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Sustainable management of Canada's boreal forests: Progress and prospects[1,2]

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Abstract: The last decade of innovation in forest management in Canada is reviewed. Institutions such as the Sustainable Forest Management Network and Canada's Model Forest Program have attempted to develop a better understanding of ecological disturbance patterns and processes. Additional research has explored socio-economic dimensions of sustainable forestry, such as ways to incorporate the aspirations of indigenous peoples, build community capacity, and facilitate forest certification. The most promising innovations tend to have both environmental benefits (sustaining non-timber values) and economic benefits (reducing costs and sustaining future timber values), making their implementation more likely. Some on-the-ground examples of "win-win" solutions at stand and landscape levels in Canada's boreal forests include: patch retention in conjunction with the creation of large cutblocks; protection of advance regeneration during timber harvesting; promotion and prediction of natural regeneration; various approaches to mixedwood (broadleaf and conifer) management; avoidance of unnecessary brush control; extended rotations and selection management for some tree species and stand types; promoting the flow of fibre to its highest value uses; and zoning in support of intensive silviculture, thereby potentially reducing harvesting pressures from lands with high conservation value. More closely emulating natural patterns of forest disturbance and forest recovery can help sustain biodiversity and ecosystem services, but may not generate all values desired from managed forests. Further research is needed to calibrate indicators of ecological sustainability. Institutional and policy innovation must also be evaluated in the context of adaptive management to improve the effectiveness of forestry practices and nurture the social license for the utilization and management of public forests.
Keywords: Canadian forestry, emulation of natural disturbance, forest practices, forestry research, non-timber forest values, sustainable forest management.

Résumé : Nous passons en revue la dernière décennie d'innovations en aménagement forestier au Canada. Des institutions telles que le Réseau de gestion durable des forêts et le Programme de forêts modèles du Canada ont tenté de développer une meilleure compréhension des patrons et des mécanismes des pertubations écologiques. D'autres ont exploré les dimensions socio-économiques de la foresterie durable telles que des moyens d'inclure les aspirations des peuples autochtones, de développer le potentiel des collectivités et de faciliter la certification forestière. Les innovations les plus prometteuses et qui ont le plus de chance d'être implantées sont celles qui incluent à la fois des bénéfices environnementaux (maintien des ressources non ligneuses) et des bénéfices économiques (réduction des coûts et maintien des ressources ligneuses dans le futur). Des exemples concrets de solutions gagnantes à l'échelle du peuplement et du paysage dans la forêt boréale canadienne sont : conserver des parcelles intactes lors de la coupe de grands blocs forestiers; protéger la régénération pré-établie lors de la récolte du bois; promouvoir et prévoir la régénération naturelle; utiliser des méthodes d'aménagement diversifiées pour la forêt mixte (conifères et feuillus); éviter le contrôle de broussailles lorsque non nécessaire; effectuer des rotations sur de longue durée et sélectionner pour certaines espèces d'arbres et certains types de peuplement; faire la promotion de la troisième transformation du bois; et établir un zonage pour une sylviculture intensive et ainsi réduire la pression de coupe sur les sites à haute valeur de conservation. Se rapprocher des patrons naturels de perturbation et de régénératioin de la forêt peut aider à maintenir la biodiversité et les fonctions des écosystèmes mais peut ne pas générer tout ce qui est espéré des forêts aménagées. D'autres recherches sont nécessaires pour calibrer les indicateurs de l'aménagement durable au niveau écologique. Les innovations institutionnelles et réglementaires doivent être évaluées dans un contexte d'aménagement adaptatif afin d'améliorer l'efficacité des pratiques forestières ainsi que l'acceptabilité sociale de l'utilisation et de l'aménagement des forêts publiques.
Mots-clés : aménagement durable des forêts, foresterie canadienne, imitation des perturbations naturelles, pratiques forestières, recherche forestière, ressources non ligneuses.

Nomenclature: Armstrong & Ives, 1995; Farrar, 1995.

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Introduction

The circumboreal forest is the most extensive terrestrial biome in the world, encompassing some 14 million km^2 and 32% of the Earth's forest cover. Thirty percent of this world resource is found in Canada, where it occupies seven boreal and taiga ecozones (58% of the nation's land area) and is responsible for approximately 60% ($26.6 billion) of annual timber-based export revenues and direct employment (211,200 people; Burton *et al*., 2003b). In many regions of Canada, the boreal forest still consists of vast unpopulated landscapes interlaced with large rivers, lakes, and wetlands. In North America and broad regions of Asia, old forests are typically evergreen and dominated by conifers, though broadleafed species often prevail in early succession, and the deciduous larch (*Larix*) species dominate some sites. The boreal biome is dominated by forests and wetlands, with some self-maintaining scrub and grassland communities. Higher elevations and latitudes exhibit progressively greater islands and peninsulas of tundra and greater prevalence of birch (*Betula*), willow (*Salix*), and/or stunted spruce (*Picea*) scrub in broad ecotones.

With slow-growing, uniform wood having excellent properties for pulping (paper-making), dimensional lumber, and plywood or other panelling, the boreal forest constitutes one of the world's largest reserves of unexploited wood fibre. But the biome also provides important habitat for large numbers of wild birds and mammals, and it supports a high diversity of little-studied organism groups such as fungi and insects. It is estimated that there are more than 23,000 identified species of biota residing in the North American boreal biome (Zasada *et al*., 1997).

The definition of "boreal forest" differs among various jurisdictions and with the purpose of any particular mapping and tabulation exercise. In general, we could call the boreal zone those arctic, subarctic, or northern mid-latitude regions that are dominated by a cold climate and able to support only a few tree genera (Burton *et al.*, 2003b). It is useful to distinguish the broad regions dominated by a "boreal climate" from those lands specifically covered by forest and woodlands (*i.e.*, excluding lakes, wetlands, and other treeless areas) and those lands supporting commercially valuable stands of boreal trees (or "operable" timber, a definition that varies according to local economic and technological conditions). Our discussion of boreal ecology, boreal forestry, and boreal communities broadly refers to lands within the circumpolar boreal zone as presented by Hare and Ritchie (1972) and by Pruitt (1978). The exact boundaries of this zone are not important to the application of concepts reported in this article, for which the boreal designation can safely be extended to the sub-boreal plateaus of British Columbia and the conifer forests of New Brunswick.

A harsh climate and poor soil development has largely resulted in the boreal region being less suitable for agriculture and less settled than many other parts of Canada. Though home to indigenous peoples and hardy souls who pride themselves for living "off the land" and on the frontier, these northernmost forests also represent the epitome of wilderness for the nation's city-dwellers. Commercial uses have historically concentrated on mining, the generation of hydroelectricity, and the harvest of furs and timber. During the last two decades of the twentieth century, the near-complete "domestication" of Fennoscandian forests and the expansion of commercial forestry into broad areas of northern Canada and Russia have prompted concerns about the sustainability of resource use throughout the boreal region. Can Canada's boreal wilderness be developed for broad social and economic benefits while at the same time sustaining its environmental values and future options?

