E. Burger and F. Louise Waterhouse

1. A significant correlation between habitat area and numbers of Marbled Murrelets has been shown at a large regional scale across hundreds of kilometres using which method?
   A) Counts of murrelets at sea adjacent to inland forested areas
   B) Low-level aerial surveys using helicopters
   C) Tree-climbing in suitable habitat
   D) Tracking murrelets back to nest sites using radio-telemetry
2. Radar counts of Marbled Murrelets flying into forested watersheds have been compared with the areas of apparently suitable habitat within these watersheds and these data show:
   A) No significant relationship between murrelet numbers and area of suitable habitat
   B) A significant negative relationship because most murrelets are concentrated in the shoreline habitat bordering the ocean in high densities
   C) A significant curvilinear relationship where more birds than expected are in watersheds with less habitat
   D) A significant linear or near-linear relationship indicating that murrelets are using nesting habitat in proportion to its availability
3. Air photo interpretation and low-level helicopter surveys are commonly used to assess the quality of Marbled Murrelet habitat using a six-rank classification scale. The available evidence from nest sites in British Columbia suggests that:
   A) Murrelets only nest in the top two ranks (Very High and High) and avoid all other habitat
   B) Most nests are found in the mid-rank (Moderate) habitat quality
   C) Murrelets generally select the higher-ranked habitats, but some nests are found in lower-ranked habitat
   D) Contrary to expectations, most nests are found in lower-ranked habitats (Low and Very Low)
   E) Murrelets show no preference and use all these habitat ranks according to availability

Answers to 'Test Your Knowledge' Questions

ARTICLE 1

1. C 2. B 3. E

ARTICLE 2

1. C (See Tables 3 and 4) 2. C (See Table 5) 3. D

ARTICLE 3

1. A 2. A 3. A

ARTICLE 4

1. C 2. E 3. B

ARTICLE 5

1. A 2. B 3. B

ARTICLE 6

1. C 2. B 3. A

ARTICLE 7

1. Wetlands.

2. Beaver dams reduce the velocity of bankfull flows by approximately 81%.

3. Channel pattern changes from wide, multi-thread pattern to narrow, single-thread pattern following loss of beaver dams.

ARTICLE 8

1. C 2. C 3. B

ARTICLE 9

1. For coastal stock, seedlings that originated from nurseries using major gene resistant (Cr2) seed sources should be used. Several coastal orchards have this type of seed available. For interior stock, seedlings that have parentage from Idaho sources should be used. Seed for these trees is available from the Bailey Seed Orchard near Vernon.

2. Select resistant stock for planting. Thin out infected trees or remove the alternate hosts to reduce local rust levels. Prune to reduce the risk of infection or to remove infected branches. Excise cankers to protect valuable individual trees.

3. Stem rusts of hard pines, such as comandra and stalactiform blister rusts, are also from the genus Cronartium. Although the hosts differ, the life cycles are identical to WPBR. Western gall rust, however, is a hard pine stem rust that transfers directly between pines without requiring an alternate host.

ARTICLE 10

1. A 2. D 3. C

JEM BC Journal of Ecosystems and Management

SUBMISSION GUIDELINES FOR AUTHORS

The *BC Journal of Ecosystems and Management* (*JEM*) welcomes contributions from practitioners, professionals, researchers, agencies, decision makers, and resource users on all topics relating to research and management of British Columbia's ecosystems. The pages of this journal are open to anyone who wants to write or read an informed, well-reasoned, and relevant article that will improve knowledge of provincial ecosystems and communities.

Both original papers and previously published papers, which have been re-written to meet the goals of *JEM*, are invited. Authors are encouraged to contact the Managing Editor before preparing and submitting a manuscript.

General Guidelines

JEM accepts three categories of papers.

- **Perspectives:** Commentaries on the current or future status of natural resource management. Papers may state an opinion, offer a challenge, or present a thought-provoking idea on natural resource management issues.
  Maximum length: 2000–5000 words.
- **Extension Notes:** Focus on simplified syntheses of existing or new research, operational trials, case studies, preliminary field results, techniques, and new tools or technology. Papers may offer suggestions to improve ecosystem management activities or provide accounts of how research results have been adopted and placed into practice.
  Maximum length: 2000–5000 words.
- **Research or Discussion Papers:** Full-length scientific research and discussion papers that cover major research projects or programs, develop new concepts in natural resource management, or test ideas with data from field and laboratory experiments, observations, or simulations.
  Maximum length: 5000–10 000 words.

Authors may submit their manuscript electronically as a virus-free email attachment. Please use a compressed format (.zip, .sit, or .sea compression) to reduce the size of large files. Text (including tables) should be provided as either WordPerfect or Microsoft Word files. Please underline all text that should appear in italics.

If figures or illustrations form a part of the manuscript, please submit these separately as high-resolution JPEG or TIFF files, noting their desired position in the text with an appropriate caption. Do not embed figures with the text in the word processing files.

If tables form a part of the manuscript, group these at the end of the document, noting their desired position in the text with an appropriate caption. All figures and tables should be referred to at least once in the text.

Style and Formatting Guidelines

JEM uses the British Columbia Ministry of Forests and Range *Forest Science Program Style Guide and Authors Manual* as its publishing standard. Authors may consult this guide online at: ***www.for.gov.bc.ca/hfd/pubs/Docs/Mr/Mr041.htm***

Title: The title of the article should convey the content of the paper in as few words as possible. Strive for titles that are 10 words or less.