This paper reviews some recent progress by ecological and forestry researchers and innovative forest managers in government, industry, non-governmental organizations, and aboriginal communities across Canada. In particular, it summarizes some of the conclusions presented in recent symposia and workshops (Bamsey, 1995; Bergeron *et al*., 1998; Korpilahti & Kuuluvainen, 2002; Leech, Whittaker & Innes, 2002; Macdonald, 2004) and emanating from the first seven years of research conducted by Canada's Sustainable Forest Management Network (Veeman *et al*., 1999; 2002; Burton *et al*., 2003a). In particular, we focus on efforts to articulate and implement the "natural disturbance model" of sustainable forest management in the southern portions of the boreal forest, where expansion of the forest products sector and energy industries (oil and gas exploration and extraction, tar sands mining, and hydroelectric dams) is greatest.

Disturbance ecology of northern forests

A good understanding of the ecology of boreal forests is a prerequisite for their sustainable management. Although boreal forests thrive in cold northern climates, it is an oversimplification to merely characterize the biome as being dominated by a snowy environment with long cold winters. Rather, it is perhaps more accurate to recognize that most boreal forests are a land of "fire and ice." This unique duality also features in the ecology of the biome, as the evolution of boreal flora and fauna has taken place under the dual pressures of deep cold and snow for most of the year and a short growing season in which wildfires, insects, and other disturbances can be surprisingly active. There are strong climatic gradients in the prevalence of wildfire as a stand-initiating disturbance, with average fire return intervals estimated to range from approximately 130 to 700 years across boreal Canada (Stocks *et al*., 2002).

Boreal forests are typically characterized by landscape-level disturbances, especially wildfire and insect outbreaks, but also occasional storm events that result in widespread windthrow (often termed "blowdown" when occurring in patches, as a stand-reinitiating event). Population explosions of insects regularly defoliate millions of hectares of boreal forest in Canada, with eastern spruce budworm (*Choristoneura fumiferana*, feeding on balsam fir, *Abies balsamea*, especially) and forest tent caterpillar (*Malacosoma disstria*, feeding mostly on trembling aspen, *Populus tremuloides*) being most prevalent (MacLean, 2004). Trees do not always die when attacked by insects, though they are more likely to succumb when exposed to two or more years of such stress. Post-outbreak tree mortality and subsequent forest regeneration can consequently be found in small patches or stretching across entire landscapes. There is growing awareness that small-scale disturbances (gap dynamics) are also important in boreal forests, especially in climates and topographic locations where fire is infrequent (Kuuluvainen, 1994; Kneeshaw & Bergeron, 1998; McCarthy, 2001; Bartemucci *et al*., 2002).

Even where wildfires prevail, fire often jumps around in response to local topography and weather, leaving islands and peninsulas of live trees that end up comprising 3 to 37% of the area mapped as burned (Eberhart & Woodard, 1987; Smyth *et al*., 2005). As is characteristic of more southerly forests, the prevalence of non-stand-replacing fires also appears to be greater than previously estimated, with surface fires being more common than crown fires on drier ridges and when the dominant tree species is resistant to fire (*e.g*., some *Pinus resinosa* stands in eastern Canada; Bergeron & Brisson, 1990). Combined with a growing appreciation of the important role of a variety of disturbance factors, such as insects (Holling, 1992), fungi (Lewis & Lindgren, 2000), snow and windstorms (Ruel, 1995), and large herbivores (Crête, Ouellet & Lesage, 2001), this new understanding of the subtleties of boreal disturbance ecology has important implications to forest management. Unlike in northern Europe, where fire and insect disturbances are relatively rare events and several fire-dependent species are becoming scarce (Heliövaara & Väisänen, 1984; Wikars, 2001), forest fires and large-scale insect epidemics remain very much a part of the ecology and life of northern Canada, with an average of 1.8 million ha of boreal landscapes burning (Stocks *et al*., 2002) and approximately 6.3 million ha of boreal forest being defoliated by insects every year (CFS, 2005).

The apparent importance of the "stand-destroying" fire fits well with the agricultural paradigm of timber management devised in previous centuries by central European foresters. It has long been suggested that fire return intervals ("ecological rotation lengths") correspond approximately to the technical culmination of mean annual increment (MAI) in even-aged stands of commercial trees (Bergeron & Harvey, 1997), primarily species of pine (*Pinus*), spruce, fir (*Abies*), birch, and aspen or poplar (*Populus*). Until about 1990, this "trees as crop" approach to forest management (with a single species in even-aged stands being the focus of attention) dominated all aspects of Canadian forest management, from inventory and timber supply analysis to silviculture (Burton *et al*., 2003b; Lieffers *et al*., 2003). This approach worked reasonably well for early-successional and light-demanding pine and poplar species, but was less well suited to the more shade-tolerant spruce and fir species, especially in stands consisting of intimate mixtures ("mixedwoods") of conifer (generally spruce or fir) and broadleaf (generally aspen, poplar, or birch) trees. The mere assumption that all stands are even-aged, initiated by a fire just a few years before the birth of the dominant trees, cannot be supported by careful studies reconstructing stand and landscape fire histories (Weir, Johnson & Miyanishi, 2000; Kuuluvainen *et al*., 2002; Bergeron, 2004). In addition, management to maintain the one-third of forest area naturally older than mean fire return intervals was largely avoided (Bergeron *et al*., 1999; Burton, Kneeshaw & Coates, 1999).

Impacts of forest harvesting and management

Today, forest management for fibre extraction and production is overwhelmingly the major agent of change acting on the boreal forest in countries such as Finland and Sweden, and it is increasingly so in Canada, where logging still disrupts much less forest area than forest fires or insect outbreaks (Kurz & Apps, 1999; CFS, 2005). In the past, large areas of public land have been leased or sold to provide a timber supply to nearby processing mills with little thought to forest renewal, which was assumed to "take care of itself." Such policies lasted until World War II in Finland and Sweden and into the 1970s and 1980s in Canada, and they continue in Asiatic Russia today. Public outrage over such "cut and run" practices, poor reforestation success, site degradation, and a lack of forest stewardship (Swift, 1983) resulted in provincial forest policy reforms and a program of federal funding for forest rehabilitation across Canada from 1985 to 1995 (CFS, 1995). A new round of forest tenures were let by provincial governments in the 1990s, especially in western Canada (Burton *et al*., 2003b), but with a stronger emphasis on the need for effective reforestation and biodiversity protection over defined forest management areas.

The standard approach to sustained yield management in much of Canada's boreal forests continues to be based on the liquidation of wild and over-mature forests and their conversion to shorter-rotation managed stands at a rate planned to match that at which the harvested stands can be re-established and re-grown. The classical model of even-aged management has meant that in intensively managed regions, naturally heterogeneous stands have been converted to homogenous, single-species stands using thinning, clearcutting, and planting. While the simplification of forest structure has been successful in promoting production of valuable timber, this has occurred at the expense of biological diversity and other values of the forest (Schindler, 1998; Spence, 2001). These concerns have spawned a series of restoration and conservation policies in Europe (*e.g*., the "Natura 2000" network; see http://www.natura2000benefits.org) to offset a history of ecological degradation that can yet be avoided in much of Canada. But unlike the history of forest exploitation in temperate and tropical regions, boreal timber harvesting is not usually accompanied by conversion to agricultural land uses (the cultivation of crops and the pasturing of livestock), and so does not usually represent a long-term loss of forest cover and indigenous ecosystems.

For most of the past two or three decades, Canada's forest management agencies and forest products industry have been severely criticized for their focus on fibre production at the expense of non-timber forest values. The alternative model of sustainable forest management (SFM) represents an evolution of sustained-yield timber management to include the conservation of all forest values, including old-growth forest, biodiversity, wildlife, non-timber forest products, and rural communities (Riley, 1995; Wang, 2004). As various governments struggled to accommodate a broad public consensus on the need to protect non-timber values, early progress generally occurred through adversarial processes, using constraint management, prescriptive policy, and regulations. As a result, change has been highly variable within and among the boreal provinces, based on provincial forest management differences and social and economic considerations. Canada now has approximately 9% of its boreal and taiga ecozones under some kind of protected status, varying from 4% in Québec to 14% in British Columbia and the Northwest Territories (CBI, 2005). Within the last 10 years, forest management policies and practices in Canada have come to be increasingly driven by science-based knowledge and broader social perspectives through institutions and programs such as the Sustainable Forest Management Network (SFMN; see http://www.sfmnetwork.ca) and Model Forest Program (MFP; see http://www.modelforest.net). As innovations in the environmental and social sciences are applied, SFM is exhibiting a more consistent, broad-based approach to forest management, with demonstrable benefits to the environment and local communities (Hebert *et al.*, 2003).

One example of the value of empirical research into broad ecological and sociological aspects of the boreal forest environment has been an increasing recognition of the value of non-timber aspects of the forest resource. Recreation value, values for conservation of endangered species, and other non-timber values appear to be increasing (Adamowicz, Armstrong & Messmer, 2003). Because the harvesting of mushrooms, berries, and firewood have usually not been monitored or regulated by forest managers and little distinction has been made between recreational and subsistence hunting of wild game, these non-timber forest products (NTFPs) have typically been under-valued in forest planning; timber harvesting can enhance some of these values but can compromise others (Duchesne & Wetzel, 2002; CFS, 2005). Combined with issues of ecological integrity and the conservation of biodiversity at landscape scales, the public desire to see management for a broader range of non-timber values calls for greater diversity in the approach to forest land management throughout the world's boreal regions (Burton & Kuuluvainen, 2001). Ecological research, technological developments, and novel socio-economic perspectives are mutually dependent elements that build on each other and must be tested, applied, and refined in the context of Canadian forest management.

If wild forests are to be cut to meet the fibre and energy needs and wants of humanity, one might ask where in the world large-scale fibre production is most appropriate. It is likely that the social and ecological consequences of harvesting boreal timber are less severe than those associated with the exploitation of temperate, tropical, or montane forests at more southerly latitudes. This is because species-level biodiversity and endemism are comparatively low, human populations are relatively sparse, and invasive/exotic species are uncommon in the boreal forest, where most species are adapted to large-scale catastrophic disturbance. Reforestation, forest restoration, and intensive timber production on marginal agricultural lands are to be encouraged in temperate and tropical regions of the world, as is bioregional self-sufficiency in fibre resources, but the logging of pristine forests in temperate and tropical biomes certainly has more severe impacts on biodiversity. Similarly, the use of non-renewable and/or energy-intensive building materials such as concrete, steel, and plastics as substitutes for wood construction also can have undesirable environmental impacts.

Increasing specialization and technical change may allow for a substantial proportion of the global demand for forest products to be met by intensive plantations. Such innovation could reduce the environmental impact on forest lands and provide a large proportion of the needed fibre (Vincent & Binkley, 1994; Hunter & Calhoun, 1996; Sedjo & Botkin, 1997; Messier, Bigué & Bernier, 2003), but it might also shift the pattern of employment in primary forest industries. Some promising avenues of intensive silviculture are being explored in Canada's boreal forests (Van Oosten, 2004; Dickmann *et al.*, 2002; Lieffers *et al.*, 2003; Messier, Bigué & Bernier, 2003). Nevertheless, the use of exotic species, aggressive site preparation and weed control, and fertilization will probably be applied only to a limited portion of Canada's boreal land base, as these techniques are most suitable for abandoned farm land.

Sustainability concepts: Defining the yardstick

Sustainability is a human concept designed to recognize the interdependence of natural and human systems and the importance of the long-term effects of human actions on natural systems. It stems from a deep desire to provide future generations with the opportunity to benefit from productive and resilient ecosystems. Precise definitions of sustainability are difficult to construct; however, the core of the concept is the management of resources to meet current needs without compromising the ability of future generations to do so. It has been argued that the multiple dimensions of sustainability collectively represent a significant socio-philosophical development in human history (Edwards, 2005).

In many respects, foresters invented the paradigm of sustainable development. The basic premise of sustainable forestry has always been to calculate the sustained yield of timber possible from a defined forest area, such that one periodically harvests no more than the amount of wood grown by living trees over the same period. This approach, with some adjustments for ecological reserves and limits to operability, remains the basis for annual allowable cut (AAC) determinations for most managed forests. Many environmental and community activists view sustained yield forestry as a barrier to progressive land management, primarily because it is industry-driven and profit-motivated. But the sustained yield concept (analogous to living off the interest without liquidating one's capital) is such a powerful one that the challenge is not to eliminate it but rather to apply it to a wider range of forest goods and services. The goal of sustainable forest management is to move from sustaining the yield of timber to sustaining a broad set of forest values into the indefinite future while avoiding declines in ecological function or productive capacity of the ecological system.

Many of the concepts of sustained timber yield remain necessary conditions of basic forest management within the SFM framework, but these concepts can no longer be considered sufficient to address the desired range of forest values. Attempts have been made in most Canadian provinces to develop enlightened constraint management (*i.e.*, management plans that consider non-timber values, but as constraints to timber production rather than as objectives in and of themselves) and prescriptive (rule-based) policy to protect environmental services. These approaches generally have had limited success in achieving SFM as long as fibre production has remained the bottom line, the criterion against which all management decisions are to be judged. The last decade has seen a growing influence of science, environmentalism, market demands, and community activism in convincing forest managers to respect non-timber forest values and the health of forest ecosystems and forest communities. But can recognition of this broad set of values prompt real reform on the ground? Can these good intentions be implemented feasibly in a real world governed by a market economy and widespread fiscal constraints?