Author Documentation: Include the names of all authors, along with their job titles and institutional affiliations, mailing address, city, postal code, and email address. Please place the primary author's contact information first.

Abstract: The abstract should appear at the beginning of the manuscript and contain 200 words or less. It should describe the manuscript topic in one sentence, if possible, and go on to briefly outline the manuscript's purpose, scope, conclusions, and management implications, if appropriate.

Keywords: Provide 5–10 words or short phrases that are applicable to your article. Keywords help us to find suitable peer reviewers, and are used in metadata records so that our archives are easily and efficiently searchable.

Headings and Subheadings: These should cover all the major concepts in the manuscript and indicate the relationship between the sections. Try to use no more than three levels of headings. Use of a numbered heading hierarchy is recommended (i.e., 1 LEVEL ONE; 1.1 Level Two; <u>1.1.1 Level Three</u>).

References: Use the author–date system when citing published works or acknowledging unpublished material in the text. List these references alphabetically at the end of the manuscript. Try to keep explanatory footnotes to a minimum. For examples of bibliographic citation style, see the articles currently posted to the *JEM* "Issue-in-Progress" website (***www.forrex.org/jem/***).

Peer Review and Publication

If the content of the article is acceptable, the Review Committee will assign the article to a peer review. Perspectives are reviewed by one extension specialist; Extension Notes, Discussion Papers, and Research Reports are reviewed by one extension specialist and two external peer reviewers from the natural resource community.

Depending on the results of the peer review, a final decision is made on the acceptance or rejection of the manuscript. A copyright release is required of all papers accepted for publication.

If accepted for publication, the author then revises the manuscript according to the reviewers' comments. Revised papers are published in the online "Issue-in-Progress" as soon as possible following an English edit and typesetting. Authors have the opportunity to approve the final proofs of their papers.

Print issues are produced as each online issue closes, approximately three times per year.

Article Levies

The author(s) will pay a levy as specified below, to be invoiced at the time of online publication of the article.

- **Extension Notes and Perspectives:** $80 per journal page to a maximum of $600. Graphics-heavy articles may be subject to a surcharge of $50 per graphic if there are more than three graphics.
- **Research Reports and Discussion Papers:** $80 per journal page to a maximum of $1000. Graphics-heavy articles may be subject to a surcharge of $50 per graphic if there are more than five graphics.

Submissions

Draft manuscripts and other inquiries may be submitted by fax, mail, courier, or email to:

Julie Schooling, Managing Editor

BC Journal of Ecosystems and Management
FORREX Forum for Research and Extension in Natural Resources
Suite 702, 235–1st Avenue
Kamloops, BC V2C 3J4
Tel: 250.371.3995
Fax: 250.371.3997
Email: ***jem@forrex.org***

JEM 2009 Subscription Form

The staff of FORREX Forum for Research and Extension in Natural Resources, along with our volunteer Communications Working Group and *JEM* Review Committee members, thank you, our readers, for guiding and supporting the evolution of the *BC Journal of Ecosystems and Management* (*JEM*). We rely on the expertise and volunteer spirit of our working group and peer reviewers to set and maintain high quality standards for *JEM*—it is this high standard that is attracting more and more discerning authors and readers.

Visit *JEM* online at: *www.forrex.org/JEM*

The 2009 subscription rate for print issues of *JEM* is $50 for individuals and $100 for institutions and organizations. Your subscription will help cover the costs of producing three print issues of *JEM* in 2009. We are offering back issues of *JEM* at the low rate of $5 each, so take this opportunity to make sure your collection of *JEM* issues is complete!

To ensure that you receive future print issues of the *BC Journal of Ecosystems and Management*, please complete the subscription form below, detach and return it to FORREX with your payment (cheque or money order).

BC Journal of Ecosystems and Management (JEM)

Please enter my subscription to *BC Journal of Ecosystems and Management* (ISSN 1488-4666).

ANNUAL PRINT ISSUE SUBSCRIPTION: January 1, 2009 to December 31, 2009—Issues 10(1), 10(2), and 10(3)

❑ New subscription ❑ Renewal

BC Journal of Ecosystems and Management	Individual	$50.00	$ ________
	Institutional	$100.00	$ ________
Back Issues of *JEM (please check boxes)*	___ issues @	$ 5.00	$ ________

❑ 1(1) ❑ 1(2) ❑ 2(1) ❑ 2(2) ❑ 3(1) ❑ 3(2) ❑ 4(1) ❑ 4(2) ❑ 5(1) ❑ 5(2)
❑ 6(1) ❑ 6(2) ❑ 7(1) ❑ 7(2) ❑ 7(3) ❑ 8(1) ❑ 8(2) ❑ 8(3)
❑ 9(1) ❑ 9(2) ❑ 9(3)

Extra postage for subscriptions within the United States	$20.00	$ ________
Extra postage for subscriptions outside North America	$40.00	$ ________
Total Amount Payable to FORREX		**$ ________**

(Canadian funds only; no taxes applicable)

SUBSCRIBER INFORMATION:

Name: ____________________

Organization: ____________________

Mailing Address: ____________________

Postal Code: __________ Phone: __________ Fax: __________

Email: ____________________

Please make cheques payable to FORREX.

Mail cheque or money order with this form to: FORREX Forum for Research and Extension in Natural Resources
Suite 702, 235 1st Avenue
Kamloops, BC V2C 3J4 CANADA

ISSN 1488-4666

Cover and text