The portfolio of forest values to be protected and enhanced typically includes timber and non-timber forest products, biodiversity and huntable wildlife, clean and abundant water, old-growth habitats, effective carbon sequestration, recreational opportunities, and the interests of communities of people living in and/or deriving their livelihood from the forest. Some values are compatible with a wide range of other values, allowing their bundling into a few zones, while incompatible values must be protected and enhanced in other zones. But assessments of compatibility can change with technical innovation and creative ideas. Thus, the tabulation and spatio-temporal mapping or allocation of forest values is an important part of tactical forest planning (Andison, 2003), The balancing and sustainability of forest values can occur both within stands (*e.g.*, by using techniques such as the retention of green tree patches and adequate levels of coarse woody debris) and within landscapes (*e.g.*, by devising a distribution of stand types and stand ages within the range of natural variability; BCMOF & BCMELP, 1995). Although the availability of dead wood (standing snags and fallen logs) may not currently be considered limiting to wildlife and biodiversity in the managed boreal landscapes of Canada, experience after one or more full rotations in northern Europe indicates that dead wood attributes need to be planned for throughout the forest life cycle and at the landscape level (Siitonen, 2001; Jonsson, Kruys & Ranius, 2005).

One of the greatest challenges facing managers committed to the sustainability of forest values is that diverse factors (such as international currency exchange rates and trade rules, domestic politics and land use policies, the extraction of below-ground resources, and the attack of natural disturbance agents) frequently require the revision of management plans and goals. Furthermore, climate change is proceeding rapidly, with its most significant effects at higher latitudes (Gitay *et al.*, 2001; Bhatti *et al.*, 2003), and threatens to modify the frequency, severity, and impact of other threats to forests and forest management plans. If "sustainability" is interpreted as "constancy", then the goal is unattainable, for boreal forests and the agents that influence them are demonstrably dynamic. On the other hand, if sustainable management aims to provide a basket of forest values, and if land managers can successfully define the bounds, risks, and rolling nature of their plans, then sustainable management of Canada's boreal forests is possible.

In juggling the many values and facets of sustainability, scaling issues and risk management become paramount. Local sustainability, or sustainability at small spatial scales, is not usually feasible. This fact may have been the biggest problem behind implementation of the "multiple use" paradigm advocated for public forest management throughout Canada (and the USA) from the 1960s to the 1980s. Balancing sustainable values over larger areas offers a better chance of sustainability in the face of risk (natural disturbance, climate change), but it does so at the cost of losing forest values in some local areas for at least some period of time. Locally compromised elements of biodiversity and human use are typically those restricted to particular, spatially defined areas (*e.g.*, animals such as salamanders with limited home ranges, viewscapes from tourist lodges). For such attributes, the protection and constancy of critical forest elements may be more important than whether they can be renewed at some time in the future.

The concept of sustainability is complex in part because it strives to leave future generations with natural systems that support their well-being and maintain their opportunity to benefit from these natural systems. However, the preferences of and technologies available to future generations are unknown. Furthermore, thresholds or irreversibilities that are difficult to predict exist in both natural and social systems. An acceptable temporal distribution of values and the degree to which they can be interchanged can rarely be defined objectively. It can be argued that compromising the long-term sustainability of one forest value (*e.g.*, high timber harvesting levels and the employment they provide) may be desirable in order to develop or enhance other forest values or assets. For example, harvesting timber at levels greater than the long-run sustained yield for several years may pay for the construction of forest roads that service an area and allow access to other resources and long-term employment.

An important consideration is that current levels of any particular value are not necessarily sustainable: the big challenge is to find the levels, the balance, and the range of variability in all values that should be sustainable on a given area of land. Pre-managed levels of old-growth forest cannot usually be sustained if trainloads of lumber are being shipped out, yet old-growth values can be sustained through a combination of protected areas, long timber rotations, partial cutting, and variable structural retention within stands. Likewise, current levels of employment in the forest harvesting and wood processing sectors are not likely to be sustained in the face of increasing mechanization, yet overall forest sector and community employment can be sustained through diversification to manage more non-timber forest goods and services. Sustainability is as much about maintaining resilience as it is about balancing outputs from a forest.

Evolving socio-economic considerations

Sustainability involves not only conservation, but consideration of intra- and inter- generational equity, efficiency in resource use, and the inclusion of timber and non-timber values in decision making. Institutional arrangements, including tenure and regulatory rules, are evolving to allow for firms and households to operate along a sustainable path (Nelson *et al*., 2003). The "rules of the game" for forestry now have to adjust accordingly in order to accommodate the full range of forest values. Equity considerations, particularly involving aboriginal peoples and their unique rights and interests in resources, are gradually being included in forest management and planning processes (Stevenson & Webb, 2003). However, while accommodation of these widely varying interests is easy to advocate, it is very difficult to implement. Movement towards sustainability will require institutional innovation (Nelson *et al*., 2003), the development of tools for measuring and managing non-timber values (Duchesne & Wetzel, 2002; Adamowicz, Armstrong & Messmer, 2003) and eliciting and incorporating public input into resource decisionmaking (Hamersley Chambers & Beckley, 2003), and other social and economic innovations.

Patterns of land ownership can also affect the prospects for implementing SFM. In Canada and Russia, more than 75% of forest land is publicly owned, and managed forests are administered by government agencies or large corporate interests that can coordinate activities over large areas. By contrast, private individuals with small forest parcels own approximately 50% of the forest land in Sweden and over 60% of that in Finland; this makes it challenging to plan SFM at landscape and regional scales. On the other hand, the heterogeneity of values represented by numerous private forest owners contributes to a diversity of management approaches and perhaps a fairer representation of many different non-timber values than can be achieved under systems of more centralized administration (Karppinen, 1998). Issues of land ownership, tenures, and the reconciliation of overlapping rights (*e.g.*, to belowground resources, to furs, and to timber) on public land are ongoing topics of debate and negotiation throughout much of boreal Canada.

A related concern is who "owns" the loyalty of those charged with the management of public forest lands. University-level forestry programs have generally evolved to educate foresters who are well versed in integrative and adaptive ecosystem management. But throughout Canada, this advance has occurred against a backdrop of widespread devolvement of provincial government responsibility for forest management to the forest products companies who hold tenures over public land. There is a conflict of interest here, in that a forester cannot be expected to work against the financial (timber, royalty/rent) interests of his or her employer. Professional associations have few mechanisms to support the independence of their members. The argument has been made that, as in Finland, the management of Canada's public boreal forests needs to be conducted, at all levels, by independent professionals answerable to the public. The public interest may be served if government agencies with clear objectives, rules, accountability, and public reporting are adequately staffed and funded to monitor forest operations, but the public must insist on a framework of monitoring and enforcement that is objective and accountable or the public resource will not be managed to support the public values considered to have the highest priority.

An important element of institutional innovation in forest management is the development of mechanisms to allow for "signals" of resource scarcity and/or degradation to be incorporated into management (Adamowicz, Armstrong & Messmer, 2003). Historically, the signals of forest scarcity or degradation have been related to timber markets (product prices, harvest costs, etc.). As the relative value of environmental services increases, these values and indicators of their status also need to find their way into the market system (Krautkraemer, 2005). The emergence of carbon markets provides an example of such signalling of scarcity. Carbon management is now viewed as valuable because of its potential to reduce and offset greenhouse gas emissions (Bhatti *et al*., 2003). International markets for carbon, although in their infancy, have sent signals to Canadian forest managers about the importance of considering carbon cycling and the impacts of forest management on carbon stocks. If similar signals can be developed for other environmental services, either through markets or through innovative regulation, the importance of these services will be reflected in management decisions. It is unlikely that the dramatic reduction in the discharge of toxic dioxins and furans from Canadian pulp mills between 1989 and 1995 (Hall, 2003) would have happened without legally empowered regulations. Conversely, the increased use of biomass (primarily wood waste) for energy generation by the forest products industry and electrical utilities has been primarily market-driven. Other reductions in the environmental footprint of the forest industry, through enhanced product recovery from feedstock, reduced water use, and greater reuse and recycling of solid wastes (Zhou, 2003), reflect the combined influence of governmental coercion, technological improvements, and economic advantage. Systems of "criteria and indicators" in support of forest certification are another mechanism by which foresters can be motivated to manage for multiple goods and services (CFS, 2000; Yamasaki *et al*., 2002). Much more empirical research is needed to test for significant threshold levels in key indicators (*e.g.*, the amount of coarse woody debris retained in managed forests, annual extent of wildfires), "calibrating" them against the probability of ecosystem deterioration and species extinctions.

Third-party certification, based on criteria and indicators of sustainability, provides some signals for the value of environmental services, through market access if not price premiums (Duinker & Trevisan, 2003; Nelson *et al*., 2003; Archer, Kozak & Balsillie, 2005). This model of third-party auditing provides for the improved management of private as well as public forest lands but still depends on the economic latitude and progressive policies of companies both selling and buying forest products. However, many environmental services provided by forests do not lend themselves easily to market mechanisms or to auditing. These services will continue to rely on public mechanisms for regulation and signalling. A combination of public monitoring and market-oriented regulatory systems (economic instruments) focusing on achieving publicly determined objectives may be the most effective approach for such issues (Weber & Adamowicz, 2002; Adamowicz, Armstrong & Messmer, 2003; Nelson *et al*., 2003).

Developing systems that send signals about scarcity of environmental services is an important component of the move towards SFM. An equally important aspect is the continued improvement of the systems for forest resource allocation or tenure. Forest tenures have been playing multiple roles as agents for economic development, forest conservation, economic efficiency, and equitable allocation of fibre over economic entities (firms, communities, aboriginal peoples, etc.). These multiple roles can conflict, weakening the tenure system's ability to provide for sustainable forest management. One such conflict is associated with the legislated linkage of particular land bases and timber types to particular processing facilities (Nelson *et al*., 2003). Such a linkage can maintain local economic conditions, but it also increases susceptibility to disturbances (because large fires or insect outbreaks could compromise much of the timber supply for a local mill) and reduces the overall economic returns to a larger region. Policies of allocating the land base to separate softwood and hardwood quota holders can also lead to increased ecological impact (Cumming & Armstrong, 2001).

While SFM (and sustainability in general) is often described in terms of maintaining values over generations, there are also expectations of equity and fairness for the current generation (Edwards, 2005). Questions of aboriginal use rights, for example, are questions of fairness. Innovative mechanisms of cooperation and co-management have been proposed to address such concerns (Stevenson & Webb, 2003). Similarly, the public is demanding an increasing role in forest management decisions in part because of a desire for inclusion in the process and a desire "to be heard." In response, a number of firms and agencies responsible for managing forests have established public advisory bodies; this is also a requirement for Canadian Standards Association (CSA) certification of forest management. These committees range from independent groups with veto power over a range of management decisions to purely advisory bodies. These groups typically consist of representatives from local communities rather than the public at large. Nevertheless, these groups are established by firms as one of the many mechanisms they require to maintain the "social licence" associated with operations on public forest lands or operations that affect public goods such as water, air, and wildlife (Hamersley Chambers & Beckley, 2003).

Recent directions in forest research: Leading or following?

Over the last ten years, there has been considerable research conducted to investigate and devise ways to balance biodiversity, community, and economic values in the development and management of the world's vast boreal forests. Precipitated by the accelerating development of northern forests for timber, pulp and paper, petroleum resources, and hydroelectric power in Canada and Russia, the protection of northern wilderness has become a goal of campaigns recently launched by a number of well-organized and well-financed environmental non-governmental organizations (ENGOs) in North America and in Europe. Viewed as "the last true wilderness," the boreal forest and the unprecedented pace of industrial development within it has been the topic of popular films (Viszmeg, 1994; Desjardins, 1999), magazine articles (Lanken, 1996; Montaigne, 2002; Savage, 2004), books (Pratt & Urquhart, 1994; Gawthrop, 1999; Henry, 2002; Schneider, 2002), and numerous newspaper articles, as well as logging road blockades and threats of forest product boycotts. These activities have raised the profile of boreal forestry in the eyes of the Canadian public and politicians and have prompted renewed interest in understanding the ecology and socio-economics of northern forestlands.

There has been a long and continuous history of international research in support of botanical exploration and ecological classification in boreal climates, the use of remote sensing for land cover classification and for change detection and biophysical measurements. All northern nations have supported considerable ongoing work on permafrost and peatland dynamics, on cold-temperature engineering and other activities related to the sustainability of human endeavours and development in boreal and Arctic regions. But most previous boreal research initiatives had emphasized ecological description and processes in the absence of human management. For example, the International Institute for Applied Systems Analysis (IIASA, located in Laxenburg, Austria) has had a program emphasizing the ecological dynamics of the boreal biome since the 1980s (Shugart, Leemans & Bonan, 1992), but it was not until recently that it identified the requirements for sustainable forestry as a key information and research priority (Zasada *et al*., 1997). The Boreal Ecosystem–Atmosphere Study (BOREAS) was started in 1990 with major support from US government agencies and with study sites in northern Saskatchewan and Manitoba. Its goal is to investigate the interactions between the boreal forest and the atmosphere, specifically to improve process models of radiative energy, water, heat, carbon, and trace constituents and their application over large spatial scales (see http://www.daac.ornl.gov/BOREAS/boreas_home_page.html). Like the decade-long experimental investigation of predator–prey cycles recently concluded in southwestern Yukon (Krebs, Boutin & Boonstra, 2001), little of this research has been of use to forest managers, though (to be fair) this was not an objective of these multi-disciplinary research efforts.

There had long been a gap between academic research on forests and the knowledge requirements for truly sustainable forest management (Baskerville, 1997). The initiative for change and innovation did not come from forestry schools, government agencies, or established research consortia such as the International Union of Forestry Research Organizations (IUFRO). Rather, change has resulted from the concerted effort of environmentalists, conservation biologists, and academic researchers working with broad-minded representatives of the forest products industry, leaping ahead of conservative (*i.e.*, slow to change) government policies and the management culture of traditionally trained foresters. The cluster of documents (Framework Convention on Climate Change, Convention on Biological Diversity, Agenda 21's 27 principles, and Guiding Principles on Forests) generated at the 1992 United Nations Conference on the Environment and Development, held in Rio de Janeiro, Brazil, also had tremendous impact on the outlook of forest managers. Perhaps surprisingly, support for the SFM paradigm across much of the circumboreal region has been achieved through broad consensus, largely without the harsh confrontations, court rulings, and job loss that were encountered in the coastal forests of Oregon, Washington, and British Columbia (Christensen *et al.*, 2000; Magnusson & Shaw, 2003). The momentum of change has left many foresters and forest management agencies straining to catch up with the new paradigm and its rapidly evolving needs.

The urgency of addressing boreal forest management issues has helped focus the activities of academic and scholarly organizations such as the International Association of Vegetation Science, leading to workshops and vigorous international collaboration (Engelmark, Bradshaw & Bergeron, 1993; Bergeron *et al.*, 1998; Korpilahti & Kuuluvainen, 2002; Macdonald, 2004). Institutional responses have seen the initiation of collaborative research in technical and socio-economic aspects of forest management as well as forest ecology. In 1991, the International Boreal Forest Research Association (IBFRA) was created to promote and coordinate research in the world's northern forests, especially with regard to environmental change (see http://www.ibfra.org). In Canada, the Model Forest Network was initiated in 1992 as a program of the Canadian Forest Service, promoting innovative forest planning and practices in eleven forest management areas, six of which are located in boreal ecozones (LaPierre, 2002; see http://www.model-forest.net).

In 1995, the Canadian Council of Forest Ministers (representing all provincial and federal agencies responsible for forestry) embraced the principles of sustainable forest management (CCFM, 1995; Rousseau, 2003). Canada's Sustainable Forest Management Network (SFMN) was created in the same year as a national Network of Centres of Excellence with federal research council support for exploring the scientific and policy issues that serve as the basis of sustainable management of boreal forests. The SFMN quickly expanded to become a research consortium with provincial and private industry funding partners, now spanning all forest types in Canada (Adamowicz *et al*., 2002; McNab, 2005; see http://www.sfmnetwork.ca. A few years later, in response to public concern, the Canadian Senate undertook a review of the state of Canada's boreal forest (SSCAF, 1999). Collectively, these initiatives led to subsequent rounds of conferences and workshops, reaching out to forest managers and forestry practitioners as well as researchers and conservation biologists (*e.g*., Veeman *et al*., 1999; 2002; Leech, Whittaker & Innes, 2002). Another legacy of this decade of social and ecological research can be seen in the development of boreal standards for forest management certification under the Forest Stewardship Council (FSC; see http://www.fsccanada.org/nationalboreal.htm) and the recent (2005) FSC certification of several million hectares of industrially managed forest in Alberta, Ontario, and Québec.

Maturation of forestry principles and practices

As the desire for SFM was growing on the part of the Canadian public in the 1990s, the concept of ecosystem management was developing in the Pacific Northwest of the USA (Grumbine, 1994). Under this approach, the forest is viewed as an ecosystem composed of numerous and often highly linked parts, with many functions yet unknown; human use of natural resources is permissible to the extent that it does not compromise ecological integrity (Kohm & Franklin, 1997). Current ecological theory has evolved away from static "balance of nature" perspectives to more dynamic, variable, and stochastic views, best encompassed in terms of dynamic mosaics characterized by a range of natural variability (Landres, Morgan & Swanson, 1999). These ideas have given rise to the development of a new dominant paradigm in forestry, for which the objective is to manage the forest in a manner patterned after its natural disturbances (fire, windthrow, insects, etc.; Attiwill, 1994; Bergeron & Harvey, 1997; Kohm & Franklin, 1997; Angelstam, 1998; Perera, Buse & Weber, 2004).

There are many elements of the "emulation of natural disturbance" concept that need to be understood in order to make it likely to work. Among other requirements, we need to:

- understand disturbance patterns and processes so that we can emulate them both with our forest management;
- characterize and recognize the often wide regional differences in disturbance patterns and processes within the boreal biome;
- understand how large-scale fires and traditional clear-cutting are and are not alike in the boreal forest at both the stand and landscape levels (McRae *et al.*, 2001; Haeussler & Kneeshaw, 2003);
- devise new models for forest planning and development at the regional/strategic level, the landscape/tactical level, and the stand/operational level using spatially explicit simulation models (Messier *et al*., 2003);
- consider the "coarse filter" aspects of biodiversity conservation as well as "fine filter" (species-specific) elements as required in a regional context;
- integrate the objectives set forth by natural disturbance concepts into operational and policy planning approaches such that managers and decision makers can find the best ways to achieve their goals while at the same time meeting the natural disturbance objectives; and
- consider both the constraints and opportunities offered by such new approaches to forest planning and development.

Following this cascade of new scientific ideas, many modifications to our current forest management practices have been implemented in order to maintain more natural forest structures, compositions, and the full complement of biodiversity and other forest values (Work *et al*., 2003). Building on innovative work in western Canada (Coates & Steventon, 1995) and the Pacific Northwest (Kohm & Franklin, 1997), different variable retention harvest systems have been tested and are now mandatory in parts of British Columbia, Ontario, Sweden, and Finland. Although still considered by some to be an as yet untested hypothesis, the basic idea is firmly grounded on our current understanding of the importance of live and dead trees for many creatures (Lindenmayer & Franklin, 2002), with patch retention generally being easier to implement (and more resilient to windthrow) than dispersed or uniform retention of mature green trees. Reflecting a disturbance regime less dominated by fire and more by insects and gap dynamics, foresters in eastern Canada are now pursuing a three-cohort model of variable rotation lengths and the use of gap-based silviculture and uneven-aged management in spruce- and fir-dominated forests (Bergeron *et al.*, 1999; Harvey *et al.*, 2003). Similar ideas have been put forward in Sweden and Finland (Angelstam, 1998; Kuuluvainen, 2002).

More and more jurisdictions throughout Canada are now adopting the principles of "mixedwood management" (Lieffers *et al.*, 1996; Smith & Crook, 1996), where mixtures of shade-tolerant conifers are grown together with shade-intolerant deciduous species such as aspen or birch. Many benefits of this approach are now being identified, including (1) a possible reduction in spruce budworm (Needham *et al.*, 1999) and white pine terminal weevil (*Pissodes strobi*) problem; (2) an increase in soil fertility; and (3) reduction in the use of herbicides and the need for spot planting to achieve full occupancy of the site by conifers (Lieffers *et al.*, 1996; 2003). As a result, the extraordinary efforts to establish pure stands of spruce, fir, or pine through the use of machines (to create mounds or berms as planting spots) or herbicides to control non-crop vegetation are rapidly being replaced by more ecologically attuned systems of forest stand management. This development has been facilitated by the fact that light hardwood fibre from poplar (aspen) species is now being utilized for pulp and paper manufacturing in the north, whereas previous pulp mills were set up only for conifer fibre, with the hardwoods usually considered a weed rather than a resource with value. When a dominant species is viewed as a resource to be managed sustainably rather than a pest to be controlled, its management then helps to protect the habitat it uses and the habitat it generates.

Part of the mixedwood management strategy is to protect the understory cohort of white spruce (*Picea glauca*) often found beneath mature canopies of trembling aspen throughout the southern boreal forests of Canada. Though requiring more careful logging (*e.g.*, on deep snow packs or with long-reach feller-bunchers), there are obvious timber supply, biodiversity, and aesthetic advantages to having a jump-start of several decades when establishing the next stand (Lieffers *et al.*, 2003). Provisions for the protection of advance regeneration are now widely practiced in northern Québec, Ontario, and Alberta. In a similar manner, efforts are being made to better predict and manipulate the natural regeneration of conifers through the modelling of dispersal distance and substrate (seedbed) distributions (Greene & Johnson, 1999; Greene *et al.*, 2002). DeLong (2002) has identified several other forest management practices that offer ecological benefits and reduced costs over standard operating procedures, including the amalgamation of dispersed cutblocks into larger openings more representative of natural patch (fire) sizes, incorporating irregular boundaries and elevated levels of residual structure; greater acceptance of broadleaf trees in assessing the free-growing status of conifer plantations; and reduced levels of conifer stocking and recognition of the importance of persistent shrub patches in wet ecosystems, thereby reducing requirements for replanting and vegetation control. These "win-win" solutions are being actively adopted throughout the Canadian boreal forest.

Several case studies of progress to SFM in boreal Canada are showcased by Burton *et al*. (2003a), and five are presented in detail by Hebert *et al*. (2003). These case studies demonstrate institutional movement from the traditional approach of sustained-yield timber management to a broader strategy of sustainable management of all forest values, viewing the forest as an ecosystem and a living landscape rather than a timber crop. Although the range of approaches to implementation indicates both a socio-economic basis and an ecological basis for the change, there are some commonalities. In many cases, social and ecological sciences have generated innovations that can lead to SFM but true change depends on creative social solutions and innovative leadership. In other cases, long-held beliefs about the nature of Canadian boreal landscapes and boreal forest ecology have simply been incorrect, so the science has had to catch up first. For example, recognition of the prevalence and importance of "skips" and residual structure after wildfires (Eberhart & Woodard, 1987; DeLong & Kessler, 2000; Smyth *et al*., 2005) has resulted in the incorporation of residual green-tree patches ("wildlife tree patches" or "variable retention harvesting") into cutblock design (Work *et al*., 2003). Likewise, recognition of the prevalence and importance of older stands (McCarthy, 2001; Kneeshaw & Gauthier, 2003) that tend to escape wildfire or insect outbreaks has suggested the need for some extended rotations or a "multi-cohort model" of forest management (Bergeron *et al.*, 1999; Harvey *et al*., 2003). A three-cohort model incorporating gap-based selection management of the oldest forests is being tested in black spruce (*Picea mariana*)–feathermoss forests in northwestern Québec (Harvey *et al.*, 2003).

Adaptive management and forest certification

We now recognize that our understanding of the complex boreal forest system is far from perfect and that our knowledge will need to improve constantly in the future. This lack of knowledge, however, should not be used to stop us from trying to do things differently and more sustainably. We need to learn by doing; our mistakes, although unfortunate, can be used to improve the way we manage forests if forestry is conducted in an explicitly adaptive framework. As Duinker and Trevisan (2003) have commented, adaptive management "can be envisioned as staying on the wrong road long and smart enough to know." Adaptive management is a structured process whereby various stakeholders agree to establish a learning and experimental process around the system they want to manage. It provides a framework by which to act and learn under constant uncertainty.

To implement an adaptive forest management plan, forest managers need to have a very good planning process with a clear vision of the forest to be managed, clear values to be managed, and the ability to forecast or model the future conditions of the forest and human systems through easily measured indicators. Once a set of comparative management options ("active" adaptive management or the option currently considered best, "passive" adaptive management) is selected, it needs to be implemented with enough resources to monitor the results and understand the differences between the planned and actual outcome (Duinker & Trevisan, 2003). Such systems of adaptive management can work well when regulatory constraints are not too stringent, so that the manager is free to try implementing innovative approaches. In much of Canada, however, current regulatory constraints are too rigid to allow the full implementation of adaptive management on public forest lands. What is required is a system of third-party audits or independent inspections that have a direct link to market access.

This need has been widely recognized by forest managers, forest products marketers, enlightened consumers, and environmental activists, such that a number of certification systems for sustainable forestry have mushroomed around the world over the last 10 years. In Canada, the most common certification systems are the performance-based Sustainable Forestry Initiative (SFI) standard and Forest Stewardship Council (FSC) principles and the management-system–based Canadian Standards Association (CSA) Z809 standard for sustainable forest management (Duinker & Trevisan, 2003). There obviously is no single "best" system, and there are marketing and political reasons why different companies have adopted different approaches. We believe that a combination of performance-based standards (to ensure basic protection of ecological values, human rights, and the rule of law) and management-based standards (to ensure a commitment to public input and adaptive management) offers the best road to sustainable management of the boreal forest.

In addition to adaptive forest management, adaptive management in policy and regulatory schemes is required. Innovation and experimentation in policy is necessary to identify approaches that may succeed in better signalling the scarcity of environmental services. There are many unknowns regarding responses to policy change and their unintended consequences, so some explicit experimentation in these areas is also required. Unfortunately, there is considerable resistance to this form of adaptive management: governments tend to be very rigid and uneasy about trying alternative policies and regulatory frameworks. Hopefully, the increased use of pilot projects (*e.g.*, in innovative forest practices, community forests, and an open log market, as tested in British Columbia over the last few years) and lessons learned from the Canadian Model Forest Program will lead the way.

Conclusion

The predominant factors regulating the change from sustained-yield timber management to sustainable forest management are cost, changing values/expectations, public pressure, and science-based information. In most cases, increased cost is incurred through AAC reduction and the costs of planning and operations, which range from 5 to 50% above those of standard command-and-control planning followed by clearcutting and even-aged timber management (Hebert *et al*., 2003). Without adequate scientific knowledge, initial attempts to implement SFM have generally been prescriptive, ecologically conservative, and often disproportionate to the desired outcome. Without information on thresholds and cost-effectiveness, it is difficult to determine realistic costs and ecologically efficient targets that can be tested. Establishing these targets is critical for an incentive-based or "results-based" forest management policy.

In general, the Canadian forest products industry is being dragged towards SFM, as ecosystem management is poorly linked to efficient wood and paper production. Even where the commitment to SFM is made, it is institutionally difficult to develop multi-scale SFM frameworks with testable targets that can be adjusted using adaptive management and the modelling of tradeoffs. Not only must tradeoffs within scales (*e.g.*, variable retention at the stand level *versus* extended rotations) be examined, but tradeoffs between ecological and economic components must be assessed. Forest managers, researchers, and policymakers have not yet established the culture of experimentation and adaptive management that is necessary to articulate the research questions and generate the science required to evolve toward SFM. In order to produce relevant questions that will generate useful answers, the industry and its government regulators must formulate an SFM framework that includes multi-scale strategies with social, ecological, and technological components. Genuine partnerships between forest managers and forest researchers, transcending the narrow cultures of each group, are a key step in meeting this objective, and progress in this regard has been made through consortia such as the Sustainable Forest Management Network.

There is obviously room for improvement in the efficiency, environmental stewardship, and social responsibility of forest products companies and forest management agencies throughout the circumboreal region. But research and innovation, as promoted by a number of national initiatives, can be nurtured with appropriate support and eventually implemented in various operational settings. The initiative and financial support for innovation has variously come from industry, academia, government agencies, and industry–community arrangements that often circumvent government involvement (Hebert *et al*., 2003). Clearly, there are many options, only a few of which have been described in this paper, for conserving biodiversity, minimizing environmental impacts, sustaining economic prosperity, and supporting communities in meaningful and effective ways. Successful attainment of the broad set of forest values, including protection of wildlife, biodiversity, forest botanicals, clean water, recreational opportunities, rural lifestyles, community stability, corporate and provincial revenue, etc., will be difficult under even the best management system. And in some cases, achievement of such a broad set of often-conflicting goals may simply be impossible on a single forest land base. Therein lies the incentive for all forest managers to undertake new and different approaches to SFM, and to coordinate their efforts with their neighbours and with other sectors and stakeholders.

Future directions and needs

There are good prospects for sustainable management of Canada's boreal forest, but progress on the various fronts has been uneven. There are still broad needs for wilderness protection, active management for non-timber values, resolution of issues of aboriginal jurisdiction, and government/corporate commitment to the rural and remote communities found in our northern forests. Large areas of the boreal biome need to be left in a natural state, dominated by natural processes of disturbance and recovery, to serve not only as a template and benchmark for our efforts at sustainable management, but also as a reserve against unforeseen disruption and degradation initiated by human activities. Much of Canada is still undergoing exploitation, with cutting happening at rates that may not even be able to sustain timber production within defined forest areas, never mind being able to sustain old-growth and associated biodiversity values (Armstrong, 2004; Coulombe *et al*., 2004). For example, some provinces endorse exceeding the long-run sustained yield of a forest land base for several decades as part of a policy to regulate the forest age-class structure and pay for road infrastructure (Utzig & Macdonald, 2000; see technical analyses for individual timber supply areas at http://www.for.gov.bc.ca/hts/tsr.htm).

Experience has shown that the cumulative impacts of multiple land uses often outstrip the management ability and management intentions of any one agency or licensee. Sustainable forest management must incorporate integrated resource management, as we cannot have sustainable land management solely by the forest products sector. Multi-sectoral and multi-agency coordination for land stewardship will be more and more necessary as commercial interests in a finite land base increase (Schneider *et al.*, 2003).

The road to sustainable forest management forces us to rethink many of the basic assumptions and tools of forestry. For example, the whole concept of "forest inventory" needs to be revamped. While we still need to know the species, density, size, and age of trees, it is now clear that the age of the oldest tree in a stand is not equivalent to "stand age" or the time since disturbance. The associated assumptions behind growth and yield modelling and timber supply analysis also need to more accurately reflect the complex stand histories and stand structures found in many boreal forests. Furthermore, reliable planning for non-timber forest values requires the inclusion of non-timber resources in forest inventory protocols.

Inventory is just one step in a framework that must demonstrate a commitment to ongoing monitoring. While the command-and-control culture has emphasized inspections to ensure compliance with regulations, a meaningful program of adaptive management would instead involve effectiveness monitoring to evaluate whether plans and practices were having their intended consequences. Such truly long-term perspectives and a commitment to continual improvement and adaptation are perhaps the most difficult cultural attributes to instill in traditionally trained forest managers. Nonetheless, throughout much of northern Canada, marketplace pressures, trade disputes, and a rapidly changing climate are all serving to impress upon those managers the dynamic realities of post-modern forestry. There is a need for ongoing research on the ecology of northern biota, the effects of climate change, the best techniques for working with natural disturbances, and the socio-economics of remote and aboriginal communities. More creative teamwork is needed to generate and test new management approaches and to evaluate and improve simulation models of forest ecosystems and landscapes, all in the context of adaptive management. Institutional innovation is clearly required so that signals of scarcity or degradation of forest resources and environmental services will be reflected in management decisions.

Some problems and proposed solutions are especially in need of attention. For example, the implementation of some sort of zoning of the boreal forest into three or more parts (for conservation, extensive multiple-use forestry, and intensive primary uses such as enhanced timber production) appears to be one of the most promising ways to enhance ecological objectives at the same time as economic and social objectives (Vincent & Binkley, 1994; Messier, Bigué & Bernier, 2003). This possibility needs to be examined. The impact of provincial government decisions to delegate forest management responsibilities to corporate interests also begs for an impartial assessment. Are company foresters in an untenable conflict of interest? Can they reasonably be expected to be the watchdogs of public forest sustainability in the absence of a framework for public oversight?

Given the extreme spatial and temporal complexity of boreal forests and the need to maintain this heterogeneity as much as possible, it is clear that simple "one size fits all" solutions will never do the job. We need to move away from regulatory approaches that cannot reproduce and maintain this ecological complexity. Forest managers need to be able to vary forest management strategies, tactics, and operations according to the balance of outcomes desired in individual stands and landscapes. Canada's northern forests, still largely wild, offer us a few remaining years of opportunity in which to chart a sustainable future for conserving ecological values while enhancing socio-economic well-being. To what extent is this possible? In 20 or 30 years we may not have the luxury of asking this question.

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